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Gordon H. Reeves, *USDA Forest Service, PNW Research Station*
Deanna H. Olson, *USDA Forest Service, PNW Research Station*
Steven M. Wondzell, *USDA Forest Service, PNW Research Station*
Peter A. Bisson, *USDA Forest Service, PNW Research Station*
Sean N. Gordon, *Portland State University*, et al.

Chapter 7: The Aquatic Conservation Strategy of the Northwest Forest Plan—A Review of the Relevant Science After 23 Years

Gordon H. Reeves, Deanna H. Olson, Steven M. Wondzell, Peter A. Bisson, Sean Gordon, Stephanie A. Miller, Jonathan W. Long, and Michael J. Furniss[1]

Introduction

The Aquatic Conservation Strategy (ACS) is a regional strategy applied to aquatic and riparian ecosystems across the area covered by the Northwest Forest Plan (NWFP, or Plan), encompassing broad landscapes of public lands administered by the U.S. Department of Agriculture Forest Service and the U.S. Department of the Interior Bureau of Land Management (BLM) (USDA and USDI 1994a). The ACS was developed during the analysis (FEMAT 1993) that led to the NWFP, but its foundation was a refinement of earlier strategies: the Scientific Panel on Late-Successional Forest Ecosystems (“The Gang of Four”) (Johnson et al. 1991), PacFish (USDA and USDI 1994b), and the Scientific Analysis Team (Thomas et al. 1993).

The ACS uses an ecosystem approach to management of riparian and aquatic habitats (Everest and Reeves 2007) and was designed to (1) protect watersheds that had good-quality habitat and strong fish populations at the time the Plan was drafted, and (2) halt further declines in watershed condition and restore ecological processes that create and maintain favorable conditions in aquatic ecosystems in degraded ecosystems (FEMAT 1993). The long-term goal (100+ years) is to develop a network of functioning watersheds that supports populations of fish and other aquatic and riparian-dependent organisms across the NWFP area (USDA and USDI 1994a). The ACS is based on preserving and restoring key ecological processes, including the natural disturbance regimes (USDA and USDI 1994a) that create and maintain habitat for native aquatic and riparian-dependent organisms, and it recognizes that periodic natural disturbances may be required to sustain ecological productivity. As a result, the ACS does not expect that all watersheds will be in favorable condition (highly productive for the same aquatic organisms) at any point in time, nor does it expect that any particular watershed will remain in a certain condition through time. If the ACS and the NWFP are effective, the proportion of watersheds in better condition (for native organisms) is expected to remain the same or increase over time (Reeves et al. 2004).

The primary objective of the ACS is to maintain and restore the distribution, diversity, and complexity of watershed-level features and processes to which aquatic and riparian species are uniquely adapted. Programs and actions under the ACS are to maintain, not prevent, attainment of this goal. The ACS designates watershed analysis as the tool for developing baseline conditions against which to assess maintenance and restoration conditions, and improvements in biological and physical processes are to be evaluated relative to the natural range of variability (USDA and USDI 1994a). ACS objectives address (1) diversity and complexity of watershed features; (2) spatial and temporal connectivity within and between watersheds; (3) physical integrity; (4) water quality; (5) sediment input, storage, and transport; (6) instream flows (e.g., both peak and low flows); (7) floodplain inundation; (8) riparian plant-species composition and structural diversity; and (9) habitat to support well-distributed populations of native, aquatic and riparian-dependent species of plants, invertebrates, and vertebrates.

The ACS sets out five components to meet its goals:

- **Riparian reserves**: Riparian reserves are specifically designated portions of the watershed most tightly coupled with streams and rivers that provide

[1] **Gordon H. Reeves** is a research fish ecologist, **Deanna H. Olson** is a research aquatic ecologist, and **Steven M. Wondzell** is a research geologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331; **Jonathan W. Long** is a research ecologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 1731 Research Park, Davis, CA 95618; **Peter A. Bisson** is a research fish ecologist (retired), U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 3625 93rd Avenue SW, Olympia, WA 98512; **Michael J. Furniss** is a hydrologist (retired), U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 1700 Bayview Drive, Arcata, CA 95521-6013; **Sean Gordon** is a research assistant professor, Institute for Sustainable Solutions, Portland State University, 1600 SW Fourth Avenue, Portland, OR 97204; **Stephanie A. Miller** is the Riparian Program lead, U.S. Department of the Interior, Bureau of Land Management, 20 M Street SE, Washington, DC 20001.

the ecological functions and processes necessary to create and maintain habitat for aquatic and riparian-dependent organisms over time, as well as habitat connectivity within and between watersheds. The reserve boundaries were considered interim until a watershed analysis was completed, at which time they could be modified based on suggestions made in the watershed analysis.

- **Key watersheds**: 5th-code (40,000 to 250,000 ac [16 187 to 101 171 ha]) to 6th-code (10,000 to 40,000 ac [4047 to 16 187 ha]) hydrologic units that were intended to serve as refugia for aquatic organisms, particularly in the short term for at-risk fish populations, and had the greatest potential for restoration, or to provide sources of high-quality water. At the time the NWFP was drafted, Tier 1 key watersheds had strong populations of fish, productive habitat that was in good condition, or high restoration potential. Tier 2 key watersheds provided sources of high-quality water.
- **Watershed analysis**: An analytical process that characterizes the features and processes of watersheds and identifies potential actions for addressing problems and concerns, along with possible management options. It assembles information necessary to determine the ecological characteristics and behavior of the watershed and contribute to the development of options to guide management in the watershed, including adjusting riparian-reserve boundaries.
- **Watershed restoration**: Includes actions deemed necessary to restore degraded ecological processes and habitat. Restoration activities focus on restoring the key ecological processes required to create and maintain favorable environmental conditions for aquatic and riparian-dependent organisms.
- **Standards and guidelines**: These directives impose specific requirements (standards) or recommended approaches (guidelines) for management activities in riparian reserves and key watersheds.

Note that a key philosophical shift occurred in the development of the ACS and NWFP as compared with efforts prior to 1993. The ACS, along with PACFISH (USDA and USDI 1994b) and the riparian component of the Tongass Land and Resource Management Plan (USDA FS 1997), made two substantive changes in how riparian management was formulated (Everest and Reeves 2007). First, they addressed riparian management at the watershed scale (5th- to 6th-code hydrologic units), with specific emphasis on maintaining ecological functions over the long term. Second, they rejected the previous philosophy of trying to define and achieve the absolute minimum set of practices that would meet stated riparian-management goals, and the concept that goals could be met by implementing yet another set of best management practices. The new (at that time) management philosophy under the NWFP represented a paradigm shift in how managers viewed resource coordination. In previous riparian rule-sets, riparian and aquatic technical specialists shouldered the "burden of proof" to demonstrate resource damage from forestry activities and the need for more comprehensive forest-practices rules to meet riparian-management goals. Under the NWFP, the precautionary principle was invoked—the burden of proof shifted (Thomas et al. 2006, USDA and USDI 1994a). Forest managers who wanted to alter the comprehensive default prescriptions for riparian management under the NWFP (described above) to pursue other management goals were required to demonstrate through watershed analysis that changes would not compromise established riparian-management goals.

This chapter focuses on the scientific literature related to the management and conservation of aquatic ecosystems, particularly as it has developed since the 10-year NWFP review (Reeves 2006), with particular emphasis on the area of the NWFP. Among the key issues considered are:

- The ecological, physical, and biological importance of headwater and intermittent streams.
- The contribution of periodic disturbances to the resilience and productivity of aquatic ecosystems.
- The inherent variation of aquatic ecosystems in space and time.
- A better understanding of the variation in where key ecological processes occur within the stream network and the development of new tools to identify these locations.

- An understanding of the variation in the capacity of aquatic ecosystems to provide habitat for various fish species.
- Awareness of climate change and its potential effects.

We provide an update on the status of species listed under the Endangered Species Act (ESA) and the components and the associated monitoring program (Aquatic and Riparian Effectiveness Monitoring Program [AREMP]) of the ACS. We also assess the implications for the potential evolution of the ACS in the next round of forest plans. Reeves (2006) provided a thorough review of the literature in the first 10 years of the ACS, and readers should refer to that publication for a review of the relevant science during that time.

Guiding Questions

Federal land managers submitted many questions that they deemed necessary to consider in the NWFP science synthesis to help with any revisions of forest plans. Because there was substantial overlap among and duplication in the questions, we distilled them into categories represented by the following eight questions to guide our update and assessment:

1. Is the science foundation of the ACS still valid, or does science developed since 1993 suggest potential changes or adjustments that could be made to the ACS?
2. What is the basis of trends observed in the ACS monitoring program, and what are the limitations, uncertainties, and research needs related to monitoring?
3. What is known about the variation in characteristics of unmanaged streams and riparian ecosystems in relation to stream networks across the NWFP area?
4. What has been learned about the effects of riparian vegetation on stream habitat and environments?
5. What effects have human activities had on stream and riparian ecosystems?
6. What is the scientific basis for restoration management in riparian reserves, and how does restoration relate to the ecological goals of the ACS?
7. What is the capacity of federal lands in the NWFP area to contribute water for a suite of economic, recreational, and ecological uses?
8. What are the potential effects of climate change on aquatic ecosystems in the NWFP area, and are these adequately addressed by the ACS?

These eight questions are not answered specifically in sequence because of the overlap among them and the variety of topics they involve. They are, however, answered to the extent possible in different or multiple sections of the chapter, and are addressed in outline in the conclusions.

Key Findings

Status of Species and Population Units Listed Under the Endangered Species Act on Federal Lands in the Northwest Forest Plan Area

In 1993, only the Sacramento winter Chinook salmon (*Oncorhynchus tshawytscha*), and the shortnose sucker (*Chasmistes brevirostris*), and Lost River sucker (*Deltistes luxatus*, both native to the Klamath River system) were listed as threatened or endangered under the ESA in the area covered by the NWFP. Within a few years of the development of the ACS, 23 evolutionarily significant units of Pacific salmon and 3 distinct population segments of bull trout (*Salvelinus confluentus*) were listed under the ESA (table 7-1). There have been three additions since the 10-year review (Reeves 2006): the Oregon Coast coho salmon evolutionarily significant unit (*O. kisutch*), and two other fish species, the Oregon chub (*Oregonichthys crameri*) and the Pacific eulachon (*Thaleichthys pacificus*). No population units of Pacific salmon or bull trout have warranted delisting since the ACS was developed.[2] However, the Oregon chub was delisted in 2015 (USFWS 2015), becoming the first fish to be delisted because of increases in numbers. Habitat on the Willamette National Forest contributed to its recovery.

The developers of the ACS anticipated the ESA listing of distinct population segments of various species of Pacific salmon, evolutionarily significant units, and other fish species. The ACS was not expected to prevent the listing of any species or distinct population segment because factors outside the responsibility and control of federal

[2] http://www.westcoast.fisheries.noaa.gov/publications/status_reviews/salmon_steelhead/2016_status_review.html.

Table 7-1—Evolutionarily significant units (ESUs) of Pacific salmon and trout (*Oncorhynchus* spp.), distinct population segments (DPSs) of bull trout (*Salvelinus confluentus*), and fish and amphibian species listed under the Endangered Species Act that occur in the area covered by the Northwest Forest Plan

Species[a]	ESU/DPS/species	National forests (NFs) and Bureau of Land Management (BLM) districts in which ESU, DPS, or species occur
1. Fish		
Coho salmon	Lower Columbia/ southwest Washington	Gifford Pinchot and Mount Hood NFs
	Oregon coast	Siskiyou, Siuslaw, and Umpqua NFs; Coos Bay, Eugene, Roseburg, and Salem BLM districts
	Southern Oregon/northern California	Klamath, Mendocino, Rogue River–Siskiyou, Shasta-Trinity, and Six Rivers NFs; Arcata, Medford, and Redding BLM districts; Kings Range National Conservation Area (NCA)
	Central California coast	Ukiah BLM district
Chinook salmon	Puget Sound	Gifford Pinchot, Mount Baker–Snoqualmie, and Olympic NFs
	Lower Columbia	Gifford Pinchot and Mount Hood NFs; Salem BLM district
	Upper Columbia	Okanogan-Wenatchee NF
	Upper Willamette	Mount Hood and Willamette NFs; Eugene and Salem BLM districts
	California coastal	Mendocino and Six Rivers NFs; Arcata and Ukiah BLM districts; Kings Range NCA
	Sacramento River winter run	Mendocino and Shasta-Trinity NFs; Mendocino BLM district
	Central Valley spring run	Shasta-Trinity NF; Mendocino and Redding BLM districts
Chum salmon	Hood Canal summer	Olympic NF
	Columbia River	Salem BLM district
Steelhead	Puget Sound	Gifford Pinchot, Mount Baker–Snoqualimie, and Olympic NFs
	Lower Columbia	Gifford Pinchot and Mount Hood NFs; Salem BLM district
	Mid-Columbia	Gifford Pinchot, Mount Hood, and Wenatchee NFs
	Upper Columbia	Okanogan-Wenatchee NF
	Upper Willamette	Willamette NF; Eugene and Salem BLM districts
	Northern California	Mendocino and Six Rivers NFs; Arcata, Mendocino, and Ukiah BLM districts; Kings Range NCA
	Central California coast	Arcata BLM district; Kings Range NCA
	Central Valley, California	Mendocino and Shasta-Trinity NFs Mendocino BLM
Bull trout	Klamath River	Fremont-Winema NF
	Columbia River	Deschutes, Gifford Pinchot, Mount Hood, Okanogan-Wenatchee, and Willamette NFs; Eugene BLM district
	Coastal—Puget Sound	Mount Baker–Snoqualmie and Olympic NFs
Lost River sucker		Fremont-Winema NF
Shortnose sucker		Fremont-Winema NF
Pacific eulachon		Siuslaw and Six Rivers NFs

Table 7-1—Evolutionarily significant units (ESUs) of Pacific salmon and trout (*Oncorhynchus* spp.), distinct population segments (DPSs) of bull trout (*Salvelinus confluentus*), and fish and amphibian species listed under the Endangered Species Act that occur in the area covered by the Northwest Forest Plan (continued)

Species[a]	ESU/DPS/species	National forests (NFs) and Bureau of Land Management (BLM) districts in which ESU, DPS, or species occur
2. Amphibians		
Oregon spotted frog (T)		Deschutes, Fremont-Winema, Gifford Pinchot, Mount Hood, and Willamette NFs; Klamath Falls and Medford BLM districts; Columbia River Gorge National Scenic Area (NSA) (S)
Cascades frog (petitioned)		Deschutes, Gifford Pinchot, Mount Baker–Snoqualmie, Mount Hood, Okanagan-Wenatchee, Olympic, Rogue River–Siskiyou, Umpqua, and Willamette NFs; Medford (S), Roseburg, and Salem BLM districts
Oregon slender salamander (petitioned)		Mount Hood and Willamette NFs; Columbia River Gorge NSA
Cascade torrent salamander (petitioned)		Gifford Pinchot, Mount Hood, and Willamette NFs; Eugene and Salem BLM districts; Columbia River Gorge NSA
Columbia torrent salamander (petitioned)		Siuslaw NF; Salem (S) BLM district
Western pond turtle (petitioned)		Fremont Winema, Mount Hood, Rogue River–Siskiyou, Siuslaw, Umpqua, and Willamette NFs; Columbia River Gorge NSA; Coos Bay, Eugene, Klamath Falls, Medford, Roseburg, and Salem (S) BLM districts

[a] Petitioned = under review for Endangered Species Act listing; T = threatened; S = suspected occurrence.

land managers contribute to the decline and recovery of fish populations and will strongly influence their recovery. These factors include:

- Degradation and loss of freshwater and estuarine habitats on nonfederal lands (McConnaha et al. 2006, NRC 1996).
- Excessive harvest in commercial and recreational fisheries (NRC 1996).
- Migratory impediments, such as dams (McConnaha et al. 2006, NRC 1996).
- Loss of genetic integrity from the effects of hatchery practices and introductions, combined with undesirable interactions (e.g., competition and predation) involving hatchery and naturally produced fish (Araki and Schmid 2010, NRC 1996).

Thus, the ACS was an attempt to develop a strategy to guide management of aquatic ecosystems on federal lands in the NWFP area that would meet potential ESA requirements. The ACS was expected to make significant contributions to the recovery of the ESA-listed fish by increasing the quantity and quality of freshwater habitat for Pacific salmon and protecting and enhancing habitats of other species (FEMAT 1993). Although the condition of habitat in aquatic ecosystems on federal lands appears to have improved at least slightly over the NWFP area, this has not been sufficient to change the status of most listed fish.

The potential of federal lands to contribute to the recovery of listed fish, particularly Pacific salmon, in many parts of the NWFP area is likely more limited than was recognized when the ACS was developed. The primary reason for this difference

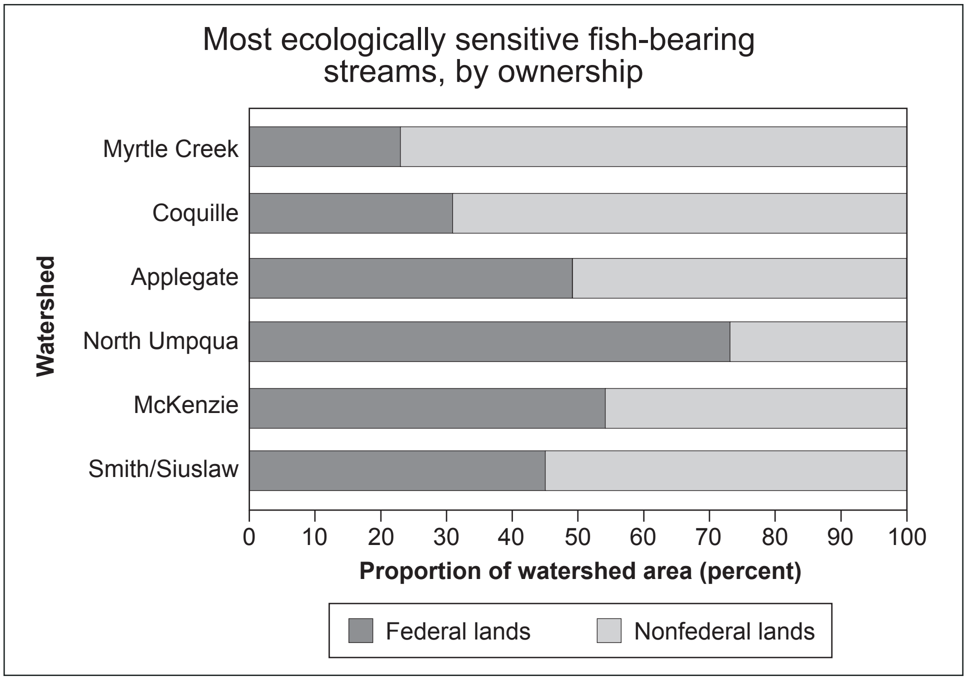

Figure 7-1—Proportion of the length of fish-bearing streams categorized as most ecologically sensitive in the six study watersheds of Reeves et al. (2016a) in western Oregon, by ownership. Ecologically sensitive areas are portions of the stream network that (1) have moderate- to high-quality habitat potential for coho and Chinook salmon and steelhead, (2) have moderate to high potential to warm if the riparian ecosystem is modified, and (3) have moderate to high potential for erosion or debris flows. From Reeves et al. 2016a.

is that, in many situations, federal lands (figs. 7-1 and 7-2) have a limited capacity to provide high-quality habitat for some of the listed fish. Federally managed lands are generally located in the middle to upper portions of watersheds, which tend to have steeper gradients and more confined valleys and floodplains, making them inherently less productive for some fish (Burnett et al. 2007, Lunetta et al. 1997, Reeves et al. 2016a). Federal lands may, however, be important sources of wood, sediment (Reeves et al. 2016a), and water (Brown and Froemke 2010, 2012) for downstream nonfederal lands, and will be important for the potential recovery of most populations. Nevertheless, their contribution to recovery may in many cases be insufficient without parallel contributions from nonfederal land ownerships elsewhere in the basin (Grantham et al. 2017).

The numbers of Pacific salmon and other anadromous fish returning to freshwater in the NWFP area are strongly influenced by ocean conditions, which are highly variable over time. Favorable conditions (cold water) tend to occur in the negative phase of the Pacific Decadal Oscillation (PDO) and the La Niña phase of the El Niño-Southern Oscillation (ENSO), when fish growth is strong and survival is high, resulting in strong returns of adults to freshwater (Mantua et al. 1997). Survival is low and numbers decline during warmer periods, especially during the positive phase of the PDO and the El Niño phase of the ENSO. Winters are cold and wet in the negative PDO–La Niña phase, which also creates more favorable conditions in freshwater (Mantua et al. 1997). A positive PDO–El Niño produces dry, warm winters, reducing streamflows, increasing water temperatures, and increasing the occurrence of fire (see chapter 3). The last extended period of high productivity was from the late 1940s to 1976 (Mantua et al. 1997), with brief periods of favorable conditions in 1984–1988, 1999–2002,[3] and 2010–2011 (Bond et al. 2015). However, beginning in 2013, abnormally warm conditions in the Pacific Ocean ("the Blob") developed because of lower-than-normal heat loss from the ocean to the atmosphere, combined with a relatively weak mixing of the upper ocean layer owing to an usually high atmospheric pressure (Bond et al. 2015). Initial effects were most notable in the North Pacific Ocean off Alaska. Ocean conditions changed noticeably along the NWFP area in 2014 as a result, and fish returns are expected to decline over the next few years.

[3] Mantua, N. 2017. Personal communication. Leader Landscape Ecology Team, National Marine Fisheries Service–Southwest Fisheries Science Center, 8901 LaJolla Shores Drive, Santa Cruz, CA 92037. nate.mantua@noaa.gov.

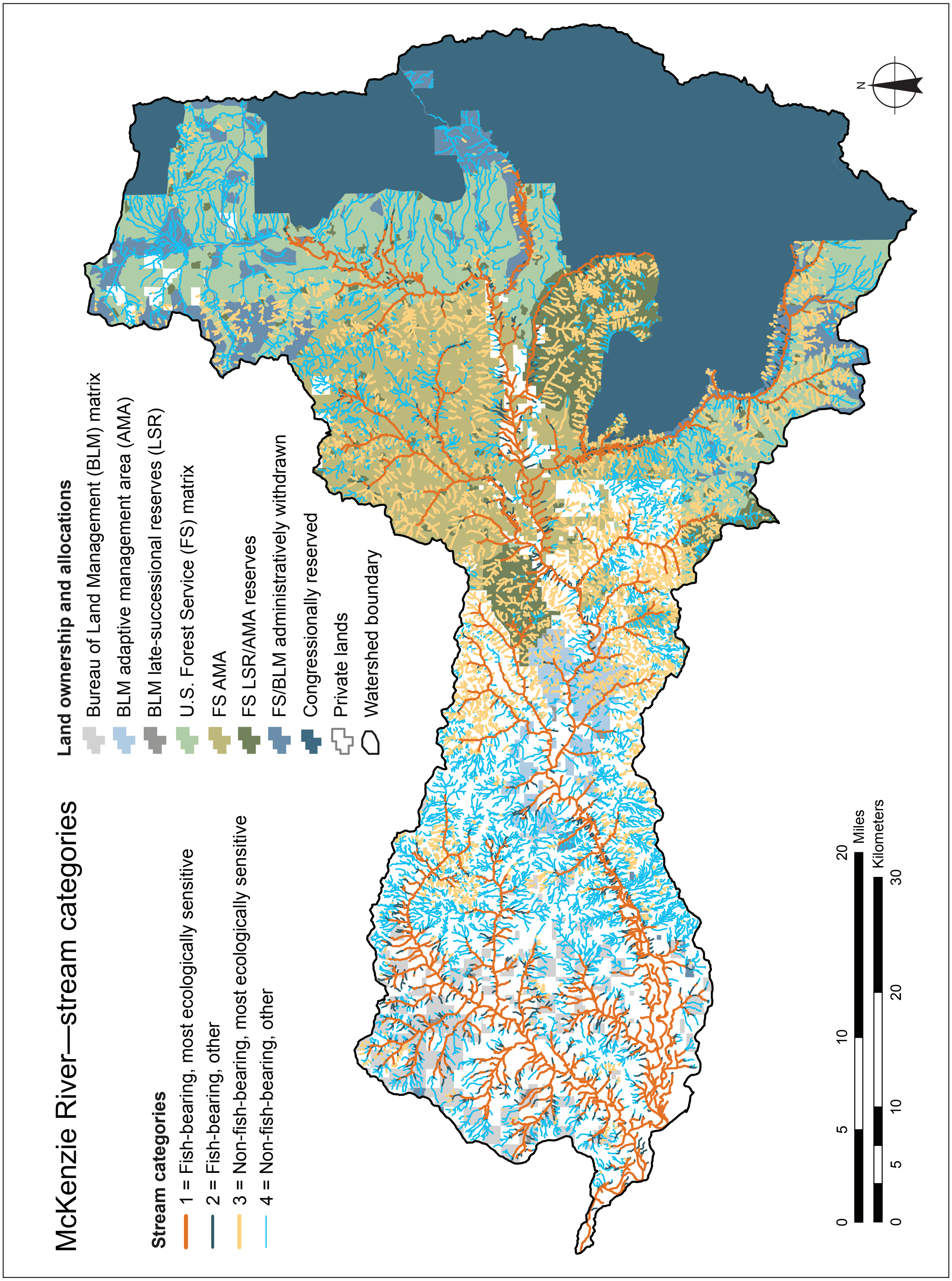

Figure 7-2—Distribution of ecologically sensitive stream reaches on federal and nonfederal lands in the McKenzie River watershed, Oregon. From Reeves et al. 2016a.

We are unable to separate the influence of ocean conditions over the last 10 years from the influence of changes in the condition of freshwater ecosystems on federal lands that may have occurred under the NWFP and ACS. The actual contribution of freshwater habitats to the persistence and recovery of anadromous salmon and trout will be relatively more important when ocean conditions move into a less-productive phase (Lawson 1993). Improvements in the quantity and quality of freshwater habitat resulting from the ACS could result in relatively greater numbers of fish entering the ocean, thus increasing the likelihood of persistence of many populations during periods of low ocean productivity. However, as noted previously, the contribution of federal lands may be more limited than expected because their potential to provide high-quality habitat is less than originally recognized when the ACS was developed.

The status of other aquatic-riparian species in the NWFP area is not as well monitored as that of Pacific salmon. The Oregon spotted frog (*Rana pretiosa*) was listed as threatened under the ESA in 2014. It is a pond-breeding amphibian now restricted to isolated populations that overlap the NWFP area in western Washington and Oregon.[4] Five other aquatic-riparian amphibian and reptile species are petitioned for ESA listing and are under status review: (1) Columbia torrent salamander, *Rhyacotriton kezeri*; (2) Cascade torrent salamander, *R. cascadae*; (3) Cascades frog, *Rana cascadae*; (4) Oregon slender salamander, *Batrachoseps wrighti*; and (5) western pond turtle, *Actinemys marmorata*. The two torrent salamanders are headwater forest species, occurring predominantly in and along the banks of small streams, with significant portions of their ranges on nonfederal lands. Nevertheless, federal riparian reserves contribute habitat for localized populations of Columbia torrent salamanders and more extensive areas for Cascade torrent salamanders. The Oregon slender salamander is found in proximity to down wood on the forest floor in riparian and upland forests, and has associations with older forest conditions (Clayton and Olson 2007). Cascades frogs are pond breeders at higher elevations in the Cascade Range, where they may be affected by multiple stressors (Pope et al. 2014). Similarly, multiple threats appear to affect western pond turtles, which may occur in stream and pond systems in the NWFP area (Rosenberg et al. 2009).

Monitoring—Aquatic and Riparian Effectiveness Monitoring Program

Watershed conditions—

The Aquatic and Riparian Effectiveness Monitoring Program is responsible for monitoring, assessing, and reporting on watershed conditions on lands governed by the NWFP. Although NWFP implementation began in 1994, AREMP implementation was delayed to accommodate the time needed for its design. The scope of the AREMP sampling design includes field-data collection across 250 watersheds in the Plan area, with a rotation of sampling among watersheds conducted each year so that the entire population of watersheds selected for monitoring would be sampled over an 8-year period. In addition, using geographic information system (GIS) and remotely sensed data are used to quantify roads and vegetation in 1,974 watersheds with federal lands in the Plan area and assess the condition of upslope and riparian areas.

Pilot monitoring of watershed conditions began in 2000, and the monitoring plan was finalized in 2003 (Reeves et al. 2004). The first full rotation of watershed visits was conducted in years 2002–2009, assessing initial status, and the second full rotation is scheduled to occur in 2010–2018 where paired assessments of most watersheds were possible owing to watersheds being resampled a second time. Reporting is on a 5-year cycle, in synchrony with NWFP establishment, with the first report covering up to year 10 of Plan implementation (Gallo et al. 2005), the second report covering up to year 15 (Lanigan et al. 2012), and the third to year 20 (Miller et al. 2017). The 20-year report includes assessment of data from the first rotation of watershed visits (2002–2009) and the first 4 years of the second rotation (2010–2013), and hence includes trend assessments based on a subset of sampled watersheds.

Changes in data collection and aggregation procedures, and in application of analytical methods, were anticipated from the onset of the development of AREMP (Hohler et al. 2001). In the late 1990s, our understanding of watershed

[4] http://www.fs.fed.us/r6/sfpnw/issssp/agency-policy/.

ecology and watershed-condition assessment approaches was acknowledged to be limited, and advances in both ecological and statistical disciplines were expected to contribute to further development of AREMP assessments. Indeed, both data sources and analyses have changed over time, with the consequence being that the results from each of the reports are not directly comparable. For example, relative to data sources, some data-collection procedures changed as attribute variability became apparent. Relative to analytical approaches, the 10- and 15-year analyses used decision support models (Reeves et al. 2004, Reynolds et al. 2014) that depended on empirical relations and expert judgment to evaluate data. The 20-year report employed a more statistical focus, with expert opinion and independent analysis of upland, riparian, and in-channel metrics. Additional discussion of adaptive processes through AREMP implementation, including anticipated next steps for research, is presented following the key 20-year findings. Although data analysis and assessment methods changed, each report reanalyzes the entire spatial and temporal dataset available at the time, and is intended to represent the most current understanding of status and trends since the beginning of the Plan.

Key 20-year findings—

The 20-year AREMP report (Miller et al. 2017) examined upslope-riparian and in-channel datasets separately. This segregation acknowledged that the source data differed significantly between these two components. Upslope-riparian data were derived from remote sensing and GIS landscape data covering all NWFP watersheds (watersheds containing more than 5 percent federal ownership, a total of 1,974 watersheds). In contrast, in-channel data were derived from annual field measurements, and therefore were limited to 213 sampled watersheds. Upslope-riparian assessments integrated five data types reflecting watershed processes: sedimentation, wood recruitment, riparian condition and processes, hydrology, and fish passage. In-channel analyses focused on three additional data types, assessed independently: physical-habitat condition, macroinvertebrate assemblages, and water temperature.

Upslope-riparian analyses integrated finer scaled data metrics reflecting indicators of key watershed processes. These processes included (1) stream-sediment delivery from landslides, based on road and vegetation disturbances, in addition to geology and climate attributes; (2) down-wood production and delivery, based on riparian and upland vegetation metrics; (3) riparian condition and associated processes as represented by stream temperature, streambank stability, and species-habitat provision based on riparian vegetation condition and riparian road density; (4) hydrology, focusing on peak flow, based on road and vegetation metrics; and (5) fish passage, based on stream gradient and assessment of barriers (e.g., dams, some road crossings). Using a multicriteria assessment approach, akin to analyses conducted in previous reports, attributes for a watershed were scored to a common 0 to 100 scale, reflecting an index of most-to-least deviation from least human-disturbed conditions.

The 20-year report found little change in the average upslope-riparian condition, from a score of 68 in 1993 to 69 in 2012. However, noticeable shifts were observed in the overall score distribution (fig. 7-3A). In particular, there was a noticeable increase in scores from the low to mid range (15 to 50) to a higher range (60 to 90), whereas the area with the highest scores (>90) decreased slightly. These patterns reflected a signature of federal land use allocations. The mean score in the most protected category of land use allocation (Congressionally reserved lands) decreased (−1), indicating greater disturbance, whereas averages for late-successional reserves and matrix lands increased (+2, +3), indicating less disturbance. The upward shift in the low-range scores is likely attributed to widespread vegetation regrowth and targeted road decommissioning in previously harvested watersheds. In contrast, the decrease in the high-end scores mainly followed the pattern of large fires during the assessment period, many of which occurred in wilderness areas, including the Biscuit Fire in southwest Oregon (2002), the B&B Complex fires in the central Oregon Cascade Range (2003), and numerous fires along the eastern edge of the North Cascade Range in Washington (2006).

It may seem counterintuitive that the most protected lands would show a trend toward more disturbance. Although this trend might be seen as negative because fire results in a loss of vegetation and an increase in riparian-upland disturbance, it is simplistic to consider this an

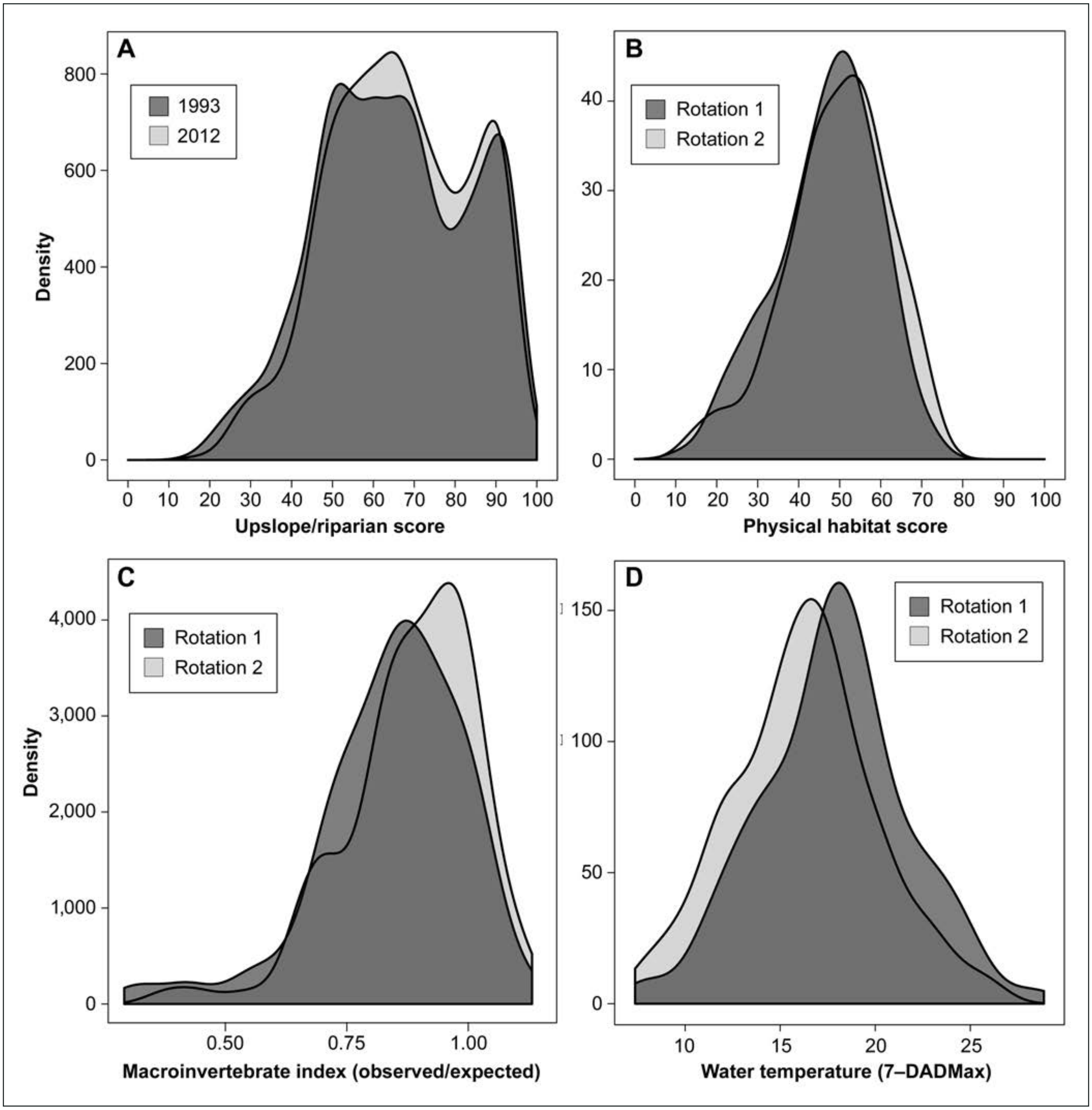

Figure 7-3—Results of the 20-year assessment of watershed conditions by the Aquatic and Riparian Effectiveness Monitoring Program (Miller et al. 2017): (A) upslope-riparian condition, (B) in-channel condition, (C) aquatic macroinvertebrates, and (D) 7-day running average of maximum water temperatures. Source: Miller et al. 2017.

adverse effect at the regional scale of forest ecosystems and their embedded watersheds. Wildfires are an integral component of long-term forest and stream ecosystem dynamics (e.g., Bisson et al. 2003, Franklin et at. 2017, Reeves et al. 1995), with direct benefits to stream habitats and biota resulting from fire (e.g., Flitcroft et al. 2016a) and related natural disturbances such as landslides (wood and sediment delivery to streams) (e.g., Benda and Dunne 1997a, 1997b; May and Gresswell 2003; Reeves et al. 2003). Aquatic-riparian ecosystems are dynamic, being multistate in space and time (Olson et al. 2017a, Penaluna et al. 2016). This recent AREMP finding highlights our nascent understanding of the range of historical aquatic-riparian conditions in the NWFP area and the cadence and extent of natural disturbance events. It also brings to the forefront the role of both passive and active management of these aquatic-riparian systems in the future to maintain and restore the dynamics of aquatic-riparian ecosystems in the region, and the importance of considering whether we need to manage for resilience. In this framework, shaped by land use allocations and trends detected therein, it is possible that development of more nuanced evaluation methods is needed to assess variation in aquatic-riparian conditions. The problem also becomes conceptually challenging, given a known shifted baseline from past anthropogenic disturbances, including the effects of fire suppression, as well as from the need to develop projections of climate change, climate extremes, and related disturbances from fire and landslides.

In-channel watershed-condition assessments conducted for the 20-year report were the first such assessments to have enough field-site revisits (about half the sample) to estimate trends. Instream conditions in subsampled watersheds in the Plan area were assessed by evaluating three separate elements: physical habitat, macroinvertebrates, and water temperature. First, for physical habitat, a composite index score (on a 0 to 100 scale, relative to unmanaged reference conditions; see below for more discussion on this topic) based on expert judgment was derived from substrate (percentage of fine substrates at a stream-reach scale), pool-tail fine substrates, and the frequency of medium- and large-size down wood. A small but statistically significant increasing trend (from 46 to 49) in overall physical habitat condition was detected when measured both on a yearly basis with all data and from the subset of watersheds that had been revisited (fig. 7-3B). Individual components of the physical habitat varied: reach-scale fine substrate showed an increasing trend in occurrence, whereas instream wood and pool-tail fine substrates showed no significant changes.

Second, an index was also derived for macroinvertebrates (fig. 7-3C), which were assessed at the site level, then grouped into taxonomic classes and compiled into a score representing the ratio of expected species based on reference sites (E = 1) (see below) to occurrence of no expected species (O = 0). Site-scale scores were aggregated into watershed scores. A positive change in the mean score was detected for macroinvertebrate diversity, suggesting a shift toward a species composition reflective of expected reference conditions.

Third, water temperature was evaluated using an integrated model that assessed 7-day maximum temperatures collected at low points in watersheds from June to September. Water temperature showed a decreasing trend, although temperature averages were still higher than federal and state standards for salmonid habitat (fig. 7-3D). Interestingly, water temperatures in all land use categories decreased, but temperatures in the most protected category showed the smallest decline, perhaps reflecting the upslope findings, which showed a signature of disturbance owing to vegetation loss in reserves.

Reflection on adaptive processes through AREMP implementation—
Here, we outline primary changes and challenges in AREMP monitoring over the past 20 years, many of which are ongoing research-emphasis areas. These topics are common, foundational aspects of many aquatic-riparian monitoring programs, representing a larger coalition of scientists and managers addressing similar themes over diverse landscapes. The science of watershed-scale ecology has followed the development of the discipline of landscape ecology, and the challenges cited here are representative of a parallel course of design and analytical adaptive processes occurring in terrestrial forest ecosystems.

Overall, NWFP monitoring, including the AREMP (Hohler et al. 2001), was framed as an adaptive-management cycle (Mulder et al. 1999). For AREMP, four primary changes and challenges over the course of the first 20 years of the NWFP have included (1) redefining the overarching objectives of watershed-condition monitoring, shifting from a salmonid habitat focus to one that was more representative of the environmental conditions of entire watersheds, while retaining selected key elements of salmonid habitats; (2) refining the indicators used in data collection and analysis; (3) reconsidering approaches to using benchmarks or reference conditions for assessment; and (4) modifying data integration methods. These four topics are discussed further below, with comparisons to other aquatic-monitoring programs for a broader perspective.

Defining objectives—

The first step in designing the NWFP monitoring modules was to define the goals and objectives of monitoring (Mulder et al. 1999). The NWFP defined the central question for aquatic ecosystems as, "Is the ecological health of the aquatic ecosystems recovering or sufficiently maintained to support stable and well-distributed populations of fish species and stocks?" (USDA and USDI 1994a, E-7). The primary fish taxa with status of concern in the NWFP area were native salmonids, hence a taxonomic focus was present from the origin of the Plan. Although particular species (owls, murrelets, salmonids) have been a principle interest of NWFP monitoring programs, concepts developed in the monitoring plan also stated that "Because of the current wide (and justified) interest in all components of biological diversity, however, the species-centric approach is no longer sufficient" (Mulder 1999, p. 29). In this vein, the language of the ACS objectives (USDA and USDI 1994a) had also included aquatic-riparian habitat conditions and species, but with a focus on multiple processes that were known to be tied to development of salmonid habitat conditions. At the time of the NWFP, emerging science on the role of disturbance in renewal of aquatic habitats also suggested a change in focus from the assessment of narrowly specified, in-channel habitat elements (e.g., a certain number of pieces of large wood per stream length) toward the ecosystem processes that form and maintain habitats (USDA and USDI 1994a). AREMP was perhaps the most ambitious of the monitoring modules in this regard, calling for monitoring a broad set of conditions in the upslope, riparian, and in-channel portions of watersheds that related to ecological processes tied to fish habitat, and evaluating these in comparison to broad distributions of conditions rather than solely on a watershed-by-watershed basis (Reeves et al. 2004).

The ACS was originally envisioned as a "coarse-filter" conservation effort (Hunter 2005, Noss 1987) (see additional discussion in chapter 12). The focus of the ACS was on restoring and maintaining ecological processes that created and maintained aquatic ecosystems for a suite of organisms, primarily ESA-listed fish, and for clean water and other ecosystem services (USDA and USDI 1994a). AREMP was, therefore, initially directed at the habitat of native salmonids, a primary responsibility of federal land managers and regulators in the NWFP area (Reeves et al. 2004). Habitat conditions for native salmonid fishes were initially used as metrics for watershed condition trend assessment, owing to their sensitivity to changes in several habitat features (e.g., water temperature, sediment, down wood). As with other coarse-filter assessments that use biotic indicators such as umbrella or flagship species (e.g., Raphael and Molina 2007), it was assumed that other aquatic and riparian-dependent organisms would benefit if watershed conditions for salmonids improved. Hence, salmonids were recognized as a focal species group, assuming that if their habitats were sustained or improved in condition over time, it would infer sustainability or improvement of the greater community of biota and the broader watershed-scale ecosystem functions and processes upon which they rely.

Development of aquatic monitoring programs requires a clear articulation of which biota and associated functional characteristics of habitats and ecosystems are being considered, and how they are likely to be altered as a result of the actions of interest (Carlisle et al. 2008, Palmer et al. 2005, Pont et al. 2006). Such species-based approaches may not fully account for the variation in species abundance or community composition present, given the spatiotemporal heterogeneity in ecosystem conditions generated by natural disturbances. Further, this natural variability in species and environmental conditions may make it difficult to identify the effects of anthropogenic disturbances and recovery from those disturbances, and thus make it difficult to assess and understand the ecological consequences of detected changes (Frissell et al. 2001). However, explicitly identifying the organism(s) of interest is essential for understanding what the monitoring results mean for those species and the fauna the species represents (Wohl 2016).

The 20-year AREMP analysis shifted from the emphasis of the 10- and 15-year analyses on evaluating habitat for salmonids to characterizing more general environmental conditions. Miller et al. (2017) used the 5^{th} and 95^{th} percentile values from a suite of physical attributes in reference sites in systems with the least human-caused disturbance (see later discussion) to determine the favorability of conditions for biota in monitored watersheds. Based on expert judgment, the 5^{th} percentile was considered the most favorable for some attributes (e.g., pool-tail fines, reach fines) and the 95^{th} for others (wood). However, Miller et al. (2017) did not identify which organisms these conditions were supposed to favor, making it difficult to understand the ecological validity of these values and the consequences of any changes detected.

This switch highlights a continuing scientific debate in the monitoring and assessment community on the merits of focusing assessments on particular flagship or umbrella taxa rather than on more general environmental processes and conditions. On the one hand, umbrella species serve as meaningful "endpoints" (Suter 2001) or "final ecosystem services" (Blahna et al. 2017) that provide relevance to monitoring results. On the other hand, in aquatic-riparian ecosystems, salmonid distributions do not reach headwater streams, which make up most of the stream length in NWFP watersheds (Gomi et al. 2002). Salmonid habitat in larger streams may not be representative of the condition of the entire watershed, unless solid ties to upstream and upslope conditions can be made. Further, the adequacy of salmonids as umbrella species has not been formally assessed (Murphy et al. 2010, Simberloff 1998), and there are questions about whether one species can be an indicator of the condition of other species (Carlisle et al. 2008). Although these two objectives for watershed-condition assessments (salmonid habitat versus watershed environmental conditions) are closely related, differences in emphasis have a ripple effect that plays out through the monitoring and assessment process, and affects how results might be interpreted relative to goals of maintaining and restoring conditions.

The original AREMP design document laid out a conceptual model that considered the interactions between upslope, riparian, and in-channel processes, all within a variable landscape (e.g., precipitation, geology) (Reeves et al. 2004). No formal assessment of relationships between upslope/riparian/in-channel indicators in the AREMP conceptual model has been published, but a number of studies are relevant to pieces of this framework. Burnett et al. (2007) developed a relative ranking, Intrinsic Potential (IP) ranging between 0 (poor) and 1 (excellent) to determine the geomorphic potential of a reach to provide habitat for coho salmon in larger streams. This work was followed by data-driven watershed-scale models of several habitat attributes important for salmon that tied upland-riparian conditions to instream habitats, including models of debris-flow-prone areas (delivering sediment to streams: Benda and Dunne 1997a, 1997b; Burnett and Miller 2007); wood recruitment (e.g., Reeves et al. 2004); and thermal loading (as a proxy to represent stream temperatures; see Reeves et al. 2016a). Several of these studies also contributed to a better understanding of instream processes connecting lower order headwater streams to higher order streams occupied by salmonids. Syntheses of these multifaceted watershed-process models have contributed to a better understanding of the multistate nature of aquatic-riparian ecosystems (Olson et al. 2017a, Penaluna et al. 2016, Reeves and Spies 2017), and integration of several of these watershed-integration models have been used to evaluate potential management options (Reeves et al. 2016a). Full incorporation of these concepts into watershed-condition assessments has been indirect to date, for example, by implicitly supporting approaches to assess upland-riparian areas and full in-channel networks from headwaters downstream. This topic deserves continued attention as AREMP procedures continue to develop, and can potentially inform the overarching objectives of the program.

Other aquatic-monitoring programs have incorporated upslope/riparian/in-channel relationships into their conceptual models, albeit in quite different ways. The National Rivers and Stream Survey (NRSA) (USEPA 2016) related four chemical and four physical habitat stressors to multimetric macroinvertebrate and fish indices using a concept of relative risk: the likelihood of finding poor biological conditions in a river or stream when stressor concentrations are high relative to the likelihood when they are low. Indirectly, these stressors, as well as three land-use metrics (urban land cover, agricultural row-crop land cover, and dam influence), were used in selecting the reference sites used to evaluate the stressor and response metrics.

PACFISH/INFISH Biological Opinion Monitoring Program (PIBO) approaches have not directly assessed upslope indicators, but have selected a set of physical-habitat indicators based on sensitivity to land-use management intensity, using road density as a surrogate (Al-Chokhachy et al. 2010). A recent assessment of the PIBO program conceptual model by Irvine et al. (2015) examined correlations between upslope (grazing, road density, percentage forested), in-channel habitat (fine sediment, temperature), and a macroinvertebrate observed/expected index. Although they found weak to no support for causal pathways related to effects of anthropogenic drivers on biological condition, they surmised that the conceptual model was sound, and the weak correlations were due to imprecision in the measurement of drivers (grazing, roads); stressors (sediment, measured in pool tails); and responses (macroinvertebrates, measured in riffles). They cited the more general issue that regional trend monitoring is not optimized for detecting causal mechanisms. A related and broader concern is that such surveys may underestimate infrequent but high-severity events (Suter 2001). In contrast, it was notable in the AREMP 20-year report that the signatures of wildfire and road decommissioning, relatively low-frequency events, were detectable in the upslope-riparian assessment because it included a full census of watersheds, rather than a limited sample. Overall, scientific work in the past 20 years has continued to support the dynamic, disturbance-based ecology of aquatic-riparian ecosystems (see "Natural Variability" section later in this chapter). Although the AREMP conceptual model has not changed, there have been numerous refinements to the indicators used, as well as to their combination and interpretation.

Selection of indicators—

In-channel biotic indicators**—**In-channel biotic metrics have proven to be particularly challenging to monitor. Although fish populations are of principal concern to managers because of regulatory requirements and their potential as umbrella or flagship species, fish-data collection was dropped from AREMP protocol in 2007 because most in-channel watershed sample sites were above salmonid habitat, and the collection of meaningful salmonid-habitat data would have required a separate and intensive effort. Similarly, streambank amphibians were dropped because of detectability issues. Variability in detection spatially within watersheds as well as temporally within the year made streambank amphibian monitoring challenging: species that were present at a site early in a season could be missed if the site is not sampled until later in the season. Further, terrestrial salamanders are fossorial (live largely subsurface) and may not have been detected even if present (e.g., Hyde and Simons 2001).

Macroinvertebrates are the only remaining in-channel biotic indicator collected by AREMP. Macroinvertebrates have come to play a central role in many aquatic-monitoring programs because of their presumed responsiveness to local environmental conditions and ease of collection (PIBO [Al-Chokhachy et al. 2010], Oregon Department of Environmental Quality [Hubler 2009], NRSA [USEPA 2016]). This commonality creates the potential for data sharing between monitoring programs, assuming sufficient similarity in the sampling methods used. However, differing results for the fish and macroinvertebrate indices in a recent national assessment emphasized the danger of relying on one taxonomic group to represent the potential responses or condition of other groups (USEPA 2016). Understanding how to reliably collect and incorporate data from taxa other than macroinvertebrates is a challenge for ongoing research; new multispecies environmental DNA methods are promising and are undergoing trial now (see app. 1).

***In-channel abiotic indicators*—**Measurement reliability has also been a challenge with abiotic in-channel indicators. Based on quality-control sampling, AREMP dropped the evaluation of pool frequency, depth, and median particle size from the latest 20-year assessment. Measurements of these parameters are still being collected, owing to the perceived importance of these indicators for assessment of habitat conditions, and the AREMP program is actively investigating ways to make current collections of these data more reliable for use in future analyses. Remaining abiotic indicators used in the latest report were pool-tail fine substrates, reach-scale fine substrates, down wood, and water temperature (Miller et al. 2017).

***Upslope-riparian indicators*—**The basic indicators used in the upslope-riparian portion of the AREMP assessments have changed little, but their evaluation has become more context sensitive. In the latest report, their combination was reorganized into an index with a more process-based structure. The new process-based model structure includes five processes that aligned it more directly with the conceptual model in the original AREMP plan: sediment and wood delivery, riparian shading, hydrology, and habitat connectivity. All these indicators are based primarily on road and vegetation data, the two major land-use metrics that can be traced backward in time to assess trends since the beginning of the NWFP. This estimation of historical data is a challenge that appears not to have been attempted by other broad-scale programs (Gordon 2014). Road and vegetation-management effects on aquatic systems continue to be active areas of research.

Of particular relevance to the AREMP assessment is work identifying the differential effects of sediment delivery from roads, based on landscape position (Al-Chokhachy et al. 2016, Black et al. 2012) and the incorporation of potential fish-habitat considerations into the measure of aquatic connectivity (Chelgren and Dunham 2015). Advances in satellite data and their classification have considerably expanded the available vegetation metrics and the ability to track these through yearly time steps (Kennedy et al. 2010, Ohmann et al. 2011). These capabilities should be examined in light of the disturbance-ecology paradigm discussed throughout this chapter.

Examining the freshwater assessment literature more generally, Kuehne et al. (2017) found a shift in measures used from field-based responses to landscape-stressor metrics. The use of upslope indicators is attractive to managers because this is where the most extensive management activities currently occur (vegetation, roads), and also because these measures are more easily collected via remote sensing and existing GIS data, and do not require more labor-intensive field surveys. Measuring and understanding both upslope and in-channel processes, and the relationships between them, is critical. Taking into account the difficulties encountered by other parallel aquatic-monitoring programs, more formal testing of the AREMP conceptual model is warranted.

Benchmarks for assessment—

In the data-assessment step of analysis, indicators are typically compared against some benchmark (alternatively referred to as standards, thresholds, or evaluation criteria) to come up with a measure of watershed or aquatic-habitat condition. This has proven to be one of the greatest challenges, particularly given the expanding recognition of the reliance of aquatic habitats on dynamic processes of disturbance and renewal. Such monitoring faces the fundamental challenge of using static measurements (with limited temporal frequency) to measure dynamic processes.

Stoddard et al. (2006) described a number of common approaches to choosing benchmarks: reference conditions, best professional judgment, interpreting historical condition, extrapolating from empirical models, and ambient distributions. The first two AREMP reports (10 and 15 year) relied on empirical models and expert judgment to set evaluation criteria (Gordon and Gallo 2011). To accommodate environmental heterogeneity, separate thresholds were solicited for seven aquatic provinces identified in the NWFP area. To accommodate environmental heterogeneity, separate thresholds were solicited for seven aquatic provinces identified in the NWFP area. In most provinces, experts were unwilling to commit to standards in higher gradient streams for some attributes (floodplain connectivity, pool frequency, pool-tail fines, and median substrate diameter), so they were not included in the evaluation of these sites.

The most recent (20-year) AREMP report switched to using reference conditions to set criteria for in-channel conditions and upslope vegetation. Reference criteria were chosen using a nearest-neighbor approach, which matched a site to the five to seven nearest reference sites, based not on geographic distance but rather on similarity of largely invariant site characteristics (e.g., gradient, geology) (Bates Prins and Smith 2007). This approach was more empirically based than previous assessments; it set standards for higher gradient stream reaches and established a consistent method across the whole NWFP area. The use of the reference-condition approach in a monitoring program has important associated assumptions. The selection of reference sites should match the distribution of states in the ecosystem, reflecting the spatial and temporal dynamics at play. These values or thresholds are often either a direct judgment call or a chosen percentile of the overall disturbance distribution. In more highly disturbed ecoregions, few sites may qualify, as was the case with the Oregon/Washington Coast Range and the Franciscan provinces in the latest AREMP assessment (Miller et al. 2016). The nearest-neighbor approach did not rely on provinces/ecoregions, but rather incorporated environmental variability more directly through site characteristics.

Another key consideration in development of reference distributions is including the entire natural range of conditions that an ecosystem can experience (Lisle et al. 2007, NRC 2000, Stoddard et al. 2006). Relative to the ACS and development of AREMP as originally conceived (Reeves et al. 2004), it was generally assumed that there is a given condition or limited set of conditions that supports aquatic organisms, primarily fish and macroinvertebrates (e.g., Karr and Chu 1998). The panel of scientists and managers who initially framed the ACS assumed that favorable conditions for fish were constrained to areas with cold water and structural heterogeneity provided by physical habitat components such as large down wood and coarse substrates—conditions often associated with old-growth forests—thus, these conditions and the associated old-growth forested riparian habitats were assumed to be most suitable for fish.

Recent studies, however, have demonstrated that native salmonids (Howell 2006, Rieman and Isaak 2010, Sestrich et al. 2011) and aquatic invertebrates (Minshall et al. 1989) are capable of adapting to and being productive in a wide range of conditions, including those following major disturbances such as wildfire that affect stream conditions. Flitcroft et al. (2016a) found that although conditions for one life-history stage of salmonids may be unfavorable, other life-history stages may find the same conditions suitable, and populations may respond positively. Native salmonids may also change life-history tactics, such as by reducing age or size at maturity (Rosenberger et al. 2015). Evolving in naturally dynamic landscapes with infrequent to frequent fire (see chapter 3) and occasional landslides, these species appear to be resilient to a broad range of disturbances and environments that occurred under the natural range of variability. It is important for monitoring programs to incorporate this new perspective into the development of benchmarks and interpretation of results to better reflect the responses of aquatic organisms to both management and natural disturbances. The range of natural conditions likely spans recently disturbed sites as well as areas that have been undisturbed for hundreds of years or longer.

However, understanding the natural range of variability for an ecosystem is often difficult, owing to the extent and magnitude of anthropogenic effects (Miller et al. 2016, NRC 2000, Steel et al. 2016, Stoddard et al. 2006). This may especially be the case in dry-forest regions in the NWFP area where fire exclusion has altered forest and riparian plant composition and structure (see chapter 3); in areas where invasive species are now a dominant component of communities (app. 1); or where the signature of past human activities (Steel et al. 2016) and pervasive "press" disturbances (Yount and Neimi 1990) such as timber harvest have influenced the entire landscape so that current conditions, which may be a departure from the historical range, may now be seen as the norm (Pinnegar and Engelhard 2008), though they may have been rare or unknown in the past. Even areas that may appear to lack any sign of current or historical land use—areas with no discernable sign of recent human-caused disturbances—may no longer be considered pristine (see chapter 12). The Pacific Northwest moist coniferous forest region has recently been described as a "human-forest ecosystem," because people are now a foundational element of the system (Olson and Van Horne 2017).

Because pristine areas may no longer exist in many, if not most, ecosystems, the reference-condition approach sometimes has been modified to use "least-disturbed conditions" as a reference (Stoddard et al. 2006). But depending on how this approach is applied, it may not include the full range of potential ecosystem conditions, especially in naturally dynamic landscapes as described above, where disturbance had been excluded. Worse, in today's human-influenced forest landscape, there may be no locations that fit even the "least-disturbed" condition (see discussion in chapter 3).

Excluding the natural range of variability in the reference population influences the assessment of current conditions (NRC 2000). This issue can be illustrated by using the down wood data from Reeves et al. (1995), who examined three watersheds in the Oregon Coast Range that differed in the lengths of time since the last large wildfire (see details in "Attribute Integration Approaches" below). If just the values from the watersheds that were at an intermediate time point and the longest time point from disturbance were included as being in the population of reference conditions, wood values would vary from 12 to 24 pieces of wood per 100 m of stream. Twelve wood pieces per 328 ft (100 m) might be considered an extremely low value, and 24 a high value. However, if the most recently disturbed system from this dataset were included in the pool of reference conditions, the lower bound would be near 6 pieces of wood/328 ft, and the score for 12 pieces of wood/328 ft would be much higher, relatively speaking. Clearly, use of reference conditions to assess monitoring trends and their ecological relevance can be problematic if a wide range of variation is not included. Articulating how reference conditions were determined and the range of conditions they represent is essential to understanding the context for comparison, whether least-disturbed conditions, old-growth conditions, or professional judgment are used.

The relatively small number of matched sites in the reference pool used for the 20-year report is a potential drawback. Further, only one site-matching metric, quadratic mean diameter of conifers, reflected forest-ecosystem characteristics; this metric is only a limited surrogate for seral stage and does not reflect forest type, both of which may influence stream characteristics. Concerning the reference-site approach more generally, there is also some question as to whether reference sites relatively free of human disturbance still exist, given widespread fire suppression and now climate change (see chapter 3) (Herlihy et al. 2008, Stoddard et al. 2006). To the extent that these concerns are true, it likely creates uncertainty concerning monitoring results that needs to be explored.

Other recent large-scale assessments have also used a variation of the reference-condition approach, but none have incorporated much detail on surrounding vegetation conditions. The NRSA (USEPA 2016) incorporated environmental variability more generally into their reference sites by selecting a different set of sites for each ecoregion. Thus, their reference distribution includes a larger number of sites than in the AREMP analysis, but the NRSA authors recognized that this approach might not account for fine-scale variability within ecoregions and made direct comparison of results between ecoregions problematic (Herlihy et al. 2008, USEPA 2016). They incorporated some finer scale measures of environmental variability (e.g., elevation) by including them as covariates in the multiple linear regression (MLR) equations that defined reference expectations for each indicator. The PIBO analysis incorporated environmental variability by using the MLR approach, but the only covariate related to forest condition was the percentage of the 295-ft (90-m) stream buffer in forested condition (Al-Chokhachy et al. 2010).

The final step in applying the reference-condition approach involves choosing evaluation thresholds from the distribution of reference values and comparing site values to these thresholds. AREMP and PIBO selected the $5^{th}/95^{th}$ percentiles of their reference distributions to define normalized scores, assuming that more extreme values might be outliers that could skew the scoring process. They then reported these values directly, so that scores approximated the percentile in the reference distribution. In contrast, NRSA chose to place all results into three classes (good/fair/poor) based on the less than $5^{th}/5^{th}$–25^{th}/greater than 25^{th} percentiles of reference. The reference-condition approach may appear to be more empirical, but it still relies on professional judgment to set evaluation thresholds.

To promote success in ACS implementation, it is important to know how gains in watershed condition are measured. Because the natural range of variability occurring in a system over large spatial and long temporal scales occurs across a multidimensional continuum, it can be difficult, if not impossible, to incorporate into assessments (see chapter 3). One potentially useful approach is the use of "state and transition" models (e.g, Wondzell et al. 2007, 2012). Although such models can be difficult to validate, they can still be useful. It can be helpful to view aquatic ecosystems as multistate systems resulting from a variety of natural disturbances, as well as exogenous or anthropogenic processes that can alter habitat conditions, biota, and ecological processes (Penaluna et al. 2016). Having the full range of potential variability classified into discrete states provides a way to begin enumerating the ways in which variation is arrayed over large spatial scales and how it changes over long temporal scales. We suggest further exploration of reference conditions and their potential utility for analytical approaches, including consideration of how to use them in concert with state-transition models such as those developed by Wondzell et al. (2007, 2012).

The concept of the reference condition remains important in land management—not because it is a goal of management agencies to restore systems to some previous reference condition, but rather because knowledge of the historical range of variability can help inform choices about desired future conditions and, thereby, help determine management and restoration goals (chapters 3 and 12). Theoretically, departure from the reference condition would provide a relative measure to evaluate watershed conditions for managers who seek to maintain or restore ecosystem and species diversity (Nonaka et al. 2007, Safford et al. 2012). The multistate conceptual approach (Penaluna et al. 2016, Reeves et al. 1995) clearly shows that "reference conditions" are, in fact, a distribution of conditions from watersheds in various ecological states, similar to successional states in terrestrial systems (see discussion later in this chapter). As such, "departure from the reference condition" is no longer just a watershed-scale question, but rather a regional-scale problem that considers the distribution of conditions across multiple watersheds.

Equilibrium versus spatially and temporally dynamic ecosystem concepts and the choice of benchmark reference conditions will become even greater challenges in future assessments given the increasing influence of climate change. There is growing concern about the extent to which ecosystems in the NWFP area, and elsewhere, have been affected by climate change and altered disturbance regimes, such as fire exclusion (Hessburg et al. 2005, Luce et al. 2012; also see chapter 3). We are likely seeing, or will soon see, the development of ecosystems that are different from the present and at least the near past (Hobbs et al. 2009, Luce et al. 2012) (fig. 7-4). Some have called this a new geological epoch—the "Anthropocene" (see chapter 12). The conditions

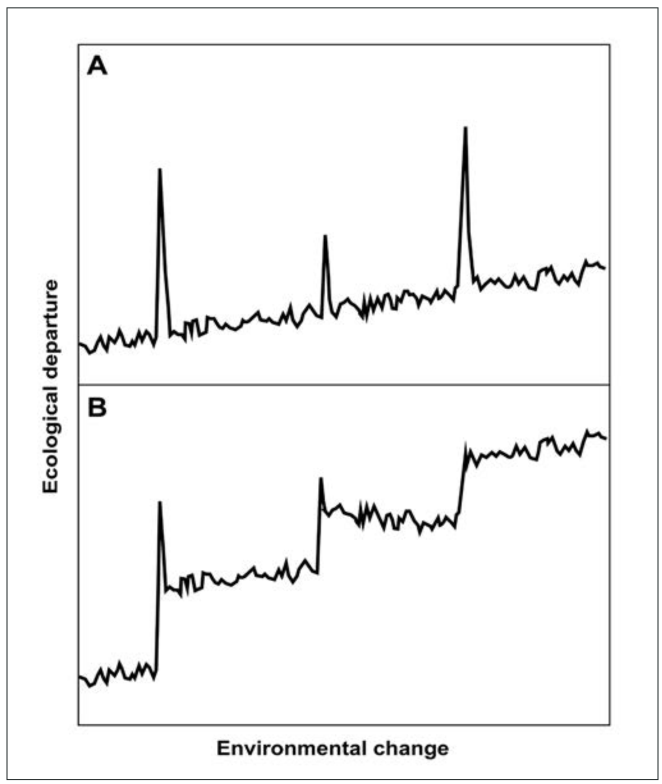

Figure 7-4—Conceptual roles for disturbance in a changing climate: (A) Disturbance could continue to operate much as it always has, with unique disturbance/recovery patterns, or (B) it could become the catalyst that forces ecosystems to shift rapidly and via alternate and uncertain pathways in response to climate. Source: Luce et al. 2012.

that result from these altered ecosystem trajectories could be very different from those that would be found in unaffected systems of the past or present, and they may not necessarily meet social or legal expectations (Luce et al. 2012). Using benchmarks based on our understanding of aquatic ecosystems today may also affect assessments of ecological consequences from natural and anthropogenic factors. We rephrase our statement from near the top of this section: the potential implications of these changes merit a primary research focus, but in the meantime it will be important that monitoring programs, whether they use reference conditions, least-disturbed conditions (e.g., Miller et al. 2017), decision-support models (e.g., Reeves et al. 2004), or other approaches, recognize and acknowledge these potential concerns in the process of analysis and the interpretation and application of results. (The topic of reference conditions is discussed in different contexts later in this report, including an expanded treatment of approaches for riparian restoration.)

Attribute integration approaches—

Integration of metrics—Watersheds and streams operate as integrated systems, and no one indicator is likely to accurately characterize their condition. A significant scientific challenge remains in how to reflect this integration in their assessment. Early efforts and ongoing regulatory guidance for assessing salmonid habitat look at a number of indicators individually, without an explicit procedure for integration (NMFS 1996, USDA FS et al. 2004). NRSA, the largest national assessment, also primarily reports on indicators separately (fish, macroinvertebrates, chemical and physical stressors), although many of their indicators are themselves composite metrics. They incorporate limited integration through their measure of relative risk, which looks at the likelihood of finding poor biological conditions in a river or stream when stressor concentrations are high, relative to the likelihood when they are low (USEPA 2016).

The AREMP monitoring plan was a pioneering attempt to integrate indicators into a composite watershed-condition index (Reeves et al. 2004). In practice, the extent of integration has declined in each of AREMP's reports. The 10-year AREMP report integrated all upslope and in-channel variables into a single score for each watershed (Gallo et al. 2005). Trend was calculated only for the upslope portion; repeated measurements of sufficient in-channel sites were not available until the 20-year report. The 15-year assessment separated upslope and in-channel metrics for two reasons. First, the upslope data (GIS and remote sensing) covered the whole region, so there was no need to restrict that analysis to the in-channel subsample. Second, little correlation was found between the upslope and in-channel results, so it was believed that these outputs offered fundamentally different types of information. In addition, the mixing of stressors and responses has been criticized in other watershed indices (Schultz 2001).

The 20-year report maintained this upslope/in-channel split, and also reported the in-channel elements of physical habitat, macroinvertebrates, and temperature separately. Temperature was split off because it was collected under a different sample design, only at the lowest point in the watershed rather than at each site. Macroinvertebrates were separated from physical habitat because they are often considered a qualitatively different type of indicator: physical habitat as a condition or stressor, and macroinvertebrates as a response. It was also believed that reporting these indicators separately would better identify problems by not obscuring high and low values in an aggregated average. Although macroinvertebrate, physical habitat, and temperature data were not integrated in the 20-year report, additional analyses may be useful to further assess a combined metric, especially as novel techniques emerge that can address issues of spatial autocorrelation along linear stream networks (Peterson et al. 2013, Ver Hoef et al. 2014).

Other monitoring programs have built condition indices by combining indicators into a more integrated value. PIBO averages its physical channel attributes into a single index score, but maintains macroinvertebrates separately (Archer and Ojala 2016). The state of Oregon combines a number of chemical metrics into an overall water-quality index but also reports macroinvertebrates separately (Hubler 2009). The national Forest Service watershed condition class combines upslope, riparian, and in-channel biotic and abiotic indicators into one overall watershed-condition score (Potyondy and Geier 2011).

Having the metrics for watershed condition assessed independently begs the question as to how to interpret overall condition relative to findings for instream habitat, stream temperature, and upland/riparian condition. Miller et al. (2017) acknowledged that reliance on a single biological metric can lead to erroneous interpretation of the biological condition of a watershed (e.g., Barbour et al. 1999), and suggested that the findings of the four separate stream metrics can be used as multiple lines of evidence to look at watershed-condition trends. So, when concordance among the measures differs within a given watershed, for example, if one or two parameters show an improving trend while the third does not change or declines, one can better understand which parameter may signal a potential issue and spur additional investigation. (See additional discussion of this issue later in this section.)

Interpreting long-term changes in a single metric can be complicated. For example, Miller et al. (2017) reported a broad-scale change in the distribution of water temperatures toward lower temperatures and an increase in watersheds with improving aquatic macroinvertebrate assemblages across the NWFP area. Nonetheless, 55 percent of waterbodies monitored by AREMP in Oregon still exceed state water-quality standards for these parameters (ODEQ 2012). One potential reason for this apparent lack of agreement between Miller et al. (2017) and the increase in miles of water-quality-impaired streams in Oregon (ODEQ 2012) is the lack of concordance among the indicators in a given watershed, as was shown in figure 7-5.

One parameter may be trending in a positive direction while another is outside or moves outside the acceptable range. Also, the number of streams surveyed by ODEQ for water-quality impairment has increased over the last 10 years, and differences in the way specific metrics are used may explain some of these apparent differences. More research is needed to fully assess whether such monitoring results represent favorable ecological changes over the long term.

Generally, analytical approaches and their interpretation for broad ecosystem assessments are still developing, including novel uses of individual metrics and multivariate methods. The initial NWFP monitoring strategy was based on identifying key stressors and a conceptual model that linked ecosystem and species components (Mulder et al. 1999). The decision-support system based on expert judgement used for interpretation of metrics in the 10-year report (fig. 7-6) is prone to subjectivity and uncertainty, however, there may be no real alternative given the needs of policymakers, the complexity of the

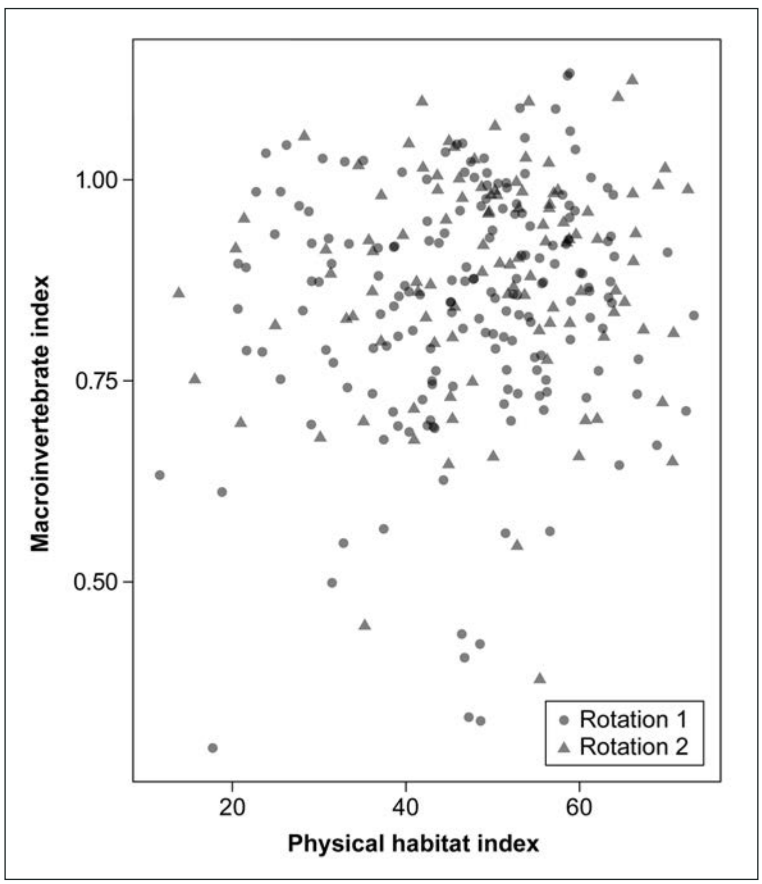

Figure 7-5—Relation between scores for overall watershed condition and condition of the macroinvertebrate communities for watersheds in the Northwest Forest Plan area in the assessment by Miller et al. (2017).

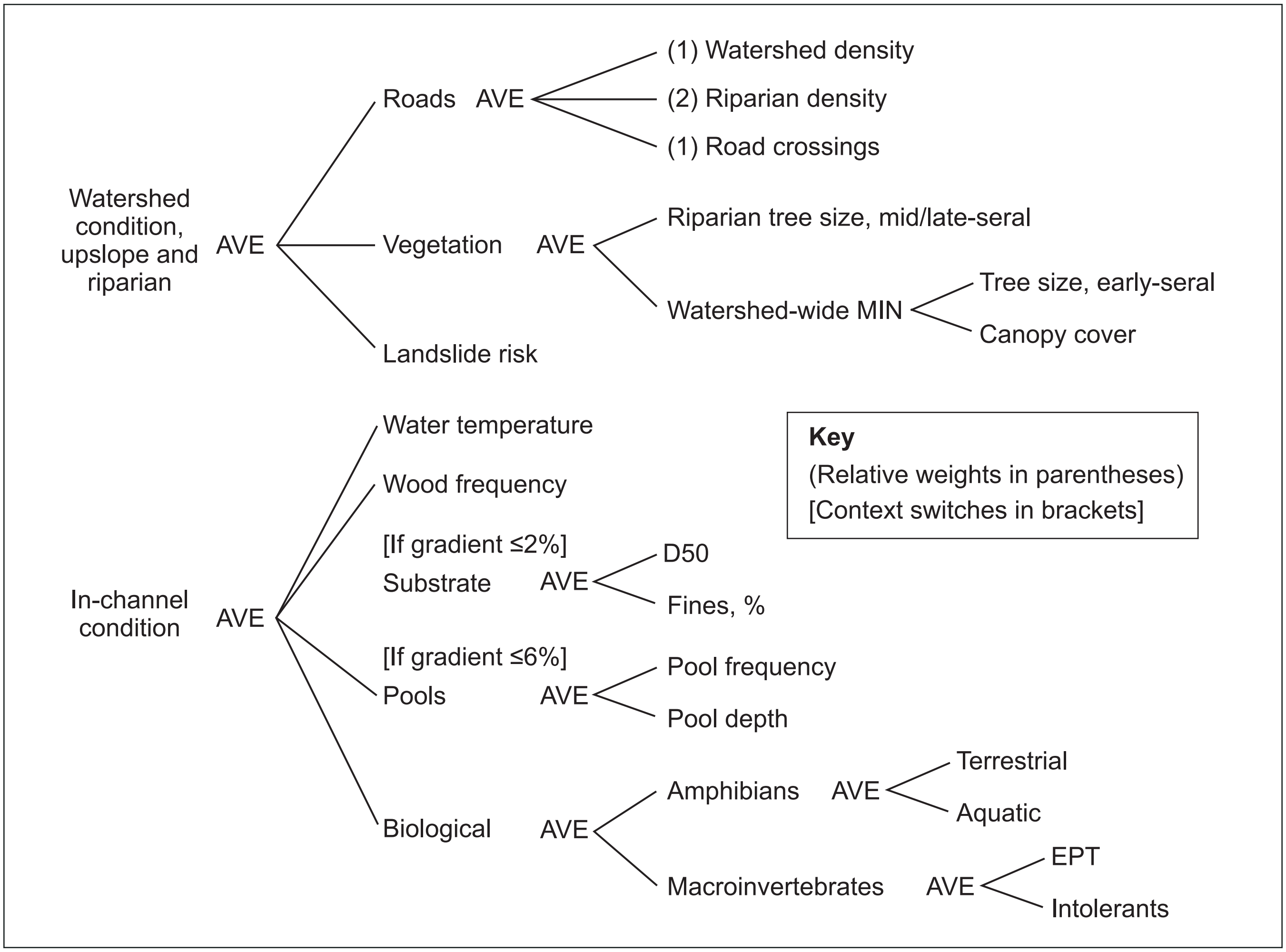

Figure 7-6—Example of a decision process for assessing the ecological condition of a watershed (Lanigan et al. 2012). AVE = average of scores; MIN = minimum; D50 = median particle size; EPT = Ephemeroptera, Plecoptera, Tricoperta index. See Reeves et al. (2004) for details.

ecological systems, and existing information gaps (Pielke 2007). The movement away from expert opinion in the 20-year report raises a new set of questions about use of single metrics interpreted independently and without an ecological framework. Carlisle et al. (2008) suggested that if one of the parameters of interest in a sampling unit (reach or watershed) is outside the threshold value for suitable conditions, the unit as a whole is outside the suitable range. A more statistically rigorous approach was described by Bowman and Somers (2006) and Collier (2009). In sum, exploration of a variety of available approaches is merited and timely.

Summarization over space and time—
A final consideration related to data integration is how to aggregate and present data over space and time. Reporting units over the spatial extents of land ownerships, land authority jurisdictions (e.g., county), and land-use allocations can address management and policy objectives, but the relationship of environmental conditions over space and time (e.g., via ecological provinces, watershed hydrological units) is also fundamental to our scientific understanding of aquatic-riparian ecosystems, particularly under the disturbance ecology paradigm (Olson et al. 2017b). Broad-scale aquatic assessments often report results by one or more aggregated spatial subunits.

Two types of units are evident in AREMP and other efforts. The first is based on ecological conditions. Similar to the other NWFP monitoring modules, AREMP reports results by seven aquatic provinces, which are similar to the physiographic zones developed in the NWFP planning process (FEMAT 1993: app. V-A). Broad ecological zones were similarly used in NRSA, both for the definition of reference conditions and the reporting of results (USEPA 2016). Hubler (2009) took a more water-centric approach, using water basins (hydrologic units, in particular HUC6, mean area ~10,000 mi^2 [~25 900 km^2]) as their principal reporting unit. Studies focused on fish populations have developed units to represent genetically and demographically independent groups of fish, referred to as evolutionarily significant units (ESUs) or distinct population segments (DPS) (McClure et al. 2003).

A second type of spatial aggregation common in the aquatic-monitoring literature is by management units. AREMP reports on indicators by NWFP land-use allocations, which generally correspond to land use intensities. The National Water-Quality Assessment targeted their sample by land use disturbance levels and so displays many of its results by urban, agriculture, and mixed-use classes (Carlisle et al. 2013). Hubler (2009) reported their results by ownerships (federal, state, private industrial, private nonindustrial). PIBO's regional reports have not broken down their data by management classes directly, but they have displayed results of all sites in concert with reference distributions, indirectly reflecting management classes (Archer and Ojala 2016).

In earlier AREMP reports, the NWFP aquatic provinces were the basis of alternate evaluation criteria. However, as described above, the most recent assessment used neighborhoods based on in-channel characteristics, and upslope zones based on forest types. Because the aquatic provinces are no longer used to set environmental parameters for the assessment, other aggregations may prove more useful. For example, the NWFP provides a common set of standards and guidelines for management in the region; they are implemented via management plans developed by each agency for each of their forests and districts. AREMP may wish to consider reporting by these unit and agency boundaries to increase their relevance to managers. Additionally, because these plans must address endangered species issues, the ESU and DPS boundaries may now be more relevant ecological units than the NWFP provinces.

AREMP's mandate is only to assess conditions on federal lands under the jurisdiction of the NWFP. However, nonfederal lands have been shown to be important, both for their effects on federal land conditions as well as for containing potentially productive fish habitat (Burnett et al. 2007, Reeves et al. 2016a, Van Horne et al. 2017). Further investigation in how to link AREMP data with assessments covering nonfederal lands could help address this gap, for an all-lands approach to watershed assessments in the moist coniferous forest ecosystem.

Because watershed conditions differ naturally over time, individual watershed ratings may be truly meaningful only when considered in some larger aggregation (Poole et al. 2004, Reeves et al. 2004). Thus, the end goal of AREMP was to look for changes in the distribution of watershed conditions in the whole NWFP area over time. As a baseline for comparison, AREMP chose to simply use conditions in the first monitoring period, because the other options considered (historical conditions, simulated natural conditions) would have been challenging to implement. Some other major programs have also used initial monitoring results as baseline conditions (Archer and Ojala 2016, USEPA 2016), whereas others have simply focused on one point in time, for example, using their most recent data (Carlisle et al. 2013, Hubler 2009). To our knowledge, historical conditions have not been estimated directly from past records, and simulation of natural conditions has been attempted only over considerably smaller spatial scales (Wondzell et al. 2007).

Finally, analytical approaches and their interpretation for broad ecosystem assessments are still developing, including novel uses of individual and multivariate methods. The rich AREMP dataset is ideal for comparison of alternative analytical approaches to assess watershed condition. Despite uncertainties and challenges faced by the 10-, 15-, and 20-year AREMP reports, reported trends support the intent of the ACS to sustain and improve conditions of federally managed watersheds in the NWFP area.

Components of the Aquatic Conservation Strategy

Riparian Reserves

Riparian reserves were intended to define and delineate the outer boundaries of the riparian ecosystem and to encompass the portions of a watershed most tightly coupled with streams and rivers (FEMAT 1993). These areas were assumed to provide the ecological functions and processes necessary to create and maintain habitat for aquatic and riparian-dependent organisms over time. This includes dispersal corridors for a variety of terrestrial and riparian-dependent organisms, and connectivity of streams within watersheds (FEMAT 1993). In 1993, the Forest Ecosystem Management Assessment Team (FEMAT) developed three management scenarios for riparian reserves along fish-bearing and non-fish-bearing streams (FEMAT 1993). Each scenario required a reserve width on fish-bearing streams of two times the height of a site-potential tree (minimum of 300 ft [91.4 m]), defined as the average maximum height the dominant tree would be expected to attain given the growing conditions at that location. On non-fish-bearing streams, the width of the riparian reserves varied from one-sixth of a site-potential tree-height (minimum of 25 ft [7.6 m]) to one-half of a site-potential tree-height to one site-potential tree-height (FEMAT 1993). One scenario was integrated into each of the 10 landscape alternatives developed and evaluated by the FEMAT (1993) scientists.

The Secretaries of the Interior and Agriculture selected FEMAT's Option 9 as their preferred option, which required a riparian-reserve network that was two site-potential tree-heights wide on fish-bearing streams and one-half of a site-potential tree-height on most non-fish-bearing streams. Interim boundaries of the riparian reserves were extended to a full site-potential tree-height on all non-fish-bearing streams between the draft and final environmental impact statements (USDA and USDI 1994a) to increase the likelihood of success of the ACS, and to provide additional protections from timber management and road building for non-fish organisms that use the area in or near streams as habitat or migratory corridors (USDA and USDI 1994a). On some fish-bearing streams, two site-potential tree-heights from the edge of a stream may not encompass the whole floodplain, which can be an important source of large wood, making it critical to recognize and protect the entire floodplain (Latterell and Naiman 2007). This was accomplished in the ACS by requiring the boundary of the riparian reserve to extend to the edge of the 100-year floodplain (USDA and USDI 1994a). These boundaries were considered interim until a watershed analysis, which could adjust the size of the riparian reserve, was completed (USDA and USDI 1994a).

Depending on the degree of dissection of the forested landscape by streams, riparian reserves along both perennial and intermittent streams may occupy between 40 and 90 percent of the landscape (FEMAT 1993, Hohler et al. 2001). Interim riparian reserves of this magnitude, coupled with key watersheds and late-successional reserves, have provided a connected watershed-level reserve system for terrestrial, riparian, and aquatic ecosystems (Everest and Reeves 2007). However, the area of the forested landscape contained in the riparian reserves has fueled a controversy regarding riparian protection, resulting in new research to evaluate prescribed widths of riparian-management areas and a reexamination of existing scientific literature on the subject (Everest and Reeves 2007). The following sections summarize some of the recent key literature relating to the functions and size of riparian reserves.

Ecological functions—
The scientific basis for delineation of interim riparian reserves in the NWFP was derived from two sets of curves showing the relationship between various ecological functions provided by riparian zones and distance from the channel (figs. 7-7 and 7-8). These curves were developed by FEMAT scientists based on the scientific literature that was available at the time, and on professional judgment when sources of information were incomplete (see table 7-2 for original sources). The original relationships (FEMAT 1993) that were incorporated into the NWFP (USDA and USDI 1994a) suggest that most ecological functions could be maintained by reserves equal to or less than the distance of one site-potential tree-height. The functions include beneficial effects of root strength for bank stability, litterfall, shading to moderate water temperatures, and delivery of coarse wood to streams (fig. 7-7A). In addition, the majority of moderating effects on sediment delivery to streams

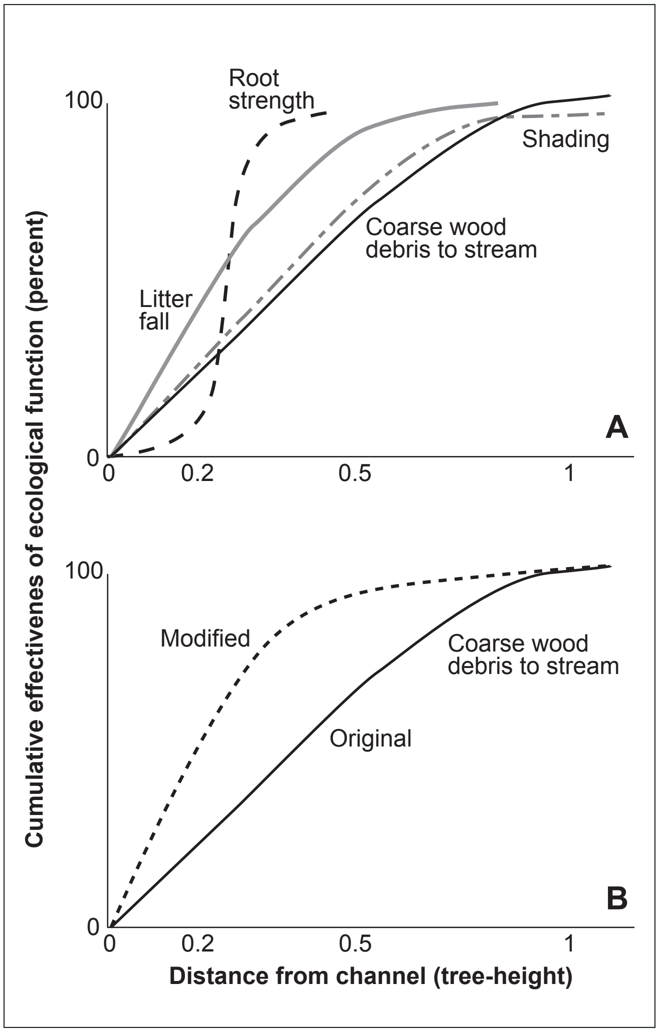

Figure 7-7—(A) Relation of distance from stream channel to cumulative effectiveness of riparian ecological functions (FEMAT 1993: V-27); (B) modified effectiveness curve for wood delivery to streams as a function of distance from the stream channel. The original curve was changed based on scientific literature developed since the original curve was portrayed in FEMAT (1993). Source: Spies et al. 2013.

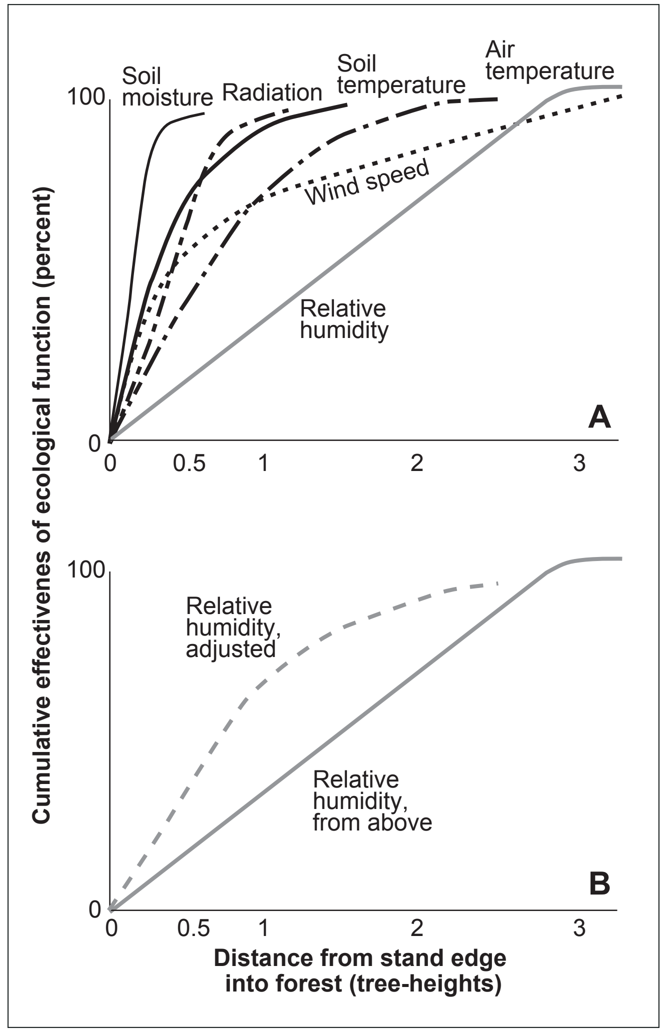

Figure 7-8—(A) Relation of distance from stream channel to cumulative effectiveness of ecological factors influencing microclimate in riparian ecosystems (FEMAT 1993: V-27); (B) modified effectiveness curve for relative humidity as a function of distance from the stream channel. The curve was changed based on scientific literature developed since the original curve was portrayed in FEMAT (1993). Source: Reeves et al. 2016a.

from overland erosion associated with upland activities generally occur within a distance of one site-potential tree-height (Castelle et al. 1994, Naylor et al. 2012). The FEMAT scientists also provided a margin for error allowing for incomplete science, unknown cumulative effects, or strategic uncertainty in defining interim riparian reserves prior to watershed analysis. Everest and Reeves (2007) concluded that science published since original development of the FEMAT curves has generally supported the original assumptions and judgments.

Recent studies of wood recruitment suggest that changes in some of the ecological function curves may be supported. According to the graph of the relationship between the cumulative effectiveness of an ecological process and the distance for wood recruitment from the immediately adjacent riparian area in fish-bearing streams, developed in FEMAT (1993), about 60 percent of wood recruitment from the immediate riparian area along fish-bearing streams occurs within one-half of a tree-height (fig. 7-7A). This graph was based on a limited number

Table 7-2—Literature sources used to develop the original curves of ecological functions in riparian reserves in FEMAT (1993)

Function	Sources
Root strength	Burroughs and Thomas 1977 Wu et al. 1986
Wood delivery	Beschta et al. 1987 McDade et al. 1990 Van Sickle and Gregory 1990
Litterfall	Professional judgment
Shading	Beschta et al. 1987 Steinblums 1977
Microclimate	Chen 1991

of studies (McDade et al. 1990, Van Sickle and Gregory 1990) and the professional judgment of scientists involved with FEMAT. More recent studies on the sources of wood (Gregory et al. 2003, Spies et al. 2013, Welty et al. 2002) found that, at least in the Cascade Range of western Oregon and Washington, about 95 percent of the total instream wood inputs from the adjacent riparian area along fish-bearing streams came from distances of 82 to 148 ft (25 to 45 m) from the stream, representing a distance of 0.6 to 0.7 of a site-potential tree-height for this area (fig. 7-7B). The shape of this curve differs from the FEMAT curve (fig. 7-7A), which showed that 95 percent of the wood-recruitment function of the same streams occurs within a distance equal to about 0.95 of the height of a site-potential tree.

A primary purpose for the extension of the boundary of the riparian reserve of the NWFP from one site-potential tree-height to two on fish-bearing streams was to protect and enhance the microclimate of the riparian ecosystem within the first tree-height (USDA and USDI 1994a). At the time the ACS was developed, the only research on the effects of clearcutting on microclimatic conditions in adjacent forests had been done in upland forests on level terrain (Chen 1991). Those studies found that the influence of recent clearcuts (10 to 15 years old) extended from tens of yards (e.g., soil moisture and radiation) to hundreds of yards (e.g., wind velocity) into adjacent unharvested stands. Based on the initial work of Chen (1991), FEMAT (1993) hypothesized that a second tree-height could provide a considerable safety margin from negative effects of intensive management on riparian areas, in terms of relative humidity and other microclimatic effects in the riparian reserve along fish-bearing streams (FEMAT 1993) (fig. 7-8A).

Since the ACS and associated ecological-function curves were originally formulated, a number of research efforts have examined the effects of forest management on microclimate in riparian areas. The vast majority of this work has focused on air temperature and relative humidity in small, headwater streams; few studies were conducted along larger streams (see review by Moore et al. 2005; also Olson et al. 2007, 2014). The magnitude of harvest-related changes in microclimate in riparian areas is usually inversely related to the width of the riparian buffer and the type and extent of management activities on the outer (upslope) edge. Some studies failed to show any edge effect between clearcuts and riparian buffers composed of intact mature forest (i.e., the extent of change in microclimatic conditions resulting from the presence of a clearcut on upslope edge of the riparian area) (Anderson et al. 2007, Rykken et al. 2007). Other studies have found that edge effects varied from a distance of 98.5 ft (30 m) (Anderson et al. 2007, Rykken et al. 2007) to 148 ft (45 m) (Brosofske et al. 1997) from the stream. At the other extreme, Ledwith (1996; as cited by Moore et al. 2005) found that above-stream temperature decreased and relative humidity increased as buffer widths increased up to 492 ft (150 m). Rykken et al. (2007) attributed the lack of an edge effect to a "stream effect," described by Moore et al. (2005), who noted that the stream can act as a heat sink and a source of water vapor during the day, thus keeping near-stream microclimates cooler and more humid than areas farther from the stream. Rykken et al. (2007) suggested that this stream effect might counteract edge effects of harvest on microclimate, thereby reducing the distance that harvest effects penetrate into riparian zones, relative to the distances measured in upland forest edges (e.g., from those projected by Chen et al. [1993] in uplands). Moore et al. (2005) also posited that cool, moist air might be carried by down-valley breezes, contributing to this stream effect.

The FEMAT microclimate curves were based on upland studies of forest-edge effects and thus they do not necessarily apply to riparian areas with a strong stream effect, protected topographic position, and retention of some canopy in the adjacent managed stand. Reeves et al. (2016a) suggest that a one tree-height buffer on fish-bearing streams (fig. 7-8B) would reduce most potential effects on microclimate and water temperature in near-stream environments from timber harvest in areas on the edge of the riparian reserve, particularly when some trees are retained in the harvest unit. In general, most studies show that microclimatic changes in temperature and relative humidity seldom extend farther than one site-potential tree-height from the clearcut edge into an intact riparian buffer composed of mature forest (see review by Moore et al. 2005 and references cited therein). However, the large variety of effects measured in different studies demonstrates that substantial uncertainties remain about the size and management of riparian reserves. These uncertainties have important implications when considering changes in the width of the NWFP riparian reserves.

Increased stream temperature following forest harvest is one of the most frequently mentioned management concerns, and one that retention of riparian buffers is clearly designed to mitigate. Generally, the smaller the riparian area and the more extensive the activities, the greater the effect on stream temperature. Clearcut logging without riparian buffers usually leads to large, post-harvest increases in stream temperature, and the width of the riparian buffer needed to limit, or even eliminate, temperature increases remains uncertain (see reviews by Moore et al. 2005 and Leinenbach et al. 2013). Given these uncertainties, management prescriptions that reduce the width of the riparian reserve or allow some tree harvest within the reserve remain controversial.

The NWFP area encompasses a wide array of bioclimatic conditions, across its latitudinal span, west to east with distance from the ocean and rain-shadow effects of mountain ranges, and with increasing elevation. Given this variation, we describe only a few broad, general patterns in riparian vegetation here. In subsequent sections, we contrast these patterns with present-day patterns in areas that were previously logged, especially where logging pre-dated the establishment of current forest-practices rules and allowed harvest right up to streambanks. Although these general trends are important considerations, we also emphasize that more detailed local knowledge will be critical for determining appropriate management goals and planning specific actions.

Riparian and upland vegetation along headwater streams in moist or wet forest types is typically dominated by conifers (Nierenberg and Hibbs 2000, Pabst and Spies 1999, Sheridan and Spies 2005) (fig. 7-9A). However, conifer density can be lower in riparian zones compared to adjacent terrestrial areas (Sheridan and Spies 2005), hardwoods are uncommon in both riparian and upslope

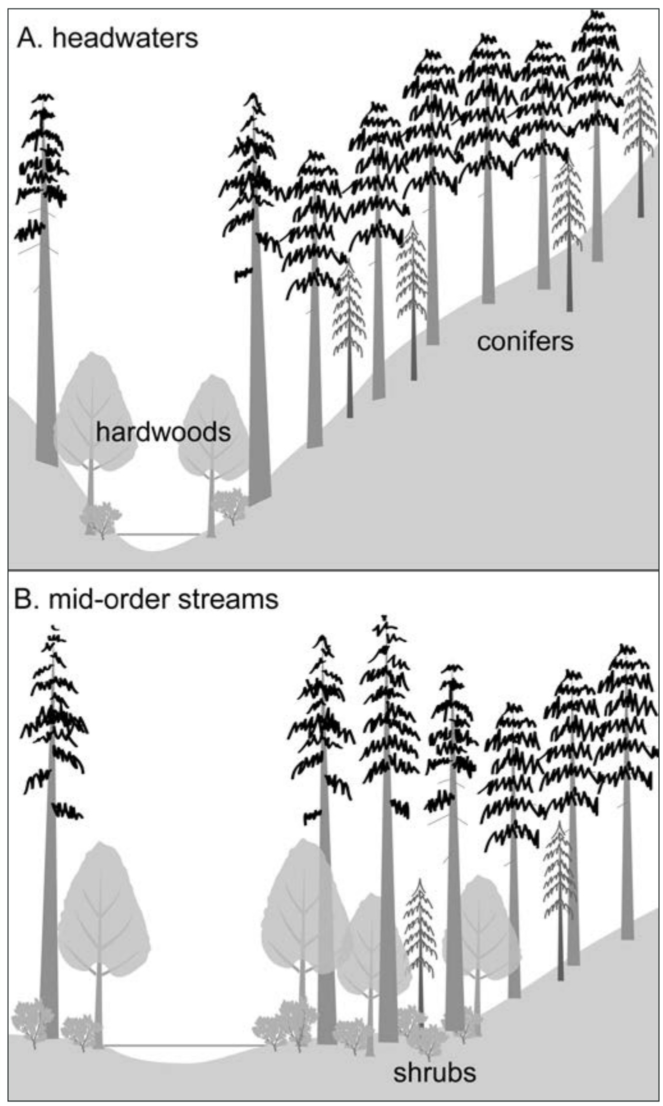

Figure 7-9—Conceptual representation of (A) vegetative conditions in headwater and (B) mid-order streams in the Northwest Forest Plan area.

areas, and there are no clear differences in shrubs between the two zones (Sheridan and Spies 2005). Many mosses and liverworts are also found at the wetted edges of small streams or on wood and rock in and along the channels (Hylander et al. 2002). In these wet forest types, tree canopies are often dense, limiting sunlight and therefore primary productivity. As a result, headwater streams depend on allochthonous (coming from outside the stream) inputs of litter and terrestrial invertebrates from the adjacent riparian forests, with as much as 95 percent coming from within 45 to 83 ft [13.6 to 25.3 m] of the channel (Bilby and Heffner 2016), as the primary energy source for aquatic and riparian organisms in these streams and for those lower in the network (Baxter et al. 2005, Gomi et al. 2002, Leroy and Marks 2006, Richardson et al. 2005, Wallace et al. 1997, Wipfli and Baxter 2010). Allochthonous material is exported to downstream areas as dissolved organic carbon, coarse (>1 mm, >0.04 inches) particulate organic matter, and to a much lesser extent, as fine particulate organic matter (Gomi et al. 2002, Richardson et al. 2005), which contribute to the productivity of fish-bearing streams. The structure and composition of the riparian vegetation determines the quality, quantity, and timing of the allochthonous input (Cummins et al. 1989, Frady et al. 2007), all of which influence overall stream productivity.

Forests in riparian zones and adjacent uplands become increasingly different as the size of streams increases (fig. 7-9B). In the middle portions of stream networks, the riparian forest is more diverse than along headwater streams (Acker et al. 2003, Johnson et al. 2000, Sarr and Hibbs 2007). Riparian forests along many mid-sized streams still remain dominated by conifers, but they are often mixed with deciduous trees such as alder (*Alnus* spp.), big-leaf maple (*Acer macrophyllum*), willow (*Salix* spp.), and cottonwood (*Populus* spp.). Big-leaf maple and California black oak (*Quercus kelloggii*) can be common in riparian zones in the southern portion of the NWFP area.

Some studies in mid-sized streams have shown that conifer basal area nearest the stream can be lower owing to reduced survival from disturbances such as flooding (Hibbs and Giordano 1996, Pabst and Spies 1999). Also, the availability of growing sites might be limited; conifers preferentially establish on "microtopographic ridges" created by old tree-falls and behind wood jams (Fetherston et al. 1995). As a result, tree density near the stream can be about half of that of upland stands (Acker et al. 2003, Rot et al. 2000, Wimberly and Spies 2001). In contrast, Pollock et al. (2012) suggested that there is little difference in tree density between upland and riparian stands. All these studies, however, did find that the basal area of conifers in streamside stands is greater than in stands farther from the channel or in adjacent uplands. Streamside trees can be among the largest in a watershed (Poage and Tappeiner 2002), and thus can be the source of the largest down trees (conifers) found in the channel (i.e., the key pieces) (Rot et al. 2000), which are generally recruited to the channel by undercutting at high water (Abbe and Montgomery 2003, Acker et al. 2003, Benda et al. 2003).

In the Oregon Coast Range, hardwoods were most abundant in the area closest to the channel of streams in the middle portion of the stream network (Pabst and Spies 1999, Wimblerly and Spies 2001), particularly in unconstrained reaches (Acker et al. 2003), and they decreased in density moving away from the channel. This mix of hardwoods and conifers is important ecologically (Sponseller and Benfield 2001, Sponseller et al. 2001) and is frequently maintained by periodic flooding (Sarr and Hibbs 2007). The vegetative diversity provides diverse habitat for a suite of terrestrial and riparian organisms; hardwoods are especially important for riparian mollusks (Foster and Ziegltrum 2013) and Neotropical migrant and resident bird species (Pearson and Manuwal 2001). Riparian areas dominated by hardwoods, particularly nitrogen-fixing red alder (*Alnus rubra*), have the potential to increase primary (Cornwell et al. 2008, Kominoski and Pringle 2009, Kominoski et al. 2011, Schindler and Gessner 2009, Swan et al. 2009) and secondary productivity and invertebrate diversity in adjacent streams (Piccolo and Wipfli 2002, Srivastava et al. 2009, Wipfli and Musslewhite 2004). Watersheds with mixed hardwood/coniferous riparian vegetation in the Oregon Coast Range received nearly 30 percent greater influx of terrestrial invertebrate biomass than streams with conifer-dominated riparian areas (Romero et al. 2005). The loss or reduction of deciduous litter could potentially influence the structure, composition, and productivity of riparian and aquatic biota (Wallace et al. 1997, 1999)

Although these broad general patterns hold across much of the NWFP area, we do not mean to give the impression that the riparian forests and their adjacent uplands were uniformly forested. Rather, these forests were a complex, shifting mosaic of vegetation patches, presenting a landscape with great spatial variability and temporal dynamics (see more detailed discussion in chapter 3). Wildfire was the primary factor driving forest dynamics across the Oregon Coast Range (Wimberly et al. 2000) and other parts of the region (see chapter 3), although windthrow, insects, and disease can also be important. As a consequence, upland forests, even when assessed at large spatial scales, showed substantial variation in the area and ages of forests. For example, over long periods, the proportion of upland forest in old-growth condition, when summed over areas of more than 4.9 million ac (2 million ha), ranged from 25 to 75 percent; at the scale of late-successional reserves as specified in the NWFP (~98,842 ac [40 000 ha]), the amounts of old growth could range from 0 to 100 percent (Wimberley et al. 2000).

In addition to the factors described above for upland forests, riparian forests are also influenced by fluvial and geomorphic processes such as floods, debris flows, and bank erosion. State-and-transition simulations of the natural disturbance regime in the Oregon Coast Range (Wondzell et al. 2012) showed that 51 percent of the riparian network was in mature forest (stand age of 66 to 200+ years). The simulations also showed that the long-term average forest composition was highly variable. Only 2 percent of the riparian network was in a nonforested condition, 28 percent was alder dominated, 40 percent was in mixed alder/conifer stands, and only 29 percent was in conifer-dominated stands (see table 5 in Wondzell et al. 2012). The specific results cited above pertain only to the central Oregon Coast Range, but it is clear that no single condition—defined by stand composition, structure, and tree age—can represent the full distribution of naturally occurring conditions over large areas. Rather, riparian forest conditions, when assessed over broad landscapes, showed a distribution of conditions that resulted from the combined influences of natural disturbances and plant succession.

Human impacts and restoration—
Riparian forests throughout much of the NWFP area have been changed by the land use activities that have taken place over the past century. As a consequence, the present-day forests may frequently differ in structure and composition from the presettlement forests that preceded them (McIntyre et al. 2015, Naiman et al. 2000, Swanson et al. 2011). This is particularly evident in an estimated 30 to 50 percent of the riparian ecosystems in the NWFP area that have been converted to plantations, based on the percentages of plantations in upland forests (see chapter 3). Riparian forested areas were harvested extensively, often to the edge of the stream, prior to the advent of current policies (Everest and Reeves 2007). In many cases, the riparian zones were subsequently planted with the most commercially valuable conifers, primarily Douglas-fir (*Pseudotsuga menziesii*), resulting in the development of dense, relatively uniform conifer stands and a decrease in hardwoods. In other cases, conifers were not successfully reestablished in logged riparian zones that are now dominated by alder with a dense salmonberry (*Rubus spectabilis*) understory, as observed at the reach scale by Hibbs and Giordano (1996). In watershed-scale simulations, Wondzell et al. (2012) estimated that, under historical conditions, 28 percent of the stream network in the Oregon Coast Range was in alder-dominated riparian forests, and that presently it is more than 40 percent. Fire suppression in dry forests with high- or moderate-frequency fire regimes has likely altered the structure and composition of riparian vegetation in ways similar to those described for upslope forested areas—namely an increase in the density of shade-tolerant conifers and a reduction in hardwoods (see chapter 3). In moist forests, with infrequent fire regimes, fire suppression has likely reduced the area of early-seral conditions in uplands and riparian areas (see chapter 3). Similarly, the removal of large conifers along rivers in the coast redwood (*Sequoia sempervirens*) range of northern California has been associated with increased dominance by alder (Madej et al. 2006). Clearly, the direct effects of logging on the structure and composition of present-day riparian forest can be varied, but overall, the distribution of conditions has changed dramatically relative to those under natural disturbance regimes.

Indirect effects of logging have also modified riparian forests. For example, rates of landslides and debris flows have increased in heavily roaded and logged watersheds (Goetz et al. 2015, Guthrie 2002, Jakob 2000), which has led to systematic changes in riparian vegetation. Debris-flow tracks are frequently scoured free of large wood and subsequently recolonized by red alder (Russell 2009, Villarin et al. 2009), with large wood deposited in runout zones. Further, the frequency of debris flows and landslides has contributed additional sediment to stream channels, driving more severe floods, with the combined effect of increasing the width of stream channels (Lyons and Beschta 1983). Exposed gravel bars within these channels are most often colonized by hardwoods, leading to substantial changes along the stream corridor.

Restoration challenges—

The changes to riparian forests described above create substantial challenges for restoration. For example, thinning of dense riparian Douglas-fir stands could open stands, allowing increased hardwood presence and thereby increasing the diversity of riparian vegetation, while also promoting growth of the remaining trees to decrease the time needed to grow trees large enough to act as key structural elements in the stream channel. Although such restoration treatments may speed the restoration of some ecological functions (USDA and USDI 1994a), they also may reduce dead wood (chapter 3), and may present risks, such as development of novel conditions and loss of a particular species or ecological condition. Concerns about the tradeoffs between potential gains and potential losses, or other management issues, appear to have limited restoration activities, particularly within the first site-potential tree-height of streams. Reeves (2006) estimated that 48,000 ac (19 400 ha) of riparian reserve in the matrix of the NWFP area was treated for restoration purposes using some form of vegetation management, primarily thinning, in the first 10 years of the Plan. Between 2010 and 2015, an additional estimated 38,719 ac (15 669 ha) in the Forest Service's Pacific Northwest Region (Region 6) were commercially or noncommercially thinned (table 7-3). FEMAT (1993) estimated that 2.2 million ac (890 000 ha) of riparian reserves were outside of other reserves and congressionally withdrawn areas in the NWFP area.

Table 7-3—The estimated area of riparian reserves in the Northwest Forest Plan area in the Pacific Northwest Region of the U.S. Forest Service where active management that produced trees for commercial (primarily in the second tree-height of the riparian reserve) and restoration (noncommercial) purposes has occurred in 2010–2015

National forest	Area of riparian reserve managed			
	Commercial		Noncommercial	
	Hectares	*Acres*	*Hectares*	*Acres*
Deschutes	168	415	461	1,139
Fremont-Winema	0	0	0	0
Gifford-Pinchot	1031	2,548	301	744
Mount Baker–Snoqualmie	125	309	0	0
Mount Hood	674	1,665	0	0
Okanogan–Wenatchee	331	818	2150	5,313
Olympic	750	1,853	454	1,122
Rogue River–Siskiyou	142	351	616	1,522
Siuslaw	3923	9,694	203	502
Umpqua	883	2,182	622	1537
Willamette	2835	7,005	No data	No data
Total	10 862	26,841	4807	11,878

Source: USDA Forest Service Pacific Northwest Region.

Because this is not the total area of riparian reserves, it is not possible to estimate the fraction of the riparian reserve in the NWFP area that has undergone restoration. However, it is clear that the area that has been treated represents a relatively small proportion of the riparian reserves in total, and of the amount that has been altered by past activities.

Primary reasons for the limited amount of restoration activity are various and probably include (1) differing perspectives about the characterization of reference conditions, conservation, and management; (2) concerns about the potential effects of mechanical treatments on stream temperature and wood recruitment; (3) concerns about rare and little-known organisms that made managers reluctant to alter default prescriptions (Reeves 2006); and (4) trust (see chapter 12). We explore the potential challenges associated with these restoration activities below.

Reference condition versus restoring function— Restoration activities necessarily require a "target" condition or conditions toward which the restoration activity is intended to move a system. One way to select a target for restoration goals is to identify a minimally disturbed condition and use it as a reference to which the current condition can be compared. The minimally disturbed condition is commonly called the reference condition. Although intellectually appealing, the selection of a reference condition is fraught with potential biases. For example, Pollock et al. (2012) set very stringent requirements on stand attributes that would be acceptable as a reference condition for Douglas-fir-dominated stands in riparian forests of western Washington state: choosing undisturbed, single-storied, conifer-dominated stands ranging in age from 80 to 200 years, and excluding stands dominated by hardwoods or shrubs that showed evidence of recent severe disturbance—including disturbances such as wildfire, insects, and disease—because these disturbances may themselves have been a product of fire exclusion or climate change. Also, stands with these features were assumed to be the successional climax forest for this size of stream, and such stands had been greatly reduced by logging.

The study by Pollock et al. (2012) illustrates some of the challenges inherent in finding reference conditions—they are often rare and may not represent the historical range of conditions that existed before extensive anthropogenic modification of upland and riparian vegetation. Ideally, reference conditions would be identified in areas with similar potential vegetation and in relatively close proximity, or at least within the same ecoregion, so that the reference provides an appropriate comparison for similar forest stands (NRC 2000). Because of their focus on older conifer-dominated patches and the assumption that these types of stands represented the primary natural vegetation of streamsides in more confined terrain, Pollock et al. (2012) were able to identify only a small portion of the existing riparian forests in which stands meeting their criteria for dominance by older Douglas-fir trees could be found (only 117, or 3.3 percent, of the 3,521 potential sites met the filtering criteria). These stands were widely scattered, spanning a broad latitudinal and climatic range in western Washington. Further, they lumped together both upland stands and riparian stands, and the only riparian reference stands were located in the western Washington Cascade Range. Thus, the applicability of the results to other stand types and locations is very limited. Nonetheless, Pollock et al. (2012) illustrated that a stringent filtering approach to identifying reference sites could contribute to characterization of reference conditions at the patch or stand scale (e.g., stand density and tree size) for evaluating riparian-management options for Douglas-fir riparian stands in western Washington. The Douglas-fir patch-scale reference conditions could also be used in setting management goals for the entire landscapes of a larger riparian zone. A similar approach could be applied to other stand types or regions to provide a more complete system of reference conditions for riparian management in the Pacific Northwest.

Another approach to setting reference conditions (although they did not call them "reference conditions" at the time) for riparian zones was used by Pabst and Spies (1999) and Nierenberg and Hibbs (2000) in the Oregon Coast Range. They sampled along first- through fourth-order streamsides without roads or a history of logging, and having no evidence of wildfire at least 80 years. Vegetation was sampled in transects from randomly selected starting points. Hence, the samples contained areas dominated by older conifers as well as patches of hardwoods and shrubs, in proportion to their occurrence in the riparian area. Smaller, recent areas of geomorphic disturbances, disease, and windthrow would have been included in the samples. The studies focused in particular on how vegetation differed between streamsides and uplands at a site, controlling for differences in environment and disturbance history. Generally, these studies found that conifer dominance decreased from the uplands to the streamside, and that many areas within 53 ft (16 m) of streams were typically a mosaic of conifers, hardwoods, and shrubs even along streams in relatively confined topographic settings. Conifer-snag densities were relatively low 17 snags/ac (6.9 snags/ha) within 53 ft (16 m) of streams, and about one-quarter of the densities found at distances of more than 53 ft (16 m) from streams (Pabst and Spies 1999). These studies could be used in developing management guidelines for riparian forests in the Oregon Coast Range. Note, however, that this approach (random samples of unmanaged riparian vegetation) did not sample many areas that had grown for several centuries since wildfire and also did not sample in large areas that were recently affected by fluvial, geomorphic, and fire disturbances, which would have been an important part of the historical range of variability in these ecosystems at watershed scales (Spies et al. 2002).

Wondzell et al. (2012) used state-and-transition models to explore the range of ecological states of the riparian network of a large river network in the central Oregon Coast Range. They used GIS methods to partition the stream network and its valley floor into discrete reaches, which were classified into potential geomorphic and vegetation types. A state-and-transition model was then developed for each potential type that included all possible states that could result from succession, natural disturbance, and land use activities. Wondzell et al. (2012) found that the structure and composition of the current riparian vegetation differed from the historical; there were fewer conifers, particularly the largest (>30 inches [76.2 cm]), and more alder-dominated patches. They clearly stated that their simulation results "should be interpreted as hypotheses of likely outcomes," and that, despite several model limitations, they can be used to "hindcast" expected historical distribution of riparian forest conditions.

Part of the debate about restoration needs for riparian areas may derive from differing views of riparian reference conditions (as a goal for restoration), and how they differ with scale and across watersheds and the NWFP region. Although many studies (e.g., Acker et al. 2003, Hibbs and Sarr 2007, Pabst and Spies 1999) have found that riparian vegetation and upland vegetation frequently differ in structure, composition, and dynamics depending on stream size, some have noted that differences between riparian and upland vegetation may be small for some stand types, and that in some cases upland sites can supplement riparian sites to increase sample size for describing target conditions for riparian management. For example, Pollock et al. (2012) noted that, for Douglas-fir-dominated stands in western Washington, "both forest types [upslope and riparian] are generally similar, but riparian stands have more live tree wood volumes and basal areas, suggesting they may be growing on sites that are more productive." Therefore, they concluded that riparian restoration in Douglas-fir-dominated riparian zones should aim to produce stand characteristics with densities and sizes of live and dead trees that are within the range of reference conditions (both upland and riparian). On the other hand, others (Gregory 1997, Pabst and Spies 1999, Welty et al. 2002, Wimberly and Spies 2001) have found that the type and magnitude of differences in features between upslope and riparian forests can be large, suggesting that upslope vegetation should not be assumed to be a reference for designing and assessing managed strategies for riparian vegetation in other stand types, or where riparian stands differ significantly from upland stands (e.g., in floodplains).

This variety of findings makes it difficult for managers and regulators to design and implement management actions in riparian reserves. We suggest that each of the approaches examined above—that of Pollock et al. (2012), Pabst and Spies (1999), Nierenberg and Hibbs (2000), and Wondzell et al. (2012)—offers important information that would contribute to building a "reference condition"-based strategy to examine current conditions, to project likely outcomes of planned management activities, and to help evaluate the tradeoffs between potential risks and benefits of any overall management strategy. For example, a modeling approach like the state-and-transition models of Wondzell et al. (2012) could be used to generate an expected historical distribution of states for the riparian vegetation within a stream network. The results could be used to identify relatively little-disturbed watersheds across the ecoregion and the monitoring plots located within those watersheds; individual plots could then be compared to specific states in the state-and-transition model. Those states could be attributed with values for various metrics (e.g., cover, basal area, tree densities, snag densities, species composition), as was done by Pabst and Spies (1999). Because anthropogenically disturbed states are also included in the state-and-transition models, something similar could be done to attribute these states with empirical data. The models could then be used to hindcast the historical distribution of state classes, and descriptive metrics from the empirical data could then be linked to the historical distribution. This result could be compared to the current condition. Also, the models could be used in forward simulations, incorporating different land use choices, to project how the distribution of conditions might be expected to change over time in response to various management strategies. Whatever approach is used, it will be important for managers and regulators to understand the limitations of the research they use to design and support proposed actions, which in turn necessitates that researchers clearly identify the limitations of their research (such as how broadly or to what ecosystem type they can be applied), and recognize the large variation in the inherent structure and composition of riparian areas across the NWFP area.

Riparian thinning and water temperature—Because the current distribution of conditions of riparian forests in many stream networks is far different from the historical distribution, there is substantial interest in active restoration treatments—especially thinning dense conifer plantations (Reeves et al. 2016a) or logging hardwood-dominated stands and replanting to convert them to conifer dominance (Cristea and Janisch 2007). Although these treatments are not inconsistent with the ACS, which generally allowed thinning for ecological objectives in the area beyond 120 to 150 ft (36.6 to 45.7 m) to a distance of one site-potential tree-height, they could potentially exceed the 0.3 °C "non-degradation standard" for water-quality effects of logging. The 0.3 °C standard is important from a regulatory perspective, limiting potential cumulative effects from multiple actions, none of which individually might be sufficient to impair water quality. Alternatively, restoration treatments might speed the attainment of desired future conditions. These decisions pose critical management challenges. Clearly, there are risks from any active restoration treatment, but choosing not to act also poses risks, not only by increasing the time needed to attain a desired future condition, but also leaving the riparian zone at greater risk of uncharacteristic disturbance—for example, dense conifer stands in dry forest zones are more prone to high-severity wildfire (see chapter 3). Also, there may be increases in primary production (Warren et al. 2016) and fish growth (Wilzbach et al. 2005) with the opening of the canopy along small and medium streams.

Reach-scale studies clearly demonstrate that solar radiation is the primary factor affecting stream-water temperatures during summer (Leinenbach et al. 2013). Thus, the likely effect of forest harvest on stream temperatures will be a function of the amount of shade lost. The largest effects will generally be seen with clearcut logging right to the streambanks, whereas retention of forested buffers tends to reduce these effects, as does thinning rather than clearcutting outside the buffer. The actual magnitude of stream-temperature increases can vary greatly and is determined by factors such as discharge, water depth, width, flow velocity, hyporheic exchange, and groundwater inflows (Janisch et al. 2012, Johnson 2004, Moore et al. 2005). Topographic shading can also influence water temperatures, particularly in small streams flowing in narrow, steep-sided valleys, as much as or perhaps more than shade from streamside forests (Zhang et al. 2017). It is important to remember that canopy removal also results in nighttime long-wave radiation loss, leading to lower water temperatures. This effect contributes to increased thermal variability, with poorly understood biological consequences.

Relatively few studies have examined the effects of riparian thinning on stream-water temperature. A few studies have examined clearcut harvesting combined with partial harvest of riparian buffers (Kreutzweiser et al. 2009, Macdonald et al. 2003, Mellina et al. 2002, Wilkerson et al. 2006). These studies, like those cited above, suggest that the effect of riparian thinning on summer stream temperatures will be correlated positively with the amount of forest canopy removed and inversely with the distance from the stream that the activity occurs, and thus the amount of shade lost (Leinenbach et al. 2013). However, the amount of shade lost from a given thinning treatment can be highly variable, and the small number of studies makes it difficult to draw strong generalities. The amount of shade lost can be smaller than the amount of tree basal area removed, and in one study, removal of 10 to 20 percent of the basal area had no measureable effect on angular canopy density (Kreutzweiser et al. 2009). Further, any shade loss and stream-temperature increases from riparian thinning are likely to be short lived because riparian forest canopies can close relatively quickly (within 3 years) after thinning (Chan et al. 2006, Yeung et al. 2017). The potential magnitude of stream-temperature increases in response to riparian thinning will be highly dependent on forest attributes outside the riparian buffer, the buffer size, the prethinned riparian forest attributes (Leinenbach et al. 2013), the thinning prescription, and the thermal sensitivity of the stream (Janisch et al. 2012). Further research is needed to improve our understanding of the impacts of thinning, but there is some evidence that light thinning may not substantially increase stream temperatures.

Managers thus face the following question: Are there places in the stream network in which riparian thinning would help speed attainment of the reference distribution, and where present-day thermal regimes would suggest that small temperature increases would not have significant detrimental effects on fish (Groom et al. 2011) or other organisms of interest? This question tends to be investigated at the reach scale. For example, Pollock et al. (2012) examined the potential effects of a thinning treatment on the development of riparian forest-stand attributes, and Groom et al. (2011) looked at summer maximum temperatures in the treated reach. Rarely are these questions expanded to consider the context of the distribution of reference conditions across the larger watershed. If they were asked, the question would then become: Are the conditions of the treated reach overrepresented with respect to the reference distribution, or underrepresented? In the Oregon Coast Range, for example, it is clear that not all reaches would be maintained in conifer-dominated mature forest under a natural disturbance regime (Wondzell et al. 2012). If dense, young, conifer-dominated stands are currently more abundant than expected from the reference distribution, then should some of those stands be thinned, perhaps mimicking windthrow events that open stand canopies and allow development of multistoried, mixed stands? If so, how many should be treated to better change the long-term trajectory of conditions from the current distribution toward one that is closer to the reference distribution?

Riparian thinning and large wood—The absence or diminished quantity of wood in streams throughout the NWFP area is a primary concern for managers and regulators because wood is important for creating habitat and performing other ecological functions. Thinning and other active management in plantations in riparian zones can reduce the potential amount of wood that can be delivered to streams (Beechie et al. 2000, Pollock et al. 2012) and the forest floor (Pollock and Beechie 2014, Pollock et al. 2012) if the trees are removed from the site. Additionally, thinning may negatively affect habitat, at least in the short run, for some species that are favored by dense conifer cover (see chapter 3 for more details), potentially increase water temperature (Leinenbach et al. 2013), and reduce carbon storage (D'Amore et al. 2015). However, there are also many potential benefits to thinning, including increasing structural diversity, species richness, flowering and fruiting of understory shrubs and herbs (Burton et al. 2014, Carey 2003, Hagar et al. 1996, Muir et al. 2002), and faster development of mature-forest conditions, including very large trees with thick limbs that may be used for nesting by marbled murrelets (*Brachyramphus marmoratus*) (Carey and Curtis 1996, Franklin et al. 2002, Tappeiner et al. 1997) (see chapter 5). Furthermore, variable density thinning of the overstory in the second-growth riparian forest could accelerate recovery of old-growth characteristics by promoting dominance of redwood in the southern portion of the NWFP area (Keyes and Teraoka 2014) (see chapter 3).

Considerable research on wood dynamics in the NWFP has been done in wet forests of California, Oregon, and Washington, but there has generally been less research in areas with drier forest types, including northern California. Riparian areas in redwood-dominated forests are particularly distinctive owing to the exceptional productivity, low mortality, and slow decay of those trees (Benda et al. 2002). Benda and Bigelow (2014) compared wood volumes across four different regions of northern California, including the Coast Range, Klamath Mountains, Cascade Range, and Sierra Nevada, as well as variation associated with forest management. They noted that coastal streams had much greater wood volumes, which they attributed to greater forest biomass and higher growth rates of redwood forests, as well as slower decay of large wood pieces. They also observed that some second-growth forests along streams in that region had wood volumes comparable to those in old-growth forests, owing to heavy debris remaining from tractor-era logging before the 1970s. Although the volumes were similar, streams in old-growth areas had fewer but larger logs (Benda et al. 2002). Benda and Bigelow (2014) also found that streams in the Cascades and Sierras that they characterized as more heavily managed had larger volumes of stream wood than less intensively managed areas in the same regions. They conjectured that managed forests could have higher rates of tree mortality because of stem exclusion (successional phase characterized by the rapid growth and biomass accumulations of a particular species, and intense competition among cohorts [Oliver 1981]) than more mature, but not yet decadent, unmanaged forests with lower tree densities.

A panel of scientists from the Forest Service and the National Marine Fisheries Service recently reviewed the published literature on the effects of thinning in riparian areas (Spies et al. 2013). Their major conclusions are summarized below:

- Accurate assessment of thinning effects requires site-specific information. The effects of thinning regimes on dead-wood creation and recruitment (relative to no thinning) will depend on many factors, including initial stand conditions, particularly stand density, and thinning prescriptions.
- Conventional thinning generally produces fewer large dead trees. Thinning with removal of trees (conventional thinning) will generally produce fewer large dead trees across a range of sizes over the several decades following thinning and the lifetime of the stand relative to equivalent stands that are not thinned.
- Thinning to develop old-growth structure is most beneficial in dense young stands less than 80 years old and especially those less than 50 years old.
- Conventional thinning can accelerate the development of very large diameter trees. In stands that are conventionally thinned, the appearance of very large diameter dead trees (greater than 40 in [102 cm]) may be accelerated by up to 20 years relative to unthinned plantations, depending on thinning intensity and initial stand conditions.
- To produce down wood immediately, thinning can leave trees that are cut as part of the restoration program (see Benda et al. 2016 for details).
- Thinning can increase the amount of pool-forming wood only when the thinned trees are larger in diameter than the average diameter of pool-forming wood (which varies with stream size).
- Effects of thinning on instream wood need to be placed in a watershed context. Assessing the relative effects of riparian thinning on instream wood loads at a site and over the long term requires an estimation of the likely wood recruitment that will occur from both the banks and downstream movement from upstream sources, and the rate of decay and downstream transport of wood from the site.
- The ecological effects of thinning on instream habitat will vary depending upon location in the stream network. Riparian-management practices can be altered to match the ecological functions of streams.
- Variation in thinning is essential to increase species diversity and heterogeneity (i.e., do not use the same prescription everywhere).

Since Spies et al. (2013) summarized the state of the science, other studies have increased our understanding of the effect of restoration thinning in riparian areas. Benda et al. (2015) simulated the idea of adding wood to channels during thinning by modeling the amount of instream wood that would result from thinning a 50- to 80-year-old Douglas-fir stand from below (i.e., removing the smallest trees to simulate suppression mortality) from 400 to 90 trees/ac (988 to 222 trees/ha), which is considered a moderate amount of thinning, then directionally falling or pulling over varying proportions of the harvested trees into the stream (table 7-4). This wood loading was compared to the amount that would be expected in the stream if the existing stand was not thinned. Not surprisingly, the amount of wood increased above the "no-thin" level immediately after the tipping simulation in all the wood-addition options. However, the cumulative total amount of wood expected in the stream over 100 years relative to the unthinned stand varied depending on the amount of wood delivered. Adding ≤10 percent of the wood that would be removed during thinning resulted in less wood in the channel over time than the unthinned option (i.e., if the stand were not actively managed). When 15 to 20 percent of the volume of thinned trees from one side of the stream was directed to the stream at each entry, the total amount of dead wood in the channel exceeded the unthinned scenario over time (table 7-4). Thinning the stand again 25 years after the first thinning further increased wood levels (table 7-4). Carah et al. (2014) found that adding unanchored wood into the stream was less costly than securing the wood, and improved habitat conditions for coho salmon. Reeves et al. (2016a) included wood addition (tree-tipping) as a component of options for managing the riparian reserves on Oregon and California Railroad Revested lands of the BLM in western Oregon to accelerate attainment of restoration objectives.

Ecological tradeoffs—There are potential ecological consequences of limiting tree harvest (thinning) only to the outer portions of the riparian reserves. A myriad of ecological processes create and maintain the freshwater habitats of Pacific salmon (Bisson et al. 1997, 2009) and the ecological context in which they evolved (Frissell et al. 1997). This is especially relevant to the goals of the ACS, which are broad and include more than aquatic conditions. Holling and Meffe (1996) contended that uniform management prescriptions often fail when applied to situations in which processes are complex, nonlinear, and poorly understood, such as in aquatic ecosystems in the NWFP area, and may lead to further degradation or compromising of the ecosystems and landscapes of interest (Dale et al. 2000, Hiers et al. 2016, Rieman et al. 2006). For example, managing for a single purpose (e.g., maximizing dead wood) may compromise or retard other ecological functions, such as development of hardwoods and shrubs or growing large trees, in areas near the stream (see previous discussion), and ultimately may alter the structure of the food web (Bellmore et al. 2013). Pollock and Beechie (2014) stated that "species that utilize large-diameter live trees will benefit most from heavy thinning, whereas species that utilize large-diameter deadwood will benefit most from light or no thinning. Because far more vertebrate species utilize large deadwood rather than large live trees, allowing

Table 7-4—Predicted change in the estimated volume of wood in a stream channel under two different harvest options (single and double entry) over the simulated 100 hundred years (includes decay) when varying proportions of harvest wood are placed or felled into the stream channel

	Change from no treatment	
Scenario	**Single-entry thin**	**Double-entry thin (25 years after first entry)**
	- - - - - - - - - Percent - - - - - - - - -	
No treatment (reference)	0	0
Thin entire stand, no tipping	-33	-42
Thin entire stand except with a buffer 32.8 ft (10 m) no-harvest buffer	-7	-11
Thin with a buffer 32.8 ft (10 m) and tip 5 percent of the harvested wood	-15	-15
Thin with a buffer 32.8 ft (10 m) and tip 10 percent of the harvested wood	-6	+1
Thin with a buffer 32.8 ft (10 m) and tip 15 percent of the harvested wood	+1	+16
Thin with a buffer 32.8 ft (10 m) and tip 20 percent of the harvested wood	+6	+24

Source: Benda et al. 2016.

riparian forests to naturally develop may result in the most rapid and sustained development of structural features." We agree that tradeoffs exist and that prioritization will be needed (see chapter 12 for more discussion of tradeoffs).

The choice of priority conservation targets (e.g., dead wood, plant-community diversity, large live trees, geomorphic disturbances) for riparian management is a difficult one to make, involving scientific criteria, risk assessment, and social values. Given the diversity of conditions in riparian areas at watershed and regional scales, it would make sense not to apply one-size-fits-all strategies, but rather to develop priorities based on a watershed-scale view (see "A context-dependent approach to riparian conservation and management" below). For example, Pollock and Beechie (2014) stated that "management strategies that seek to create a range of large live and dead tree densities across the landscape will help to hedge against uncertain outcomes related to unanticipated disturbances, unexpected species needs, and unknown errors in model assumptions." It will be important to consider the full suite of ecological functions across a watershed; focusing only on one condition or metric may limit recovery of riparian ecosystems in ways that prevent full achievement of the broad objectives of the ACS. Given these broad objectives, a more comprehensive watershed- and regional-scale consideration of all ecological processes, and studies to develop new and more complete approaches, may be more fruitful than focusing on only one or two metrics.

A context-dependent approach to riparian conservation and management—
A key component of the ACS is watershed analysis (FEMAT 1993), which is supposed to provide the context of a given location for adjusting the boundaries of, and allowing activities within, riparian reserves. However, the intent of watershed analysis was never realized (Reeves et al. 2006), owing to a number of factors including cost of analysis and the need to consider a multitude of species and their ecological requirements. Neither FEMAT (1993) nor the NWFP (USDA and USDI 1994a) provided explicit criteria for changing the riparian reserve boundaries or demonstrating that proposed changes would meet or not prevent attainment of ACS objectives over the long term. In addition, at the time, credible analytical tools to aid decisionmaking were lacking (Reeves 2006); a fixed-width approach is easy to administer and apply and is less costly than developing site-specific recommendations (Richardson et al. 2012). As a result, adjustments have proven difficult for the agencies to make (Naylor et al. 2012, Richardson et al. 2012), and interim boundaries of the riparian reserves remained intact in the vast majority of watersheds (Baker et al. 2006).

Since the development of the ACS, there has been a call in the scientific literature to allow discretion in setting site-specific activities (Kuglerová et al. 2014, Lee et al. 2004, Richardson et al. 2012), which can be economically beneficial (Tiwari et al. 2016). Greater flexibility in the management of riparian areas would depend on the "context" of the area of interest (Kondolf et al. 2006, Montgomery 2004), and the primary management objective for the specific area (Burnett and Miller 2007). However, development of such an approach has been limited because of the reliance on "off-the-shelf" and one-size-fits-all concepts and designs, rather than on an understanding of specific features and capabilities of the location of interest (Kondolf et al. 2003, Naiman et al. 2012). A mix of approaches could be undertaken, recognizing ecological and other goals such as timber harvest, especially if applied over larger spatial scales (Burnett and Miller 2007, Miller and Burnett 2008, Olson and Rugger 2007), and if consideration is given to the distribution of populations of concern and connectivity among them (Olson and Burnett 2009, Olson and Kluber 2014, Olson et al. 2007).

There have been a few attempts to design and implement a site-specific approach. Cissel et al. (1999) proposed a plan based on variation in the disturbance patterns (in this case, wildfire) in the target watershed, and called for harvest of some older trees and a revision of the interim riparian reserves for the Central Cascades Adaptive Management Area. Olson and Rugger (2007) proposed a two-tiered approach to riparian management to first identify reaches in which sensitive species occur, then manage their critical habitat elements, hence varying riparian reserve management with species distributions. Olson and Burnett (2009) applied sensitive-species filters to criteria for designations of habitats for connectivity within and among watersheds. Interwatershed connections provided by riparian areas are critical avenues of movement to new habitats. None of these approaches have been implemented to date.

Reeves et al. (2016a) proposed a context-dependent approach for management of the riparian reserves in the matrix of federal lands in western Oregon that divided the riparian reserve into inner and outer zones, with management tailored to the specific features and characteristics of individual stream reaches (Option B of Reeves et al. 2016a). The context-dependent option was informed by new research, tools, and concepts, including:

- The influence of the width of riparian area on microclimate (see earlier discussion).
- Movement of amphibians along non-fish-bearing streams (Olson and Burton 2014, Olson et al. 2007).
- The distance to, and sources of, wood for fish-bearing streams (Spies et al. 2013).
- Intrinsic potential, a concept for assessing the capability of a given set of geomorphic conditions in a stream reach to provide habitat for selected species of Pacific salmon (Burnett et al. 2007).
- NetMap (Benda et al. 2007), a geospatial platform for watershed analysis that can, among other things, identify the location of some key ecological processes that influence aquatic and riparian ecosystems on the landscape and in the stream network.
- Concepts for managing riparian ecosystems and the activities that affect them, such as ecological forestry (Franklin and Johnson 2012) and tree-tipping (Benda et al. 2016).

Under the context-dependent option, current interim riparian reserves of two site-potential tree-heights along fish-bearing streams and one site-potential tree-height along non-fish-bearing streams would be retained in late-successional reserves and other special land designations (Reeves et al. 2016a). In lands allocated as matrix under the NWFP, the area of interest for aquatic conservation (Reeves et al. [2016a] referred to this as the riparian conservation area) extended upslope from the stream for a distance equal to the height of one site-potential tree along fish-bearing and non-fish-bearing streams. The riparian conservation area was divided into an inner and an outer zone depending on "ecological context," based on four characteristics of each stream reach—susceptibility to surface erosion, debris flows, thermal loading, and habitat potential for target fish species—to determine the width of the inner zone. The entire riparian conservation area of the most ecologically sensitive stream reaches along fish-bearing and non-fish-bearing streams could be managed solely for ecological goals for fish and other aquatic and riparian-dependent biota. In other fish-bearing and non-fish-bearing streams, the inner zone was 100 ft (30. 5 m) and 50 ft (15.3 m) wide, respectively (Reeves et al. 2016a). Active management was limited to stands age 80 years or younger in reserves (Spies et al. 2013), and tree-tipping (Benda et al. 2016) was used throughout the riparian reserve to ensure that harvest did not negatively affect wood recruitment to the stream (table 7-4).

Using the matrix in BLM-managed lands in western Oregon to illustrate the application, Reeves et al. (2016a) estimated that an average of 46 percent of the riparian reserve in a watershed would be managed solely for ACS goals. Also, an estimated average of 36 percent would achieve ACS goals along with other potential goals, which could include timber production, and 18 percent could be managed for a variety of purposes, including wildlife and timber, in accordance with NWFP requirements (Reeves et al. 2016a). In late-successional and other reserve allocations, which cover approximately half of the BLM lands in western Oregon, interim riparian reserves would remain unchanged. Assuming that half of the interim riparian reserves on BLM lands in western Oregon would remain unchanged, and applying their study estimates of changes in matrix, Reeves et al. (2016a) estimated that about 72 percent of the interim riparian reserves would remain solely devoted to ACS goals, and 19 percent would likely meet ACS goals and could also provide opportunity for achievement of matrix goals including limited timber production. The reduction of the width of the riparian reserve along fish-bearing streams to one tree-height would return an estimated 9 percent of interim riparian reserves to matrix on these lands.

The analysis of Reeves et al. (2016a) was not intended to provide a single recommendation for managing riparian ecosystems. The primary purpose was to reevaluate riparian-conservation strategies using the latest scientific evidence. This or other options should be viewed as working hypotheses to be tested with monitoring and adaptive-management experiments. The analysis provides an example of how a context- and landscape-dependent approach could be designed to address multiple conservation goals of the ACS, the commodity goals of the NWFP, and the significant challenges of climate change. Although new science has refined our understanding of the ecological processes in riparian ecosystems, uncertainties and information needs remain. Thus, an adaptive-management approach and further research are critical to continual improvement and evaluation of this and other options for meeting the goals of the ACS (Stankey et al. 2005).

Key Watersheds

Tier 1 key watersheds (a total of 141, covering 8,154,500 ac (3 300 000 ha) (fig. 7-10) were intended to serve as refugia for aquatic organisms or to have high potential for restoration (USDA and USDI 1994a). Tier 2 key watersheds provide sources of high-quality water, and comprised 23 watersheds covering a total of about 1,112,000 ac (405 000 ha) (fig. 7-10). Key watersheds are aligned as closely as possible with the late-successional reserves of the NWFP (areas designated to protect late-successional and old-growth ecosystems) and other officially designated reserve areas to maximize ecological efficiency (USDA and USDI 1994a), and to minimize the amount of area in which timber-harvest activities were restricted. A primary objective for tier 1 key watersheds is to aid in the recovery of ESA-listed fishes, particularly in the short term (FEMAT 1993). Tier 1 key watersheds in good condition at the time of the Plan's inception were assumed to serve as centers for potential recovery of depressed populations. Those with degraded conditions were expected to have the greatest potential for restoration and to become future sources of good habitat.

The trend in the condition of key watersheds differed among assessments. Gallo et al. (2005) reported that a greater proportion of the key watersheds had their condition scores improve than did non-key watersheds. Lanigan et al. (2012) found key watersheds to be in better condition than

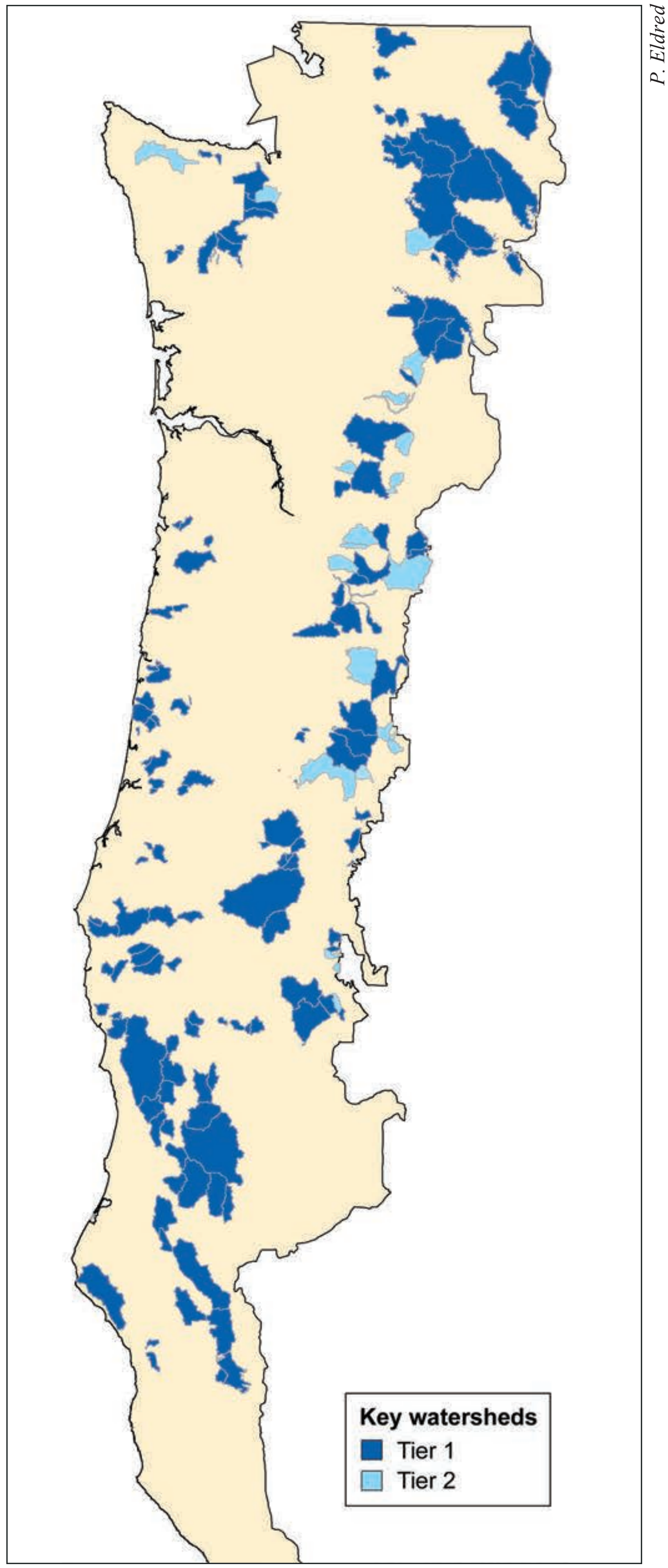

Figure 7-10—Location of key watersheds in the Northwest Forest Plan area.

non-key watersheds, primarily because more than twice as many miles of roads were decommissioned in key watersheds as in non-key watersheds (Gallo et al. 2005, Lanigan et al. 2012), suggesting that land management agencies appear to recognize key watersheds as priority areas for restoration. Miller et al. (2017), however, saw no statistical differences between the two groups.

Key watersheds were originally selected based on the professional judgment of the scientists involved with the development of the ACS, in consultation with fish and aquatic biologists and hydrologists from the national forests and BLM districts covered by the NWFP. Also, they were tightly aligned with late-successional/old-growth reserves, based in part on the assumption that streams in old-growth forests would be most favorable for fish (FEMAT 1993). New techniques (e.g., NetMap, Benda et al. 2007) and understanding of aquatic ecosystems now provide a different perspective on aquatic ecosystems and how they operate in space and time.

New concepts such as intrinsic potential of fish habitat (Burnett et al. 2007), projections of climate change, and new questions as to whether stream conditions in old-growth forests are actually most favorable for native salmonids (Bisson et al. 2009, Reeves and Bisson 2009, Reeves et al. 1995) are pivotal concepts that reframe our understanding of aquatic ecology and ecosystems. No formal evaluation of the potential effectiveness of the network of key watersheds was conducted during development of the NWFP, or has been undertaken since it was implemented. Fish populations in need of attention are clearly identified now, and it would be useful to investigate whether the current system is beneficial to those fish in terms of the overall distribution and the suitability of individual watersheds. Additionally, the distribution of other sensitive aquatic-riparian species (e.g., ESA-listed or petitioned herpetofauna) could contribute to this assessment.

Watershed Analysis

Watershed analysis was designed to provide the context for management activities in a particular sixth-field watershed as the basis for developing project-specific proposals and determining restoration needs. It was envisioned as an analytical and not a decisionmaking process, involving individuals from a variety of scientific disciplines (USDA and USDI 1994a). Management agencies were expected to complete a watershed analysis before activities (other than minor ones) were initiated in key watersheds or riparian reserves (USDA and USDI 1994a). The version of watershed analysis advocated in the NWFP differs from previous versions (e.g., Washington Forest Practices Board 1993) and involves multiple disciplines and issues other than those that are specifically aquatic.

Baker et al. (2006) estimated that about 500 watershed analyses had been done by 2003, but that the quality and effectiveness of these analyses differed widely. No formal assessment of watershed analyses has been completed as of this writing, so it would be prudent to conduct a comprehensive review and evaluation, and consider incorporating new analytical tools such as NetMap (Benda et al. 2007) to help improve the process and reduce costs while increasing the usefulness of the product. The watershed analysis process could also be reexamined so that it is conducted more efficiently and considers the appropriate spatial scales, including the watershed of interest and its context within the larger basin or region. The latter could be particularly relevant for effective planning at a landscape scale and to deal with climate change.

New Perspectives on Conservation of Riparian and Aquatic Ecosystems

The ACS was premised on the view that aquatic ecosystems were dynamic in space and time, exhibiting a range of potential conditions, similar to the terrestrial systems in which they are embedded (FEMAT 1993). Aquatic ecosystems in Pacific Northwest forests are multifaceted and complex, and can be conceptualized as a set of ecological states (Penaluna et al. 2016, Reeves et al. 1995, Rieman et al. 2015), each with particular abiotic and biotic conditions, functions, and processes at any given time. The number and variety of ecological states in a domain (i.e., the range of conditions or range of natural variability for an ecosystem) is in constant flux in response to changes in local conditions, stochastic processes, legacies of past disturbance, and time since past disturbance (Beechie et al. 2010; Benda

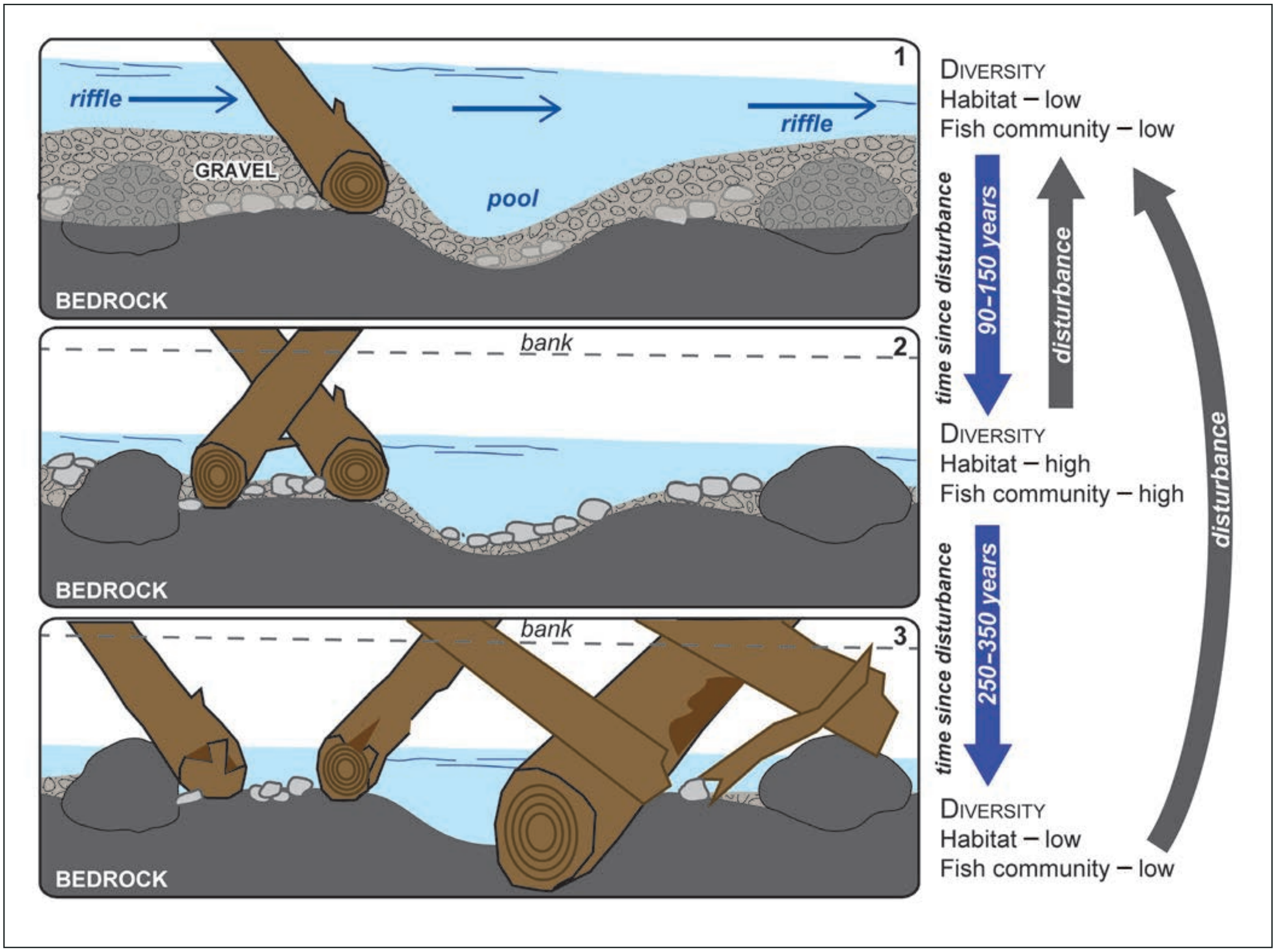

Figure 7-11A—Examples of the range of conditions that aquatic ecosystems experience: (1) a stream 90 to 100 years after the last disturbance, (2) 160 to 180 years, and (3) more than 330 years (Reeves et al. 1995) (see table 5 for specific details).

et al. 1998; Liss et al. 2006; Miller et al. 2003; Reeves et al. 1995; Resh et al. 1988; Rieman et al. 2006, 2015; Wondzell et al. 2007). Examples of the variation that aquatic ecosystems can experience through time are shown for the central Oregon Coast Range (Reeves et al. 1995) (fig. 7-11A and table 7-5), and eastern Oregon (Wondzell et al. 2007) (fig. 7-11B). Larger streams and rivers in the lower portion of the network are less variable through time; those in the upper and middle portions are more dynamic (Naiman et al. 1992). Because of the variation in the size and asynchronous nature of disturbance events (Allen et al. 1982, Malard et al. 2002, Schindler et al. 2010, Wiens 2002), conditions will vary over time among watersheds, resulting in a mosaic of biophysical conditions across the landscape. Unmanaged and minimally disturbed aquatic systems may actually exhibit a wider range of conditions than more heavily managed systems (Lisle 2002, Lisle et al. 2007).

A contrasting view holds that aquatic ecosystems tend to be in an equilibrium or steady state, and when disturbed, they are expected to return to predisturbance conditions relatively quickly (Resh et al. 1988, Swanson et al. 1988). Biological (Vannote et al. 1980) and physical conditions (Rosgen 1994) are presumed to be relatively constant through time and to be "good" (barring human interference) in all systems at the same time. Conditions in aquatic systems with little or no human influence and natural

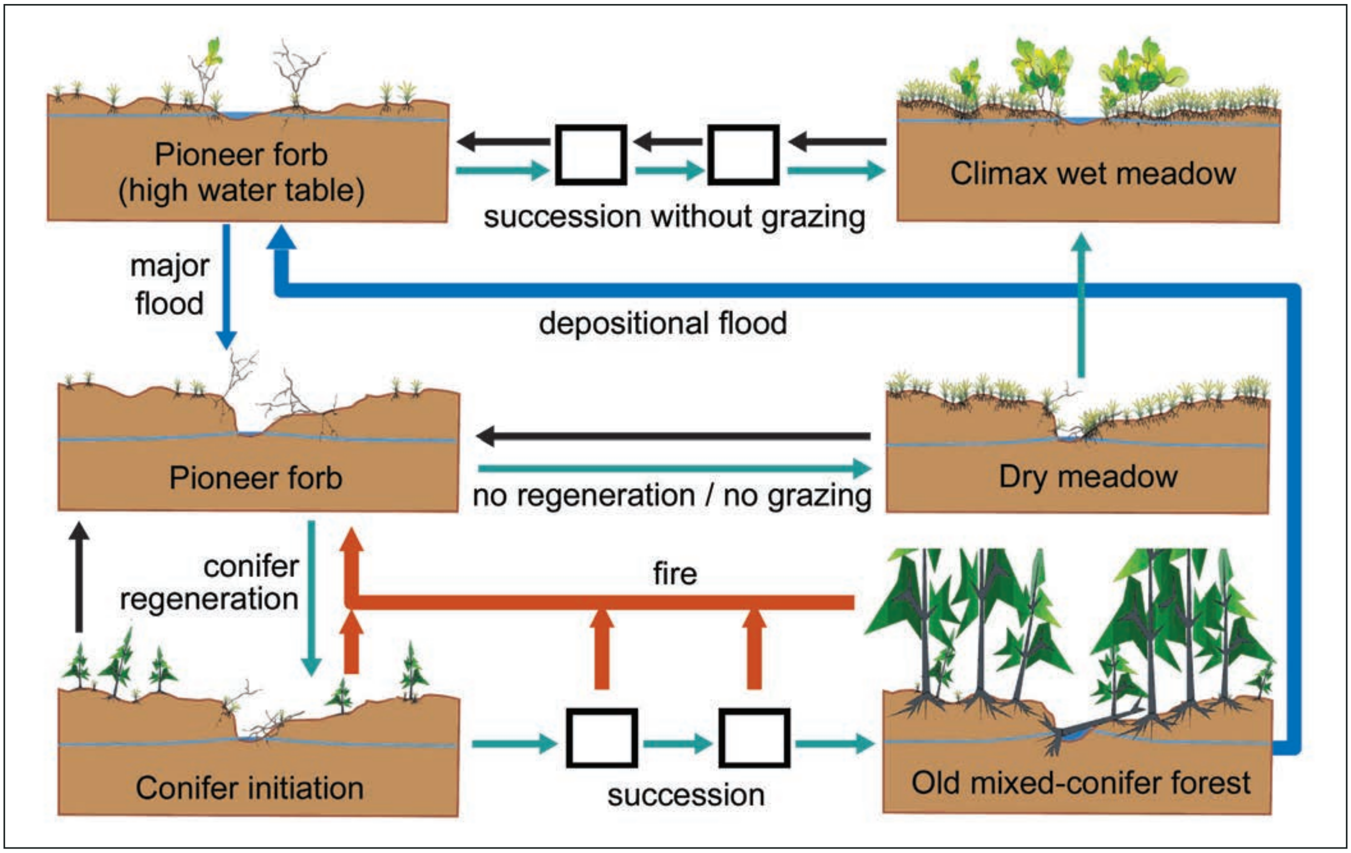

Figure 7-11B—Examples of the range of conditions that aquatic ecosystems in eastern Oregon can experience through time (Wondzell et al. 2007).

Table 7-5—Features of streams from the Oregon Coast Range used in figure 7-11A

Feature/stream	Harvey Creek (1)	Franklin Creek (2)	Skate Creek (3)
Time since disturbance (years)	90–100	160–180	More than 330
Number of pieces of wood/100 m	7.9	12.3	23.5
Mean depth of pools (m)	0.9	0.35	0.1
Dominant substrate	Gravel	Gravel	Bedrock
Percent of fish assemblage juvenile coho salmon	98.0	85.0	100.0
Percent of fish assemblage juvenile steelhead	1.0	12.5	0
Percent of fish assemblage juvenile cutthroat trout	1.0	2.5	0

Source: Reeves et al. 1995.

disturbance, particularly those associated with late-successional and old-growth forest, are assumed to have the most favorable conditions for fish (Fox and Bolton 2007, Murphy and Koski 1989, Pollock and Beechie 2014, Pollock et al. 2012) and other aquatic organisms, and are most frequently used as references against which the condition of managed streams (e.g., Index of Biotic Integrity) (Karr and Chu 1998) and effects of management actions can be assessed. Systems experiencing disturbances, such as wildfire or floods, are often immediately "restored" by attempting to reduce or eliminate erosional processes. For example, fences were placed in headwater streams following a wildfire in Colorado to reduce the potential for erosion and debris flows (Chin et al. 2014). However, reaches lower in the stream network downcut, creating other concerns. Although this static ecosystem view is being questioned in the general ecological literature (Hiers et al. 2016, Jackson et al. 2009, Montgomery 1999, White and Jentsch 2001, Wohl et al. 2014), it is still being used to guide management and assess effects on aquatic ecosystems, and persists in environmental laws and policies developed in the 1970s, such as the Clean Water Act (Craig 2010).

Resilience is the capacity of an ecosystem to absorb change and remain within the ecosystem state and domain in the face of natural disturbances and human stressors (Desjardins et al. 2015). As ecosystems undergo larger shifts from human stressors, the ecosystem can be redefined, with a completely different set of characteristics and a compromised or altered range of conditions (Bisson et al. 2009, Reeves et al. 1995). Some ecosystem components may persist through this transition, whereas others may be new components arising from human or climatic alterations, including the development of novel states that may result in the loss of selected ecosystem services and conditions for at least some native species (Penaluna et al. 2016).

The physical aspect of these dynamics is understood conceptually (see review in Buffington 2012), but few mechanistic models currently exist to help us understand the potential effects of management on dynamic ecosystems (but see Wondzell et al. 2007), especially under climate change. As a result, consideration of dynamics remains largely conceptual, and holistic models of basin function (i.e., watershed analyses) are generally lacking, limiting the development of process-based applications of river management and restoration (Beechie et al. 2010). Also, there is also a tendency to focus on mean or median conditions while overlooking temporal variability as "noise" and losing sight of the considerable inherent variability that characterizes riparian and aquatic ecosystems (Fausch et al. 2002, Montgomery 1999), which is ecologically critical (Hiers et al. 2016). Accounting for this variability and for nonstationarity of fluvial processes is central to assessing potential effects of climate change on riverine ecosystems (Buffington 2012, Miller et al. 2003, Montgomery 1999). However, being able to incorporate this variability into restoration and mitigation actions may be limited by social concerns (Kondolf et al. 2006) (see chapter 12).

Consideration of large spatial and temporal scales is critical to the development of management and conservation strategies for ecosystems (Dale et al. 2000, Holling and Meffe 1996), including a range of conditions for aquatic ecosystems (Fausch 2010, Fausch et al. 2002, IMST 1999, Liss et al. 2006, NRC 1996). This shift requires moving from the current focus on relatively small spatial scales, with little or no consideration of the relevance of time, to a focus that considers large spatial scales, specifically ecosystems and landscapes, over relatively long periods (tens to hundreds of years) (Bisson et al. 2009, Naiman and Latterell 2005, Poff et al. 1997, Reeves et al. 1995). An example of the importance of relations between scales can be seen in the "portfolio effect" of the behavior of populations of sockeye salmon (*O. nerka*) in Bristol Bay, Alaska, identified by Schindler et al. (2010). This study found large variation in the number of fish in any local population over time. However, the variation among the many populations was asynchronous—not all were high or low at the same time. As a result, the total number of fish was relatively constant at the landscape scale, a pattern similar to the amount of old growth historically found in the Oregon Coast Range (Wimberly et al. 2000). This pattern appears to be disrupted in heavily managed systems (Moore et al. 2010).

Both the NWFP and new Forest Service planning rule (USDA FS 2012a) require managers to consider large spatial scales in designing, implementing, and evaluating management actions. The new planning rule also emphasizes ecosystem goals based on ecological integrity. This can be daunting given the lack of scientifically sound examples of how to design and implement forest management at large temporal and spatial scales (North and Keeton 2008, Reeves and Duncan 2009, Thompson et al. 2009) and the lack of adequate tools and guidance. Shifting the management focus to the landscape level and longer time intervals requires recognition of the principles of hierarchy theory and the relation among levels of organization to increase the potential for success of future riparian policies and practices (Fausch 2010, Fausch et al. 2002).

Regulators may recognize the need to apply policies and regulations across broad areas, but may be constrained by the regulatory framework in which they are operating, and generally default to single standards that are applied across broad areas (e.g., National Marine Fisheries Service's matrix of pathway and indicators) (NMFS 1999). This premise is inappropriate for addressing complex, multifaceted landscapes, however (Allen and Starr 1982; O'Neill et al. 1986, 1989); instead, it is important to recognize that a multiwatershed landscape operates differently through time than does a single watershed, and that smaller spatial scales tend to be more variable over time than larger scales (Benda et al. 1998, Wimberly et al. 2000). Increasing levels of aggregation, especially as spatial scales increase, may obscure important system processes (Clark and Avery 1976) and may result in unrealistic expectations for ecosystems and contribute to the contention that often surrounds large-scale management proposals (Allan and Curtis 2005, O'Neill et al. 1986, Shindler et al. 2002). Also, the failure to recognize the different levels of ecological organization and the potential response of each to component parts of disturbance and management may incur unintended economic and social costs, such as repeated investment in ineffective restoration and management strategies (Caraher et al. 1999, Dale et al. 2000).

The emerging consideration of ecosystem dynamics and large spatial and temporal scales has implications for approaches to restoration of aquatic-riparian ecosystems. Many restoration efforts have focused mainly on improving habitat attributes, primarily wood placement, and to a lesser degree on shade improvement for water temperature. These efforts too often aim to bring "stability" to degraded systems, and are viewed as the final phase of restoration (see Palmer et al. 2014). The dynamic approach, not yet broadly practiced, focuses on restoring ecological processes (Beechie et al. 2009, 2010; Bernhardt and Palmer 2011), including periodic inputs or reoccurrences of these important habitat attributes. This requires a shift from reliance on striving only to develop a particular condition (e.g., number of pieces of wood per unit length) or channel classification (e.g., Rosgen 1994) to a quantitative approach based on ecological processes, theory, empirical field methods, and limited modeling (Kline and Cahoon 2010, Wohl et al. 2005).

Some researchers have pointed out that although restoration of ecological processes, such as flow, water temperature, habitat complexity, and connectivity, is a critical consideration in restoring many streams, it may not be sufficient for degraded channels, and can even worsen the ecological condition of the stream (Louhi et al. 2011, Tullos et al. 2009). For example, in restoring floodplain overflow potential, if riparian trees are removed from a previously closed-canopy stream, the underlying energy regime may change from one based on allochthonous resources to one driven by primary production. This may shift the stream farther from the desired ecological state and often toward algae-dominated streambeds and higher temperatures (Robinson 2012, Sudduth et al. 2011). Similarly, if the hydrologic regime is restored but there is no nearby source of invertebrate colonists, then the instream communities will remain altered (Sundermann et al. 2011). Finally, an overreliance on an in-channel focus (small-scale) may not address the stressor(s) that most limit recovery of the aquatic ecosystem; quite often this factor is water quality, and thus ecological recovery will not occur until the stressor is addressed (Beechie et al. 2010, Kail et al. 2012, Selvakumar et al. 2010). Examples of process-focused restoration are presented below in the section on climate change.

In addition to considering spatial complexity, temporal dynamics are particularly important to understand because many key ecological processes such as canopy closure, tree-fall, and fuel loading are related to the age of trees in riparian areas as well as time since disturbance. Temporal dynamics can be examined using models, but long-term studies and monitoring are needed to understand how systems respond over time (Hassan et al. 2005). One strategy that may be appropriate is to design monitoring to focus more on changes following major disturbances rather than focusing simply on short-term trends.

The other challenge posed by a dynamic perspective of aquatic ecosystems is the consideration of large spatial scales. Restoration efforts are generally performed at small spatial scales, with only a relatively small percentage of any watershed actually treated (Ogston et al. 2014, Roni et al. 2010). Roni et al. (2010) estimated that a minimum of 20 percent of the habitat of a given species in a watershed should be restored to detect a 25 percent increase in smolt (salmon or steelhead) numbers, the minimum detection level for most monitoring programs. They found that floodplain restoration yielded greater increases than in-channel restoration. However, because of the large variability in numbers for most populations (Bisson et al. 1997, Schindler et al. 2010), Roni et al. (2010) suggested that 100 percent of the habitat should be restored to have a significant ecological impact.

Non-Fish-Bearing Streams

The ecological importance of headwater streams, which generally make up 70 percent or more of the stream network (Downing et al. 2012, Gomi et al. 2002), was not well known or understood at the time the ACS was developed, but it is now better established in the scientific literature (Leigh et al. 2016, Richardson and Danehy 2007). Headwaters are sources of sediment (Benda and Dunne 1997a, 1997b; May and Lee 2004; Zimmerman and Church 2001; see review by MacDonald and Coe 2007) and wood (Bigelow et al. 2007; May and Gresswell 2003, 2004; Reeves et al. 2003) for fish-bearing streams; provide habitat (Kelsey and West 1998, Olson et al. 2007) (see chapter 6) and movement corridors (Olson and Burnett 2009, Olson and Kluber 2014) for several species of native amphibians and macroinvertebrates (Alexander et al. 2011, Meyer et al. 2007), including recently discovered species (Dieterich and Anderson 2000); and may be important sources of food for fish (Kiffney et al. 2000, Wipfli and Baxter 2010, Wipfli and Gregovich 2002, Wipfli et al. 2007; also see reviews by MacDonald and Coe 2007 and Clarke et al. 2008). Wood jams in small streams are important sites of carbon storage (Beckman and Wohl 2014), and these streams export large amounts of carbon; one-third is emitted to the atmosphere and the remainder transported downstream (Argerich et al. 2016).

Tributary junctions of headwater streams with larger channels are important nodes for regulating material flows (Benda et al. 2004, Gomi et al. 2002, Montgomery et al. 2003) and cold water (Ebersole et al. 2015) in a watershed, and are the locations where site-scale effects from management activities are often observed (Richardson and Béraud 2014). These locations have unique hydrologic, geomorphic, and biological attributes and differ in the types and amount of materials delivered to the channel, making them sites of high biodiversity (Benda et al. 2004, Danehy et al. 2012)

Headwater streams are among the most dynamic portions of aquatic ecosystems (Benda et al. 2005, Hassan et al. 2005, MacDonald and Coe 2007, Naiman et al. 1992). Headwater habitats may range from simple to complex, depending on the amount of time since disturbance (such as landslides and debris flows). Following evacuation by a debris flow, headwater depressions and channels fill with material from the surrounding hillslopes, including large wood that falls into these channels, forming obstructions behind which sediments and wood accumulate (Benda and Cundy 1990, May and Gresswell 2004), and then empty again with the next landslide or debris flow (fig. 7-12). As a result, headwater streams are likely to exhibit a range of conditions across the landscape at any point in time.

This cycle of filling and emptying results in a punctuated movement of sediment and wood to larger, fish-bearing streams (Benda et al. 1998, Naiman et al. 1992), contributing to the long-term productivity of many aquatic ecosystems (Benda et al. 2003, Hogan et al. 1998, Reeves et al. 1995). A common consequence of past clearcutting is an absence of down wood to replenish the refilling process. This lack of wood may result in a chronic movement of sediment to larger channels, which could lead to both non-fish-bearing and fish-bearing channels developing characteristics different from those that occurred before forest management. Such conditions could be outside the range of variability to which native biota are adapted (Beschta et al. 2004), limiting the effectiveness of conservation and recovery programs.

Wood enters streams via chronic and episodic processes (Bisson et al. 1987). Chronic processes, such as tree mortality and bank undercutting (Bilby and Bisson 1998, Murphy and Koski 1989), generally introduce single trees or a relatively small number of trees at frequent intervals. Wood from headwater streams, which originates from within 131 ft (40 m) of the channel (May and Gresswell 2003), is delivered to fish-bearing streams by large, infrequent events, such as windthrow (Harmon et al. 1986), wildfire (Agee 1993), severe floods, landslides, and debris flows (Benda et al. 2003; May and Gresswell 2003, 2004; Reeves

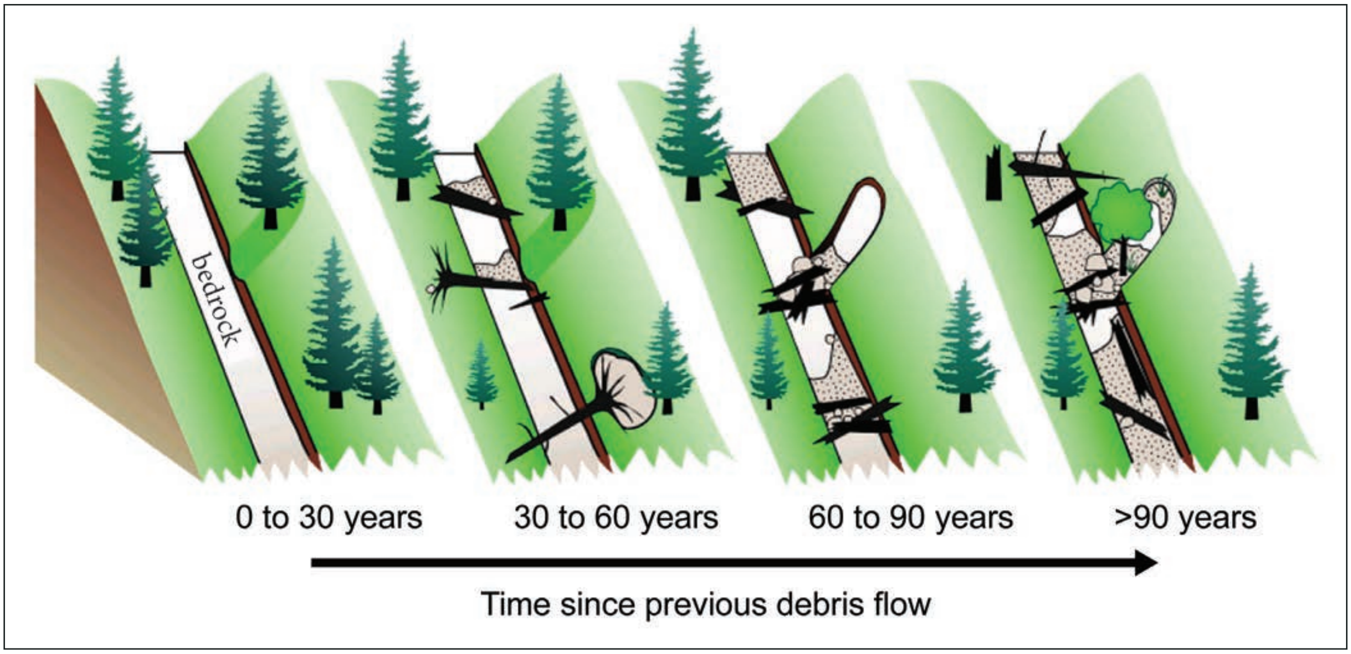

Figure 7-12—Conceptual illustration of the changes in channel morphology based on the time since the previous debris flow (May and Gresswell 2004).

et al. 2003). Geomorphic features of a watershed influence the potential contribution of upslope wood sources. Steeper, more highly dissected watersheds will likely have a greater proportion of wood coming from upslope sources than will watersheds with lower stream densities and gradients. Also, there is wide variation in the potential of headwater streams to deliver sediment and wood to fish-bearing streams, depending on channel steepness and angle of entry along the run-out track, among other factors (Benda and Dunne 1997a, 1997b; Brayshaw and Hassan 2009; Burnett and Miller 2007; May 2007). Culverts and other stream crossings can also impede wood movement from smaller to larger streams (Trombulak and Frissell 2000).

The presence of large wood from headwater streams influences the behavior of landslides and debris flows and the response of the channel to such events. Large wood in debris flows and landslides influences the run-out length of these disturbance events (Lancaster et al. 2003). Debris flows without large wood move faster and farther than those with wood, and they are less likely to stop high in the stream network. A debris flow without wood is likely to be a concentrated slurry of sediments of various sizes that can move at relatively high speeds over long distances, scouring substrate and wood from the affected channels. These types of debris flows are more likely to negatively affect fish-bearing channels, as compared to the potentially favorable effects that result from the presence of wood. Woodless debris flows can further delay or impede the development of favorable conditions for fish and other aquatic organisms. In contrast, those containing wood can help store sediments (Bunn and Montgomery 2004) and build terraces that can persist for extended periods (Lancaster and Casebeer 2007, May and Lee 2004).

Intermittent streams, which can make up half the total length of the stream network (Datry et al. 2014), connected to larger fish-bearing streams can provide important seasonal habitats for spawning and rearing by fish (Boughton et al. 2009, Wigington et al. 2006). In the Oregon Coast Range, growth and survival of juvenile coho salmon was higher in intermittent streams than the perennial mainstem (Ebersole et al. 2006, 2009; Hance et al. 2016). Identification, protection, and restoration of these streams is important to the success of conservation efforts for native fish across the NWFP area.

A rich non-fish community inhabits headwater streams throughout the NWFP area. For example, Olson and Weaver (2007) found 3 species of fish and 12 species of amphibians in stream reaches in 12 western Oregon study sites ranging from Mount Hood to Coos Bay. In this study and Olson and Burton (2014), torrent salamanders (*Rhyacotriton* spp.) dominate intermittent streams and appear to be sensitive to thinning in narrow riparian-management areas; NWFP riparian reserves appear to be benefiting retention of this aquatic-dependent community in abundant small streams in the region. Nevertheless, two torrent salamander species are currently petitioned for listing under the ESA; both have ranges that include significant tracts of nonfederal lands.

Continuing and Emerging Topics of Concern

Water

Federal lands are important sources of fresh water for human consumption, recreation, agriculture, and environmental needs in the United States. These lands produce an estimated 24.2 percent of the Nation's water supply, 18 percent and 1.5 percent from Forest Service and BLM lands, respectively (Brown et al. 2008). In the West,[5] federal lands contribute 66 percent of the mean annual water supply, 51 percent of which comes from Forest Service lands and 5.4 percent from BLM lands (Brown et al. 2008). Management strives to maintain the quality and quantity of this water. The extent of the contribution of federal lands to regional water supplies was not well quantified at the time the NWFP and ACS were developed.

The contribution of water from federal lands specifically in the NWFP area is also important; however, exact estimates are not currently available and were beyond the scope of this review. At the state level, the majority of water in the three NWFP states (California, Oregon, and Washington) originates from federal lands (table 7-6), with the bulk coming from Forest Service lands. Within the NFWP area, the amount of water flowing from federal lands varies among national forests and watersheds. Some forests, such as the Deschutes and Willamette National Forests, make relatively large contributions, 40 percent or more, to the flow of rivers whose watersheds they include (figs. 7-13A and 7-13B, respectively). Contributions from other forests are smaller (less than 20 percent) (fig. 7-13C) but nonetheless important. See "Climate Change" below for potential future issues pertaining to water supply and stream temperatures.

Roads

Roads provide necessary motorized access for forest management, recreation, and other beneficial purposes (Gucinski et al. 2001), but they can also have detrimental effects on native biodiversity and ecosystem function. The focus of the NWFP and ACS has been to address the negative effects of roads on aquatic ecosystems through a broad program of road decommissioning and upgrading, including remediation of chronic sedimentation and barriers to aquatic organism movement. Several syntheses describe the types, causes, and effects of road networks on streams, and meta-analyses concerning the ecological effects of

[5] The West is defined here as including the states of Arizona, California, Colorado, Idaho, Montana, New Mexico, Nevada, Oregon, Utah, Washington, and Wyoming.

Table 7-6—Contribution of federal lands and agencies to the total mean annual water supply of states in the Northwest Forest Plan area (percentage of mean annual water supply)

State	All federal lands	Forest Service	Bureau of Land Management	Other
		Percent		
California	61.1	46.6	5.5	9.0
Oregon	55.3	44.0	9.4	2.0
Washington	60.2	41.5	0	18.7

Source: Brown et al. 2008.

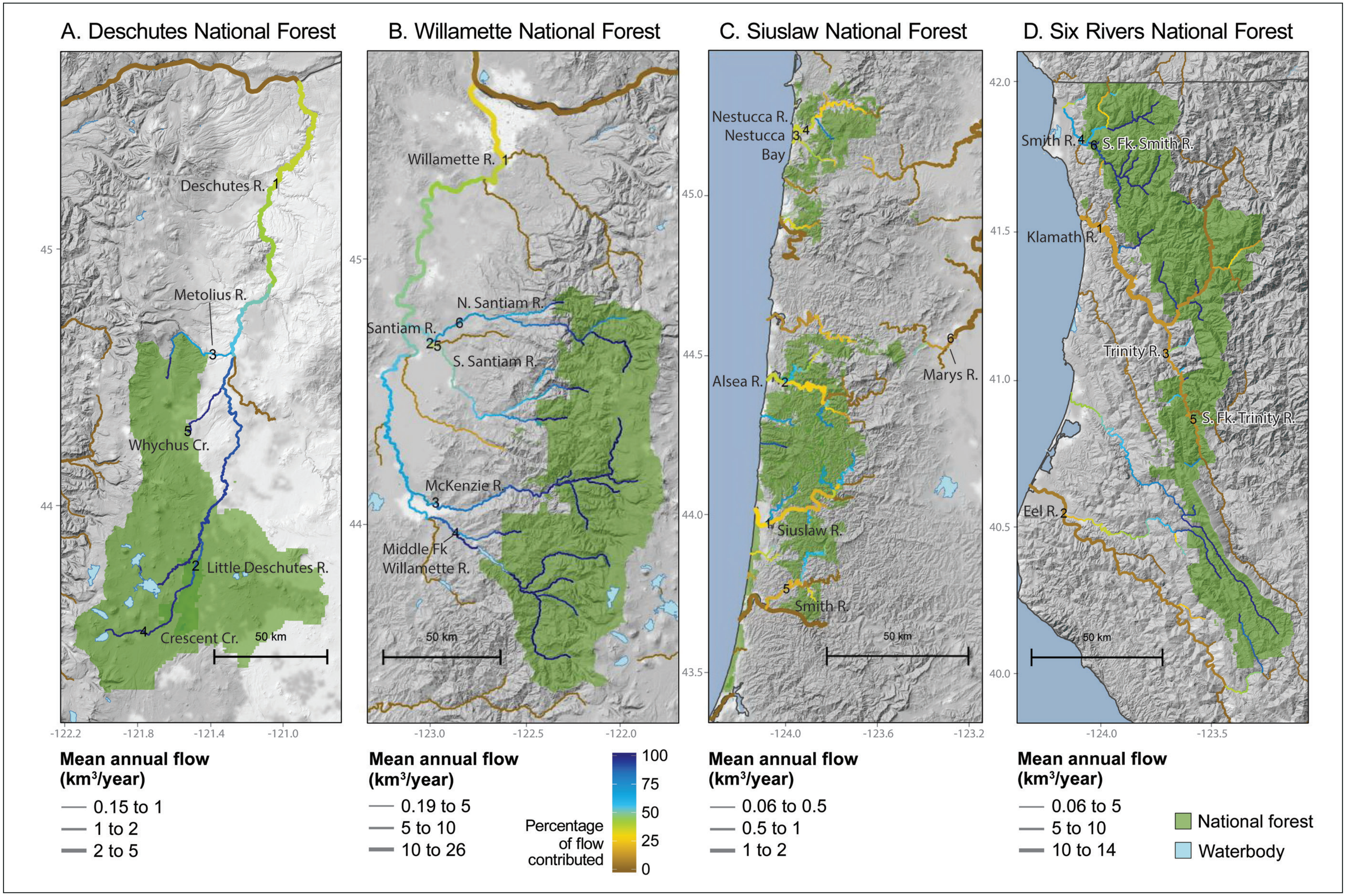

Figure 7-13—Contribution of selected national forests in the Northwest Forest Plan area to the mean annual flow of adjacent watersheds: (A) Deschutes National Forest, central Oregon Cascades; (B) Willamette National Forest, western Oregon Cascades; (C) Siuslaw National Forest, Oregon Coast Range; and (D) Six Rivers National Forest, coastal northern California. (https://www.fs.fed.us/rmrs/projects/national-forest-contributions-streamflow).

roads in general and specifically the delivery of sediment from mountain roads with low maintenance standards have been published (Croke and Hairsine 2006, Forman and Alexander 1998, Jones et al. 2000, Trombulak and Frissell 2000). Reducing the effect of roads and associated infrastructure remains a challenge for federal management agencies and others.

The vulnerability of roads to hydrologic changes and the associated effects on aquatic and riparian ecosystems differ based on topography, geology, slope stability, design, location, and use. Roads can affect streams directly by:

1. Accelerating erosion and increasing sediment loading (Allan 2004, Daigle 2010, MacDonald and Coe 2008, Suttle et al. 2004).
2. Imposing barriers to the migration of aquatic organisms, including access to floodplains and off-channel habitats (Clarkin et al. 2005, Daigle 2010, Gibson et al. 2005, Sagar 2004, Trombulak and Frissell 2000).
3. Increasing stream temperatures (Wenger et al. 2011).
4. Causing changes in channel morphology (Daigle 2010, Hassan et al. 2005).
5. Introducing exotic species (Daigle 2010, McKinney 2001).
6. Increasing harvest and poaching pressure (Lee et al. 1997, Trombulak and Frissell 2000).
7. Changing hillslope hydrology and resulting peak flows (Daigle 2010, Jones and Grant 2001).

Roads penetrating remote and otherwise intact forested landscapes can have particularly significant effects on aquatic ecosystems (Forman 2003, Havlick 2002, Trombulak and Frissell 2000). The ecological consequences of these effects are shown in table 7-7.

The effects of roads differ widely depending on local features (Al-Chokhachy et al. 2016). Recently developed techniques, such as the Geomorphic Roads Analysis and Inventory Package (Black et al. 2012), can be employed to identify priority locations of sources of sediment, including culvert failures, landslides, and gullies. A modified version of this technique has been incorporated into NetMap (Benda et al. 2007) to reduce the amount of field time needed to assess roads. Evaluating the effectiveness of new analytical approaches and focusing on treating limited lengths of roads could be a research priority.

A significant number of watershed-improvement actions implemented under the NWFP and other large-scale forest planning efforts involve decommissioning roads that have a high probability of contributing to landslides, and that are not regarded as essential to meeting local forest objectives, as well as removing road-related impediments to upstream and downstream movements of aquatic organisms (Switalski et al. 2004). The watershed-analysis component of the ACS identified forest roads where (1) drainage systems hastened runoff from storms and promoted sedimentation of streams, (2) unstable fill materials concentrated water and increased the risk of landslides, and (3) the roadbed encroached on riparian zones (Kershner 1997). Since NWFP implementation, the Aquatic and Riparian Effectiveness Monitoring Program estimated that 6.7 percent of the road network has been removed or closed (5,390 out of 80,750 mi total [8674 of 129 954 km]) in the NWFP area.[6] Additionally, 10 percent of the road crossings that impeded the movements of aquatic and riparian organisms (209 of 2,114) have been made passable on Forest Service Region 6 lands in the NWFP area since NWFP implementation.[7]

Though restoration of fish passage is often listed as a top priority for stream restoration in the Pacific Northwest (Roni et al. 2002, USGAO 2001), recent work has contributed much to our understanding of just how complex this issue is in practice (McKay et al. 2016). Advances have been made in culvert inventory and assessment (Clarkin et. al 2005), ecosystem-based restoration approaches (USDA FS 2008), and effectiveness monitoring (Heredia et al. 2016, Hoffmann et al. 2012). Until recently, however, the ecological benefit of these efforts has been difficult to quantify beyond the level of individual projects. A new

[6] Miller, S. 2016. Personal communication. National riparian program lead, U.S. Department of the Interior, Bureau of Land Management, 1849 C Street NW, Washington, DC 20240.

[7] Capurso, J. 2017. Personal communication. Regional fish and aquatic program manager, U.S. Forest Service, 333 SW First Ave., Portland, OR 97204, jcapurso@fs.fed.us.

Table 7-7—Summary of effects of road on aquatic ecosystems and associated biota

Ecological effect	Habitat loss/degradation	Habitat fragmentation	Direct mortality
Low population density	✓	✓	✓
Low population reproductive rates	✓		✓
Area occupied restricted	✓	✓	✓
Decreased habitat connectivity	✓	✓	
Overharvest			✓
Changes in water quality	✓		✓
Changes in hydrologic functions	✓	✓	✓
Change in wood and sediment recruitment	✓	✓	✓

Source: Modified from Robinson et al. 2010 and Daigle 2010.

study evaluating the effectiveness of passage restoration at the level of an entire forest (the Siuslaw National Forest) (Chelgren and Dunham 2015) found that individual culvert replacements successfully increased the probability of upstream access for all fishes in the study area. Results of this work also showed that the net benefit of culvert replacements was fairly modest across the extent of the forest when expressed in terms of gains in kilometers of stream occupied or increases in fish numbers resulting from restoration. The authors hastened to add that some limitations of the study design could have influenced these findings (Chelgren and Dunham 2015), but results of this study nonetheless point to the value of programmatic (vs. project-only) evaluations of culvert restoration. This echoes more general recommendations for following the cycle of adaptive management on national forests (Marcot et al. 2012) and the recommended scales for managing watersheds (Fausch et al. 2002, Neeson et al. 2015).

Much of the guidance for fish-passage restoration on federal lands in the Pacific Northwest was issued by an assessment in 2001 (USGAO 2001). This assessment highlighted the need for larger scale assessments, as noted above, as well as the economic challenges associated with passage restoration, which are only beginning to be addressed. For example, a followup to the Chelgren and Dunham (2015) study by Reagan (2015) evaluated costs and benefits of remaining culvert replacement opportunities on the Siuslaw National Forest in relation to multiple objectives, including benefits to fish (estimated from Chelgren and Dunham 2015), maintenance of transportation networks, and the probability of culvert failures based on culvert size and influences of floods and major erosional events in streams. The Reagan (2015) analysis explicitly quantified economic costs and benefits of restoration in relation to these objectives and their relative assumed values. This work (along with others in the region, e.g., Chelgren and Dunham 2015) has demonstrated the value of a proactive, economic analysis of multiple objectives to identify priorities for restoration investments in a programmatic context. These new tools, if applied, can more completely address standing recommendations to land management agencies in the Pacific Northwest (e.g., USGAO 2001) to more efficiently invest limited resources to benefit fisheries and other management objectives through culvert replacements.

Because road access management must take into account social, economic, and environmental objectives (Daigle 2010), the decisionmaking process for dealing with roads is complex. A decision matrix for identifying actions is shown in figure 7-14. In many cases, limited funds or socioeconomic issues may preclude closing or removing roads identified as high priority for treatment on the basis of their effects on riparian ecosystems. Also, a road network may be needed to effectively implement landscape-scale restoration projects that might involve widespread thinning and prescribed fire (Franklin and Johnson 2012), and for fire management, fuel reduction, and fire control. Studies

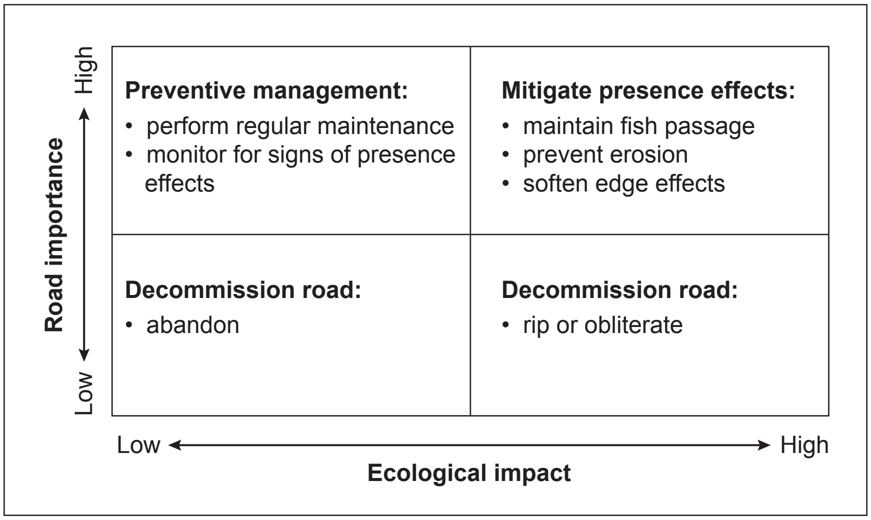

Figure 7-14—A decision matrix for identifying potential options for managing roads. (Modified from Robinson et al. 2010).

in Redwood National Park suggest that removal of logging roads can yield carbon-storage dividends, in particular by preventing soil erosion (van Mantgem et al. 2013). The vast road system on private and state lands that abut federal lands also needs to be considered in road assessments. Understanding how to balance fire management, recreation, and other needs against potential negative aspects of roads will require a concerted cooperative effort of managers and physical, biological, and social scientists, other organizations, and the public. (See next section for additional discussion of roads.)

Climate Change

Since 1994, our knowledge of climate change in the NWFP area has greatly improved, just as dealing with climate change has become an important aspect of environmental planning in the Forest Service and BLM. Many advances have come from models that forecast trends in temperature, precipitation, and snowpack, and associations of these trends with the habitat conditions for various species. Although there is general agreement about the direction of trends in many meteorological parameters, the rates and amounts of change at specific locations in the NWFP area differ among models (Climate Impacts Group 2009; see also chapter 2). Further, other climate-related changes such as increases in forest insect and disease outbreaks and uncharacteristically severe wildfires may accentuate the undesirable effects of meteorological and hydrological trends, resulting in threats to the integrity of both terrestrial and aquatic ecosystems. Although developing proactive measures that would ameliorate undesirable effects of climate change on forest resources was not a centerpiece of the NWFP, one of the Plan's main objectives was to restore forest ecosystems that were resilient in the face of natural and anthropogenic disturbances. The question is: how well does the NWFP address climate-related threats to native fishes and other aquatic biota as they are currently perceived? (See chapter 2 for further details.)

In this section, we focus on a review of recent advances in our knowledge of the likely effects of climate change on native fishes of the NWFP area. We examine climate-change effects on fish life cycles, with a principal focus on anadromous salmonids, a group of species that has received the most scientific attention, as well as significant conservation effort (table 7-8) (see additional discussion in app. 2). Watershed improvements undertaken through the NWFP are related to potential climate effects on fish life cycles, and to the capacity of populations to adapt and persist through time. Finally, we discuss the role that federally managed forests in the NWFP area play in conserving native fishes in a changing climate, when viewed in a broader matrix of different land ownerships and other landscape-scale uses.

Table 7-8—Species of Pacific salmonids considered in this section and their typical freshwater and marine residence times

		Residence time	
Species		**Freshwater**	**Marine**
Pink salmon	*Oncorhynchus gorbusha*	Less than 30 days	2 years
Chum salmon	*O. keta*	Less than 30 days	2 to 5 years
Sockeye salmon	*O. nerka*	Few months to 2 years	2 to 5 years
Coho salmon	*O. kisutch*	1 to 2 years	1.5 years
Chinook salmon	*O. tshawytscha*	Few months to 1 year	2 to 6 years
Steelhead	*O. mykiss*	1 to 3 years	2 to 4 years
Coastal cutthroat trout	*O. clarkii clarkii*	2 to 4 years	Short forays into nearshore environment

Climate change in the Northwest Forest Plan area—
Projected changes in climate are usually derived from models based on historical data coupled with scenarios incorporating alternative assumptions about future greenhouse gas emissions. These assumptions range from high global rates of economic development and human population growth to conservative industrial and population-growth rates and widespread implementation of "clean" technologies. Model outcomes are often displayed as incremental changes in an environmental parameter of interest such as air temperature, sea level, or precipitation over a fixed period. Projected changes in climate under different scenarios are plotted to provide a range of outcomes at a given point in time, with scenarios incorporating intermediate assumptions about future greenhouse gas emissions generally believed to represent the most realistic expectations.

Air and water temperatures—
Virtually all climate models forecast a gradual rise in air temperature by the end of this century. Recent changes in climate appear to be happening more rapidly than in at least the past 1,000 years (IPCC 2007), and have included a global average warming of 1.4 °F (0.8 °C) during the past 120 years. According to the IPCC (Intergovernmental Panel on Climate Change) (IPCC 2014), most general circulation models predict that 2 to 7 times more warming will occur by early in the next century, with projected increases in mean global surface temperatures by 2100, ranging from 2.7 to 3.6 °F (1.5 to 2.0 °C) relative to the 1850–1900 time frame, depending on carbon dioxide (CO_2) emission scenarios (IPCC 2014). The 2014 IPCC synthesis report (IPCC 2014: 10) states:

> It is **virtually certain** that there will be more frequent hot and fewer cold temperature extremes over most land areas on daily and seasonal timescales, as global mean surface temperature increases. It is **very likely** that heat waves will occur with a higher frequency and longer duration. Occasional cold winter extremes will continue to occur. [emphasis theirs]

The finding that climate change will include both gradual long-term temperature trends as well as increases in the frequency and duration of extreme events has important implications for aquatic ecosystems in the NWFP area.

Air-temperature changes in forests of the NWFP area are predicted to be generally consistent with global climate models, although somewhat more variable, with forecast increases ranging from 1 to 6.3 °F (0.5 to 3.5 °C) in the remainder of this century, depending on the greenhouse gas emission scenario used in the model and on forest location (Latta et al. 2010). Overall, these authors noted that relative temperature increases were more apparent at higher elevations than at lower elevations, and that proximity to the Pacific Ocean moderated the rate of change. Mote and Salathé (2010) examined a broad suite of IPCC climate models and found that, by the 2080s, average air temperatures in the Pacific Northwest were predicted to increase 2.9 °F (1.6 °C) under the coolest scenario and by 10.3 °F (5.7 °C) under the warmest scenario. In most models, the greatest absolute temperature increases were projected for summer months, although warming was also forecast in other seasons. Sea-surface temperatures showed less warming over the same period than those modeled over land.

Similar to air temperatures, water temperatures are expected to rise in much of the NWFP area as a result of climate change (Isaak et al. 2011 [NorWeST model]). Modeled water temperatures were developed primarily from models of the relation between air and water temperatures, and are projected to be stressful to lethal for many native salmonids (e.g., Isaak et al. 2012, Wade et al. 2013) (see app. 2 for more details). More recent studies suggest that the extent of temperature change may not be as great as originally projected, particularly at higher elevations (Isaak et al. 2016). However, other researchers (Arismendi et al. 2014) have questioned the ability to project future water temperature from past relations between air and water temperatures. In addition, Arismendi et al. (2013a) found that recent trends in water temperature have been more variable than those reported by Isaak et al. (2012)—using empirical records, they found that water temperatures increased in some systems and decreased in others. Also, Leach et al. (2016) also found variability in water temperature in a headwater stream of the Oregon Coast Range that was not captured by the NorWeST model (Isaak et al. 2010), but noted that the model was not designed to track such small-scale effects. Although there is some uncertainty about the extent of temperature changes that streams in the NWFP area will experience, it is clear that dealing with water temperatures will be a major challenge for managers.

Potential patterns of changes in water temperature are highly variable when examined at the local scale (Leach et al. 2016, Reeves et al. 2016b, Turschwell et al. 2016) (fig. 7-15). This variability is a result of local conditions such as stream orientation, topographic shading, and elevation, and strongly influences physical and biological attributes and resultant ecosystem integrity (Gomi et al. 2002, Thorp et al. 2006). Understanding this variability will be crucial to developing effective restoration and mitigation programs and prioritizing specifically where to target efforts. Watershed analysis tools such as NetMap (Benda et al. 2007) can help identify areas that can provide thermal refugia and areas in which riparian restoration efforts (fig. 7-16) could help reduce water temperatures to levels less stressful or even optimal for native fish, despite climate change (Justice et al. 2017, Lawrence et al. 2014, Ruesh et al. 2012).

Hydrology—

Predicted future changes in streamflow on national forests in the Pacific Northwest are fundamentally tied to changes in the region's climate. Predicted changes in annual precipitation are much less certain, and most models project that future precipitation will remain approximately the same as it has been for the past 50 years (Salathé et al. 2007). Most predictions of changing streamflows for the Pacific Northwest therefore focus primarily on the effects of changes in temperature. Seasonal changes in precipitation are showing up in the data (Safeeq et al. 2013) but are difficult to resolve regionally, and consequently are not as well understood.

A key factor affecting both high and low streamflows in the future will be the fate of snow and the seasonal snowpack. Snowpack dynamics are important to understanding streamflow regimes because snow represents a dominant form of storage on the landscape. When precipitation falls as snow, it is not available for runoff or groundwater recharge until it melts. Similarly, the rate and timing of snowmelt are first-order controls on both peak and low streamflows, as discussed below.

A particularly crucial dimension of snowpack dynamics is the geographic location of the rain-snow transition on the landscape. This transition is controlled by elevation and determines how much of the winter precipitation falls as rain versus snow. Although often visualized as a fixed elevation, this transition is better seen as a stacked sequence of elevationally controlled zones or ranges with imprecise and regionally varying boundaries (Klos et al. 2014, Nolin and Daly 2006). In general, for any area, there is an elevation below which virtually all winter precipitation falls as rain and above which it falls as snow. Elevations in between are defined as the transitional snow zone (TSZ) that receives both rain and snow; snow and the snowpack usually will not persist all winter.

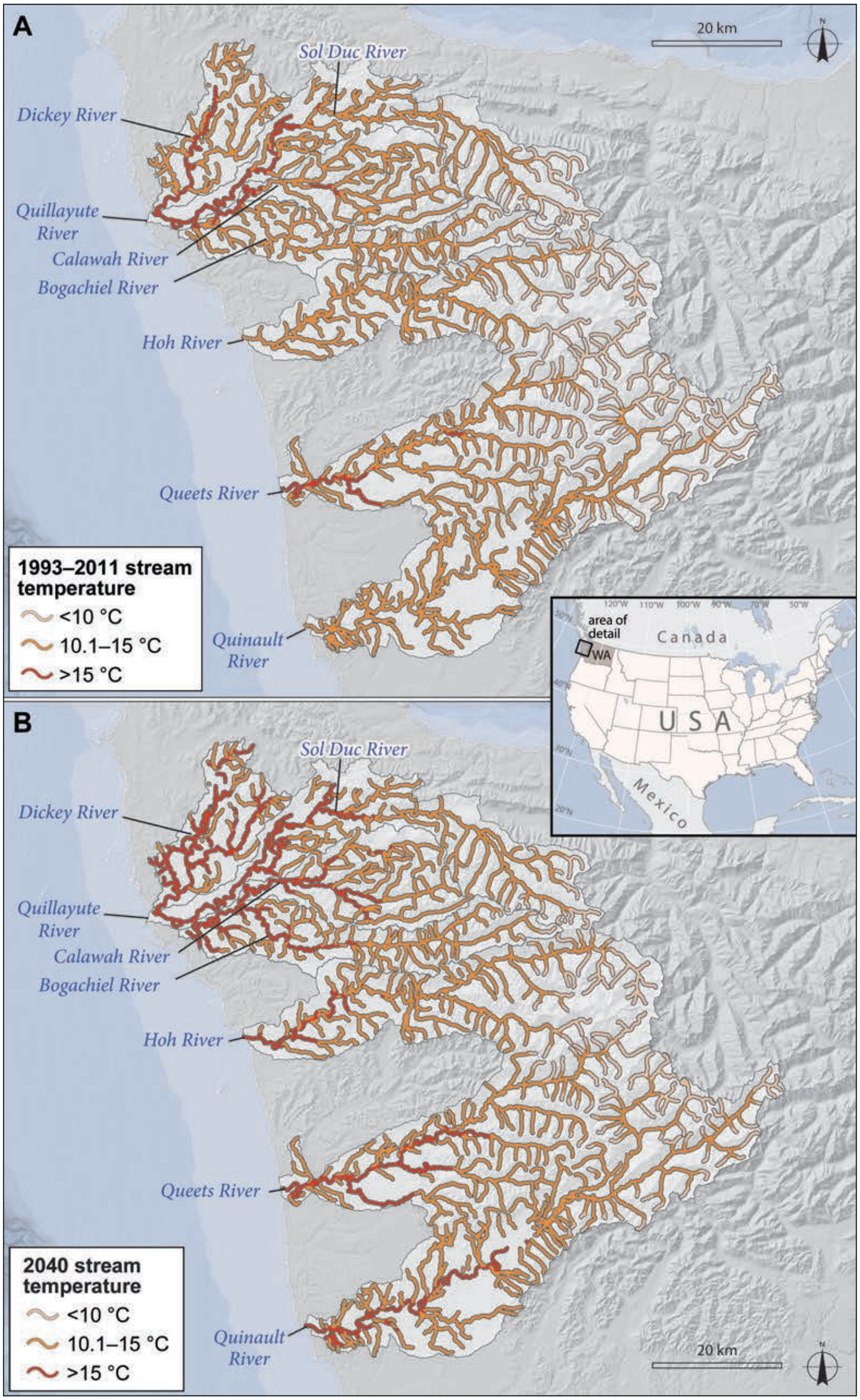

Figure 7-15—(A) Current and (B) projected (2040) summer water temperatures (°C) in the study basins in the Treaty of Olympia area (Reeves et al. 2016b).

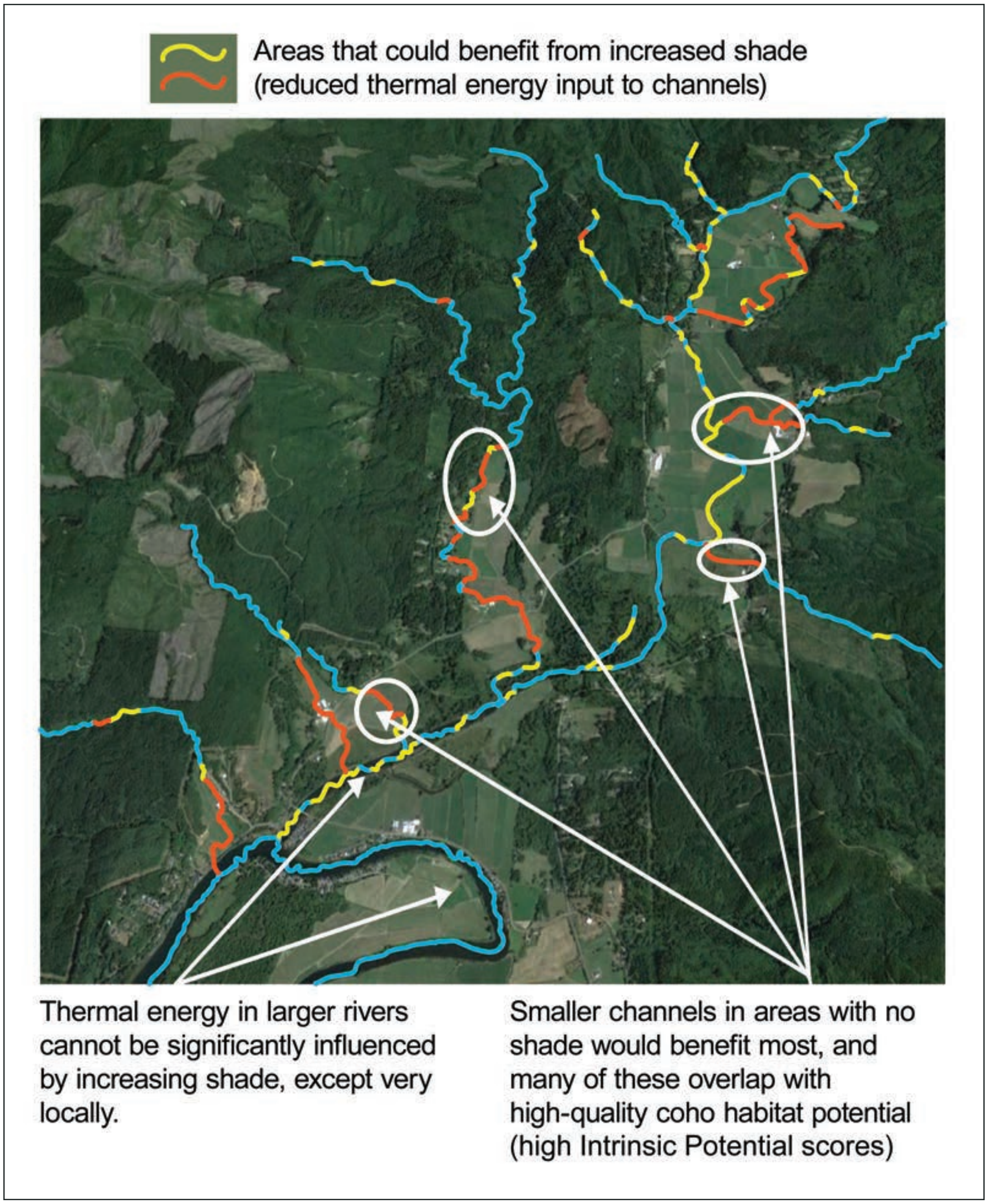

Figure 7-16—Example of identification of potential locations where riparian restoration could provide potential thermal refugia for native fish. Analysis from NetMap. (Modified from Benda et al. 2007.)

The widely varying elevational gradients in the Pacific Northwest in general, and on national forest lands in particular, therefore impose considerable variability in the response of the landscape to changing climate. Depending on the proportion of the landscape that occupies each of these zones, a warming climate, hence a rising snow line, may transition the landscape from a zone dominated by seasonal snow accumulation and melt (snow zone) to one that receives a mixture of rain and snow (and rain-on-snow)—the TSZ. Or it may push the landscape out of the TSZ and into the rain zone (Klos et al. 2014, Luce et al. 2014a)

The effects of a changing climate are already apparent in the snow data for the Pacific Northwest. As winter and spring temperatures have warmed over the past 50 to 70 years, spring snowpacks have been smaller (Hamlet et al. 2005, Mote 2003, Mote et al. 2005) and have melted out earlier (Hamlet and Lettenmaier 2007, Stewart et al. 2005). Moreover, the aforementioned zonal changes are already occurring in some landscapes as snow zones transition to the TSZ, and the TSZ becomes rain dominated (Tohver et al. 2014). These trends are expected to continue across much of the region (Luce et al. 2014a).

However, snowpack dynamics alone do not determine what future streamflow regimes will look like on national forests in the NWFP area. Recent work has shown that another first-order control is the landscape-scale drainage efficiency: the inherent, geologically mediated efficiency of landscapes in converting recharge (precipitation) into discharge (Safeeq et al. 2013, 2014; Tague and Grant 2009). In essence, the drainage efficiency determines how quickly precipitation, either as rain or snowmelt, becomes streamflow. Although drainage efficiency is "hard-wired" into the landscape on millennial timescales, and thus is not changing with climate, it mediates the climate-influenced signals and therefore has to be considered in predicting future streamflow regimes. This is particularly true for low-flow regimes, but influences peak flows as well. Basically, the drainage efficiency of a landscape is determined by the rate at which water moves through the subsurface. In steep landscapes with shallow soils, water rapidly moves laterally through the subsurface via both saturated and unsaturated pathways, drainage efficiency is high, and streams respond quickly to recharge events. In flatter landscapes with deep, permeable, porous, or fractured bedrock, water moves slowly as deep groundwater, drainage efficiency is low, and streams respond slowly to recharge events but may have sustained high base flows.

Effects of climate change on peak flows—Here we broadly consider how both climate and drainage efficiency can shape predictions of future streamflows on national forest lands. We distinguish between effects on peak and low flows, as the mechanisms of streamflow generation are different in each case. Finally, we discuss how these broad predictions can be refined for individual forests, a topic beyond the scope of the current analysis.

There are several hydrologic mechanisms by which climate could increase peak flows in rivers and thus their propensity to flood. More intense or frequent rainstorms are one mechanism, and some research has suggested that a warming atmosphere may result in a more northerly storm track for the North Pacific, potentially resulting in more intense precipitation (Salathé 2006). However, these results have large uncertainties and are not well represented in most global circulation models. A somewhat better-understood mechanism is the shifting potential for rain-on-snow (ROS) events in the Pacific Northwest as the climate warms. ROS events are known to be a potent flood-producing mechanism in steep mountain landscapes in the Pacific Northwest (Harr 1981, Marks et al. 1998, McCabe et al. 2007). In general, landscape susceptibility to ROS events is determined by climate and topography; the effects of climate warming on ROS are similarly influenced by the same controls; and climate warming may increase, decrease, or not affect the risk, depending on whether snowpacks are cold or warm (i.e., near the freezing point). As summarized by Hamlet and Lettenmaier (2007):

> Cold river basins where snow processes dominate the annual hydrologic cycle (<6 °C average in midwinter) typically show reductions in flood risk due to overall reductions in spring snowpack. Relatively warm rain-dominant basins (greater than 5 °C average in midwinter) show little systematic change. Intermediate or transient basins show a wide range of effects depending on competing factors such as the relative role of antecedent snow and contributing basin area during storms that cause flooding. Warmer transient basins along the coast in Washington, Oregon, and California, in particular, tend to show increased flood risk.

A more recent analysis looked at a range of factors influencing peak flows, including ROS in Oregon and Washington, and developed a model of sensitivity to peak-flow increases based on perturbing the temperature in the model using warming scenarios from 2020 to 2080 and the A1B[8] emissions scenario (Safeeq et al. 2015). The analysis yielded regional sensitivity maps for Oregon and Washington that can be used to characterize the risk on individual national forests and landscapes. They concluded

[8] This scenario assumes a future world of rapid economic growth and global populations peaking in the mid-21st century, then declining with the rapid introduction of new technology, with a balance between the use of fossil fuels and non-fossil-fuel sources.

that corresponding changes in snowpack dynamics may result in large (more than 30 to 40 percent) increases in peak flows, primarily in the Cascade Range and Olympic Mountains. The North Cascades, in particular, were most vulnerable (fig. 7-17). Lower elevation areas were less likely to be affected but were still vulnerable to larger floods generated from upstream reaches in vulnerable landscapes. These watersheds are also likely more susceptible to warming (Arismendi et al. 2013a, 2013b; Poole and Berman 2001; van Vliet et al. 2011, 2013). Streams at higher elevations should retain flows; with stable, cooler water temperatures, they will be critical cool-water refugia for native fish (Isaak et al. 2012, 2015; Luce et al. 2014b; Lusardi et al. 2016; Wenger et al. 2011).

Effects of climate change on low flows—Snowpack dynamics and drainage efficiency combine to determine the sensitivity of individual landscapes to a warming climate (Safeeq et al. 2013, Tague and Grant 2009). There has been a general trend over the past 50 years for less snow in winter and earlier snowmelt, resulting in reductions of spring, early-summer, and late-summer flows in the Western United States (Leppi et al. 2012, Safeeq et al. 2013), with the lowest flows showing the greatest decreases across the Pacific Northwest (Luce and Holden 2009). Hydrologic models such as the variable infiltration capacity (VIC) model, coupled with downscaled climate simulations, have been used to generate predictions of future low flows across much of the Pacific Northwest (e.g., Hamlet et al. 2013).

However, snowpack changes are not the only factor determining future low flows. Other recent work has shown that the drainage efficiency (slow versus fast) mediates the signal from climate-induced changes in snowpack and snowmelt. Employing a simple exponential-decay model to describe the recession behavior of streams, coupled with a regional-scale estimation of variations in aquifer-drainage characteristics, Safeeq et al. (2014) developed a sensitivity map for changes in summer streamflow across Oregon and Washington. As with the VIC products and peak-flow maps previously described, these maps provide water and landscape managers with a spatially explicit representation of where future changes in low flows are likely to be most pronounced. For example, these maps show that areas drained by young volcanic rocks with deep, slow groundwater systems, such as the High Cascades, may be particularly vulnerable to declines in summer streamflow, whereas areas with shallow subsurface aquifers and limited potential to store water are less sensitive to changes in low flows. Climate-change effects on summer low flows may be compounded by effects of forest-vegetation conditons. Perry and Jones (2017) found that average daily streamflow in smaller streams in summer in watersheds with 34- to 43-year-old plantations of Douglas-fir was 50 percent lower than streamflow from reference basins with 150- to 500-year-old forests. The change in flows is also likely to be highly variable among watersheds in a given area (fig. 7-18).

Assessing climate change effects on streamflow at the scale of individual national forests—The discussion above highlights how existing tools and models can be used to give technically sound predictions about the magnitude and timing of streamflow changes in specific landscapes. Although not a trivial exercise, any national forest can use the spatially explicit models already developed to make first-order forecasts for changes in streamflow regimes. The products to date cover most but not all forests in the area of the NWFP. Extending results to these unmapped forests (mostly in northern California) would require some extrapolation, but is well within the scope of the existing data. Tools and approaches such as the concept of "hydrologic landscapes" can expedite this process (Patil et al. 2014, Wigington et al. 2013, Winter 2001).

Furthermore, there are several examples to date of individual forests or groups of national forests and other federal and nonfederal landholders that have coordinated efforts to develop detailed assessments of likely hydrologic changes that can serve as models for other forests and regions. Specific examples include the Olympic National Forest (Halofsky et al. 2011), the Quinault Indian Nation on the Olympic Peninsula (Reeves et al. 2016b), the Blue Mountains Adaptation Partnership (Halofsky and Peterson 2017), and the upcoming report from the South Central Oregon Adaptation Partnership.

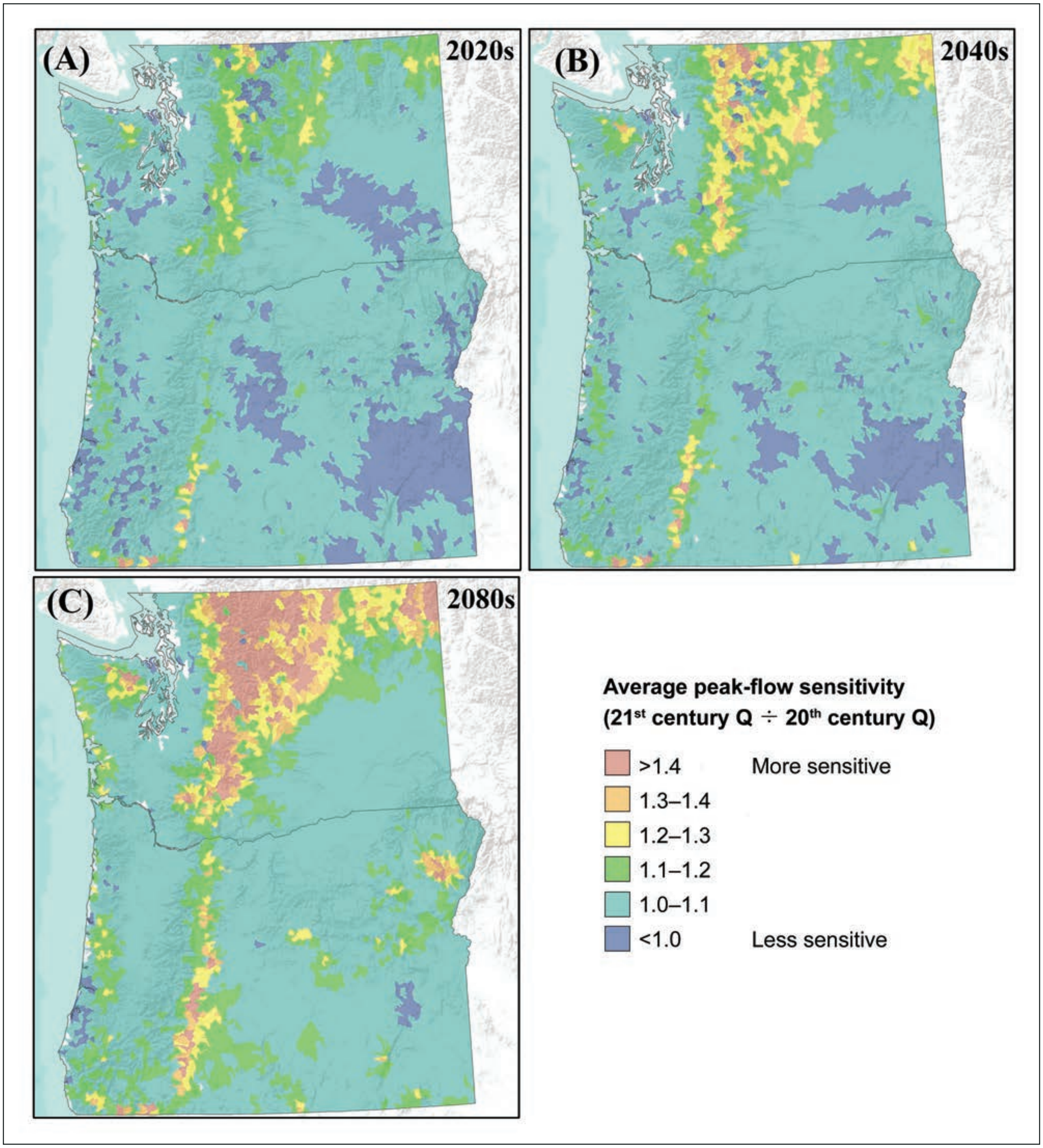

Figure 7-17—Sixth-field hydrologic unit-scale average peak-flow sensitivities across all flood magnitudes (Q2, Q10, Q25, Q50, and Q100) under A1B emission scenario for the (A) 2020s, (B) 2040s, and (C) 2080s, in which red is more sensitive and blue is less sensitive. (Modified from Safeeq et al. 2014.)

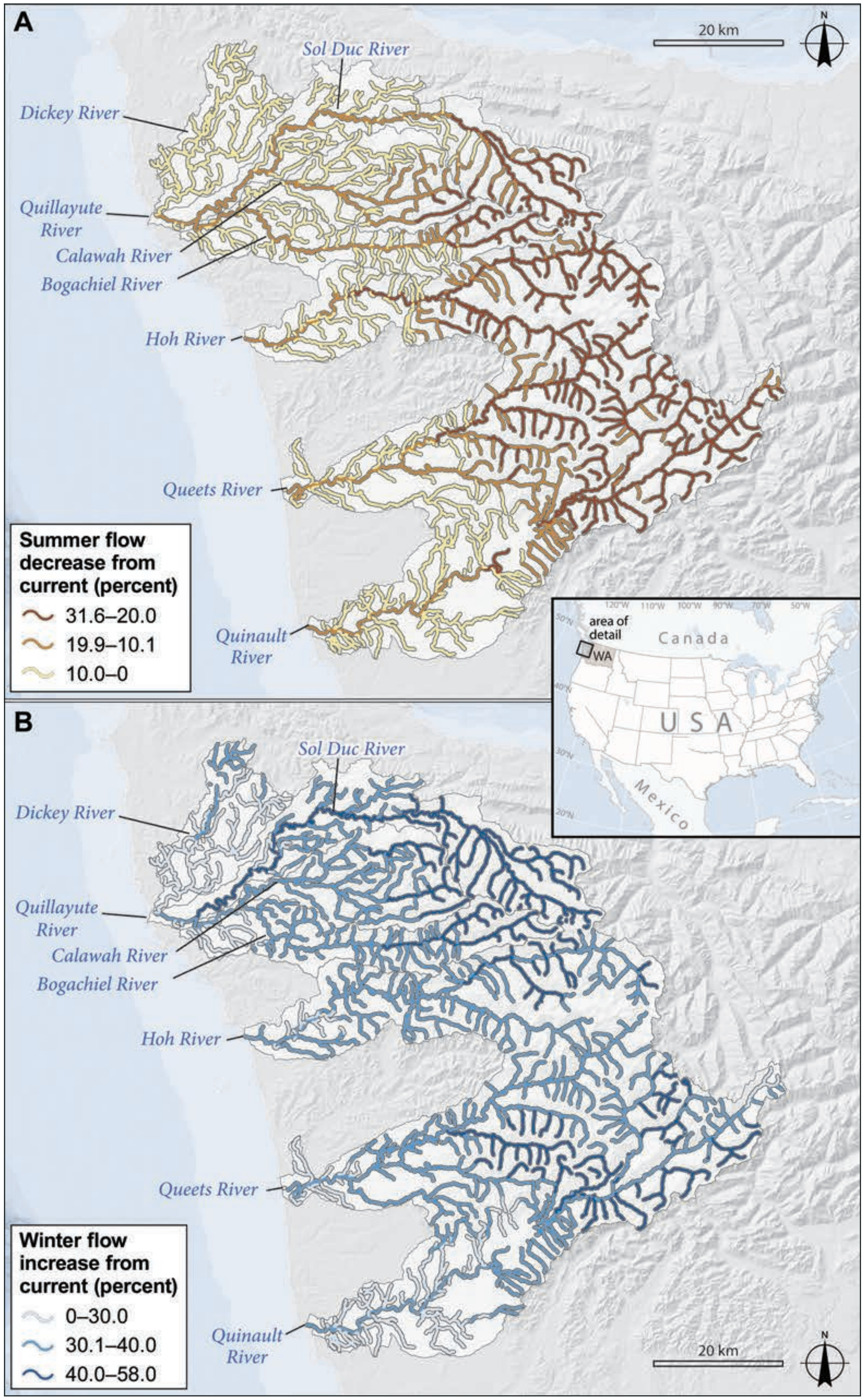

Figure 7-18—Percentage of reduction in average (A) summer and (B) winter flow levels from current to 2040 in study basins in the Olympic Peninsula area (Reeves et al. 2016b).

Extreme events—Increased frequency of extended, severe droughts and intense winter-storm events (IPCC 2014) will also affect aquatic ecosystems and fish populations in forested landscapes (Ward et al. 2015). The pattern of changes will differ widely within and among watersheds depending on local features, making it difficult to generalize the effects. However, changes in the seasonal timing of annual hydrographs and more frequent extremely low or high flows are very likely to affect native fish populations. Changes in flows that lead to earlier spring runoff and prolonged periods of summer low flows could have important implications for the habitat of (ISAB 2007) and food chains encompassing fish and other aquatic organisms (Power et al. 2008, Wooton et al. 1996) (see discussion in app. 2 for more details). Amphibians that inhabit ephemeral ponds and streams are likely to be especially vulnerable to drought and general climate change effects (Blaustein and Olson 1991, Shoo et al. 2011).

Ocean conditions—

Over the past several decades, the importance of the marine environment to fish that spend part or all of their lives at sea has been recognized as a major factor regulating population abundance. Climate-related changes in the ocean that are potentially important to native fishes in the NWFP area include acidification (Orr et al. 2005), increased sea-surface temperatures (IPCC 2007), changes in wind and current patterns (Rykaczewski and Dunne 2010), and sea-level rise (IPCC 2007). Absorption of anthropogenic CO_2 by the upper ocean decreases pH and carbonate-ion concentrations (Hendriks et al. 2010, Orr et al. 2005), increasing acidity and inhibiting the ability of planktonic organisms to form calcium carbonate, a key component of their exoskeleton. Many of these organisms form the base of the food chain that supports anadromous fishes during the marine phase of their life cycles. The subarctic Pacific Ocean has naturally higher carbon concentrations than most other ocean basins, and the effects of acidification are expected to occur sooner and be more pronounced there (Cooley et al. 2012).

Rising sea-surface temperatures may reduce the amount of preferred thermal habitat for anadromous salmonids in the ocean and potentially limit their marine distribution (Aziz et al. 2011, Welch et al. 1995). As areas with suitable temperatures decrease or shift northward, Pacific salmon could become concentrated in smaller foraging zones, resulting in increased competition for limited food resources (Grebmeier et al. 2006, Johnson and Schindler 2009, Mantua et al. 2009, Welch et al. 1995). Salmon may be able to partially compensate for these changes by using cooler subsurface waters; however, deeper water may provide reduced food resources, increased competition with other marine species, or greater exposure to predation (Hinke et al. 2005, Myers et al. 1996).

Other potentially important climate-related changes in the marine environment include sea-level rise (IPCC 2007) and altered patterns of coastal upwelling (Wang et al. 2015). The consequences of sea-level rise for nearshore fishes are uncertain and will be strongly influenced by local topography; new habitat could be created in some areas but lost in others (Flitcroft et al. 2013). Saltwater inundation may affect species that sometimes spawn immediately above tidewater (e.g., pink and chum salmon, *Oncorhynchus gorbuscha* and *O. keta*). Both positive and negative effects on estuaries are also possible as new land is inundated, and the degree to which estuarine productivity is altered will be influenced by the extent of human development. Where development of estuary and coastal shorelines is extensive, sea-level rise will likely result in more seawalls, channelization, and other measures to prevent flooding during storm surges (Neumann et al. 2015).

Changes in the patterns of coastal upwelling in the NWFP area could have very significant effects on anadromous fishes as well as other animals that depend on marine food webs. Wind-driven ocean currents regulate the strength of coastal upwelling along the Pacific Coast, where nutrients from deep-ocean waters fuel plankton blooms that are critical to marine food webs that support salmon (Francis and Sibley 1991). Long-term shifts in the timing and intensity of coastal currents and upwelling have accompanied climate change in the eastern Pacific Ocean, with winter and spring storm tracks gradually shifting northward (Salathé 2006) and upwelling along the coast in the NWFP area becoming more erratic and unpredictable (Bylhouwer et al. 2013). Anadromous salmonids are particularly vulnerable to changes in upwelling because survival of fish in the first few weeks after entering the ocean depends heavily on their ability to feed and grow large enough to avoid predation (Beamish and Boullion 1993, Pearcy 1992, Walters et al. 1978).

The occurrence of interdecadal shifts in sea-surface temperatures and related weather patterns (Pacific Decadal Oscillation—PDO) from cool/wet to warm/dry conditions (Mantua et al. 1997) further complicates the productivity of marine environments along fish migration routes, with more favorable ocean conditions occurring when the NWFP area is in a cool/wet phase than in a warm/dry phase. Wang et al. (2015) used a suite of climate models to forecast upwelling over the remainder of this century and found that, by the year 2100, coastal upwelling will likely start earlier, end later, and be more intense in the northern latitudes (British Columbia, Canada, and southeast Alaska) than in southern latitudes (northern California and Oregon). Wang et al. (2015) also noted that an intensification of upwelling could actually promote plankton productivity, but in extreme cases could also result in large swaths of anoxic conditions developing over broad areas, leading to massive die-offs of marine life where such conditions develop. Taken together, the new information on climate-related PDO cycles and trends in upwelling patterns suggest that the marine environment along the Pacific Coast is becoming more variable spatially and temporally, with northern California and Oregon being somewhat more likely to exhibit unpredictable ocean conditions than more northerly latitudes. For migratory organisms such as anadromous salmonids whose life cycles are adapted to being in the right place at the right time for feeding and reproduction, introducing more variability into the part of their life cycle where most growth occurs is likely to add to population destabilization.

Climate effects on fish life cycles—
Although the extent to which a particular fish population in the NWFP area will be affected by climate change depends to a large degree on changes that occur at the local level, climate-related effects, both favorable and unfavorable, can accumulate across multiple life-history stages. Restricting an understanding of climate influences to a single life-history stage may well underestimate the total effect on the population. Further, because of the wide geographic distributions of many native fishes and the heterogeneity of aquatic environments in which they reside, climate effects may be expressed differently across the range of a given species. Locally adapted life histories differ over broad landscapes and among different species; even stocks of the same species can exhibit dissimilar responses to similar climate trends (Schindler et al. 2010). A number of papers have investigated the potential effects of climate change on Pacific salmon, but these have primarily been overviews (e.g., Bryant 2009, ISAB 2007) or results of modeled effects on a given life-history stage (e.g., Crozier and Zabel 2006, Rand et al. 2006) and its associated habitat (e.g., O'Neal 2002). A comprehensive review of the effects of climate change on native fishes in the NWFP area across their ranges, including effects accumulated across multiple life-history stages, is lacking.

Understanding the potential consequences of altered future conditions, particularly where the perceived effects may not be lethal, requires consideration of the effects at each life-history stage (Fleming et al. 1997, ISAB 2007, Jonsson and Jonsson 2009). Changes at one life stage can cascade throughout the remaining stages, significantly altering population response. Focusing on anadromous Pacific salmonids, it is possible to examine the overall impacts of climate change by identifying effects at each life-history stage and discussing how those effects might be propagated through succeeding stages. These effects and potential management options are listed in table 7-9. It is also possible to identify attributes of Pacific salmon life cycles that promote their adaptive capacity to climate change, along with options for managers and decisionmakers to enable and enhance those attributes to mitigate potential effects of climate change in the NWFP area.

Other climate-related factors—
Climate warming will lead to an increase in the area burned by wildfires (IPCC 2014) (chapter 2). Wildfire trends in the NWFP area will be complex because the area includes a wide array of forest types, elevations, weather regimes, and forest-management histories (Hessburg and Agee 2003); hence risks of damage to native fish habitats are likely to be highly variable across the region. In addition to altering wildfire frequency and intensity, climate change will also

Table 7-9—Potential effects of climate change on anadromous salmonids of the Pacific Northwest, by life-history stage

Life stage and habitat	Potential effect of climate change	Ecological consequences	Ecological implications	Potential actions
Adults:				
Ocean	Acidification (Hendriks et al. 2010, Orr et al. 2005)	Reduced growth and survival	Lower productivity of freshwater because of reduced amount of marine-derived nutrients and eggs (Bilby et al. 1996, Cederholm et al. 2001, Garner et al. 2009, Gende et al. 2004, Helfield and Naiman 2001, Lang et al. 2006, Schindler et al. 2003)	
	Increased sea-surface temperatures (Aziz et al. 2011, IPCC 2007)	Smaller size at return	Reduced population reproductive capacity (Hankin and McKelvey 1985, Healey and Heard 1984)	
		Change in life-history expression (*Oncorhynchus mykiss*)	Loss of steelhead life history (migratory) and increase in rainbow trout life history (resident) (Benjamin et al. 2013, Quinn and Myers 2004, Rosenberger et al. 2015, Sloat and Reeves 2014)	Population monitoring with consideration of life-history types
Freshwater	Sea-level rise (IPCC 2007)	Increased estuary habitat	Increased life-history diversity (Bottom et al. 2005)	Population monitoring with consideration of life-history types
		Loss of spawning habitat in areas close to coast	Reduced population productive capacity	
		Increased flooding during surge events	Reduced egg survival	
	Increased water temperature (Isaak et al. 2010)	Increased stress	Reduced survival to spawning grounds (Martins et al. 2011, Rand et al. 2006) and population reproductive capacity (Miller et al. 2011, Pankhurst et al. 1996) Increased susceptibility to disease and parasites (Chiaramonte et al. 2016, Johnson et al. 1996, Miller et al. 2011, Ray et al. 2012)	Monitoring water temperatures in entire stream network to identify and protect areas of thermal refugia

Table 7-9—Potential effects of climate change on anadromous salmonids of the Pacific Northwest, by life-history stage (continued)

Life stage and habitat	Potential effect of climate change	Ecological consequences	Ecological implications	Potential actions
Eggs and alevins:				
Freshwater	Elevated winter water temperatures	Increased rates of development (McCullough 1999, Neuheimer and Taggart 2007)	Smaller size at emergence (Beacham and Murray 1990, Elliott and Hurley 1998)	Year-round monitoring of water temperatures
		Earlier time of emergence (Holtby 1988)	Increased growth rates, earlier timing of smolting, and smaller size at ocean entry, but decreased marine survival (Holtby and Scrivener 1989, Schindler et al. 2005)	Increase availability of floodplain and off-channel habitats
	Increased winter flows (Hamlet and Lettenmaier 2007, Hamlet et al. 2005, Tague and Grant 2009)	Increased scour of redds (Battin et al. 2007)	Reduced survival (Battin et al. 2007, Leppi et al. 2014, Shanley and Albert 2014)	Increase connection to floodplain, remove roads and infrastructure that restrict access to floodplain, with wood placement in and near low-gradient spawning areas
		Increased landslides and flooding (Dale et al. 2001, Hamlet and Lettenmaier 2007, Miller et al. 2003)	Decreased habitat quality in short term but improved conditions in long term (Bisson et al. 2009; Flitcroft et al. 2016a; Reeves et al. 1995; Rieman et al. 2006, 2015)	Road removal and culvert improvements in most susceptible areas Silvicultural treatment of plantations in most susceptible areas to increase size of trees
Juveniles:				
Freshwater	Higher spring flows (Hamlet and Lettenmaier 2007, Hamlet et al. 2005, Tague and Grant 2009)	Increased access to floodplain and off-channel habitats	Increased growth and survival if floodplains and off-channel habitats available (Brown and Hartman 1988, Moore and Gregory 1988, Peterson 1982a); decreases if not	Increased access to floodplain and off-channel habitats
	Earlier onset of low flows (Hamlet and Lettenmaier 2007, Hamlet et al. 2005, Tague and Grant 2009)	Reduced habitat availability (Battin et al. 2007, Luce and Holden 2009, Mantua et al. 2010, Stewart et al. 2005)	Reduced survival (Battin et al. 2007, Mantua et al. 2010)	Identify areas in network that are likely to be refugia during low-flow period and improve habitat conditions, including improving riparian conditions to reduce water temperature

Table 7-9—Potential effects of climate change on anadromous salmonids of the Pacific Northwest, by life-history stage (continued)

Life stage and habitat	Potential effect of climate change	Ecological consequences	Ecological implications	Potential actions
	Increased summer water temperatures (Isaak et al. 2010)	Reduced growth and survival if temperature increases are beyond favorable range (Crozier and Zabel 2006, Isaak et al. 2010, Marine and Cech 2004, Royer and Minshall 1997, Scarnecchia and Bergersen 1987)	Smaller size and reduced survival (ISAB 2007, Quinn and Petersen 1996)	Improve riparian conditions
		Increased growth if temperatures move into more favorable range		
		Altered outcomes of interactions with other species (ISAB 2007, 2012; Petersen and Kitchell 2001; Reeves et al. 1987)	Reduce growth and survival (ISAB 2007, Petersen and Kitchell 2001, Reeves et al. 1987) Change in structure and composition of fish communities (warmwater species increase) (ISAB 2012)	
	Increased nonsummer water temperatures	Increased growth rates (Ebersole et al. 2006, Sogard et al. 2010)	Increased growth and survival	Year-round monitoring of water temperatures Provide access to intermittent streams, off-channel habitats, and floodplains
Smolts:				
Freshwater	Earlier onset of low flows (Hamlet and Lettenmaier 2007, Hamlet et al. 2005, Tague and Grant 2009)	Altered timing and rate of ocean migration	Decreased marine survival (Holtby 1988, Rechisky et al. 2009)	
	Warmer water temperatures (Isaak et al. 2010)	Smaller size at ocean entry	Reduced marine survival (Holtby and Scrivener 1989, Quinn and Peterson 1989, Slaney 1988)	Improve riparian conditions
Ocean	Altered timing of ocean upwelling (Barth et al. 2007, Snyder et al. 2003)	Reduced availability of food resources (Nickelson 1986, Scheurell and Williams 2005)	Reduced marine survival (Holtby and Scrivener 1989, Quinn and Peterson 1989, Slaney 1988)	

influence outbreaks of insects and forest diseases (Spies et al. 2010) in some cases, leading to alterations of forest stands that affect aquatic habitats. Wildfires, insects, and forest diseases should not be viewed strictly as threats to native fishes, however—they may also provide benefits. They can create openings and patches along water bodies that result in more complex stream channels and greater biodiversity (Flitcroft et al. 2016a, Reeves et al. 1995, Rieman et al. 2006). In addition, the erosional processes that accompany these disturbances are important for recruiting wood and coarse sediment that form essential habitats for many aquatic organisms (Benda et al. 2004). Thus, actions that seek to control erosion and other ecological processes that occur following wildfire may have long-term and unintended negative consequences for aquatic ecosystems (Chin et al. 2016, Harris et al. 2015).

The effects of climate change on aquatic ecosystems in the NWFP area expressed through wildfires, insects, and diseases will be complex and difficult to predict, but it will be important to examine the current responses to wildfire and consider making potential changes to allow fire to be more ecologically beneficial. Climate change will likely influence the expansion of nonnative plant and animal species in the NWFP area, while at the same time either reducing or even extirpating native species (Dale et al. 2001, Garcia et al. 2014, Urban 2015). Nonnative species include undesirable invasives, species undergoing expansion of their native ranges, and nonnative species deliberately introduced for commercial, recreational, or cultural reasons. They can occur in both terrestrial (riparian) and aquatic ecosystems. Nonnative species are not always harmful to native fishes or their habitats, but in many instances they can (1) compete with, prey upon, hybridize with, or infect native species with novel pathogens; (2) greatly alter the structure of food webs; or (3) cause habitat changes that reduce the productivity of desirable aquatic organisms. See appendix 1 for a detailed discussion of invasive species in the NWFP area.

Sanderson et al. (2009) provided a useful summary of underappreciated threats to salmon posed by nonnative vertebrates, invertebrates, and plants. They concluded that threats posed by nonnative species may equal or outweigh threats posed by traditionally perceived causes of decline—habitat alteration, harvest, hatcheries, and hydroelectric production. Many of the nonnative fishes known to harm native fishes of the NWFP area are warmwater fish species deliberately introduced from eastern North America. In some river basins, these forms have largely displaced native fishes from dominant roles in the aquatic food webs of low-elevation, low-gradient rivers (ISAB 2012). Continued warming will favor the expansion of warm-adapted species in western North America (Rahel et al. 2008), and shrinking headwater flows resulting from longer, drier summers (Moore et al. 2007) could force cool-adapted native species lower in drainage systems, where there will be greater opportunity for unwanted interactions with established populations of introduced game fishes. Restoration of riparian areas, however, can help reduce water temperatures and the potential negative consequences of climate change related to elevated water temperatures (Justice et al. 2017, Lawrence et al. 2014)

Restoration and response to climate change under the Aquatic Conservation Strategy—

Watershed improvements implemented in the Northwest Forest Plan area—An important goal of the NWFP was to create a managed federal forest landscape in which natural ecological processes sustained healthy populations of native fish and wildlife (USDA and USDI 1994a). Architects of the ACS recognized that federally managed forests might anchor the recovery of imperiled native fishes, but because of their location relative to state and private forests as well as other types of land use (which tended to be located in lowland areas), they could not ensure that appropriate conservation measures would be applied throughout the full suite of freshwater environments to which many native species, particularly anadromous salmonids, were exposed (Sedell et al. 1997). Nevertheless, many of the aquatic-conservation actions that emerged from the NWFP were considered at the time to provide more protection to aquatic and riparian habitats than had ever before been implemented on multiple-use forests in the Pacific Northwest (NRC 1996). The region's national parks and designated wilderness areas were also considered to possess high-quality habitats in which natural ecosystem processes could operate. However, because of their scarcity and location (Reeves et al. 2016a, Sedell et al. 1994), such areas were generally believed to be inadequate to prevent species or their distinct population segments (evolutionarily significant units) from becoming imperiled, or to hasten recovery. Given the impact of climate change on fish life cycles as discussed above, how the framework and standard of guides of future forest plans could address these potential effects merits priority for future research.

Restoration of mid- and late-seral forest stands—Concurrent with the restoration of mid- and late-seral stands in the NWFP area, the region will likely see a reduction in large openings caused by regeneration harvests (clearcuts) and by wildfire, as a result of continuing fire suppression (see chapter 3). As forest stands grow older in the seasonally transient snow ("rain-on-snow") zone, snowfall interception by branches will diminish the accumulation of ground-level snow and will prolong melting and runoff processes during subsequent rain events (Harr 1986). Peak flows were found to increase by as much as 20 percent in small watersheds and 30 to 100 percent in larger basins over a 50-year period in the western Cascade Range of Oregon in response to road building and clearcutting (Jones and Grant 2001). However, a recent synthesis of peak-runoff studies in western Oregon and Washington (Grant et al. 2008) concluded that the incremental contribution of clearcutting to peak flows in the transient snow zone was minor relative to other types of human disturbance, and would likely be confined to stream reaches possessing 2 percent gradients with sand and gravel substrates. In areas in which climate change results in an expansion of the transient snow zone, restoration of late-seral stands is likely to reduce the frequency and possibly duration of flows that are capable of mobilizing substrates of some fish-bearing streams, which could benefit survival of developing fish eggs and alevins as well as the abundance of amphibians and benthic macroinvertebrates.

One climate trend with important implications for native fishes is the lengthening of low-flow periods during the warm season; aquatic organisms in watersheds with reduced snowpack will be especially affected by lower summer flows. Although not thoroughly investigated, the capture of fog by tree branches in areas with summer fog can result in "fog drip" that contributes to runoff during times when rainfall is scarce (Harr 1982). Whether climate change will alter the frequency of foggy days in the NWFP area is poorly understood, but there is preliminary evidence that the intensification of wind-driven upwelling in the California current as a result of increased CO^2 could lead to more fog and increased moisture flux along the Pacific Northwest coast during the upwelling season (Snyder et al. 2003). However, Johnstone and Dawson (2010) reported that fog frequency along the northern California coast declined by 33 percent in the 20th century. Nonetheless, restoration of late-seral stands will result in taller trees with larger limbs, which could capture more moisture and deliver some of it to streams during a season when water is in short supply.

Increasing the amount and sources of large wood will help aquatic ecosystems and associated biota meet the challenges of climate change. The progressive impoverishment of large wood in Pacific Northwest streams, particularly large-diameter, habitat-forming tree trunks and rootwads, has long been recognized (Bisson et al. 1987, Sedell and Swanson 1984). Climate change is expected to change the frequency and severity of fires and the incidence of forest-pathogen outbreaks in many parts of the NWFP area (see chapters 2 and 3). However, the ensuing recruitment of large wood to streams, a key component of fish habitat, may be limited if landslide-prone headwalls that normally deliver this material to channels during and following natural disturbances no longer contain trees of the size needed to form and maintain structural fish habitats. The importance of wood recruited to streams from unstable hillslopes is often underappreciated. For example, Reeves et al. (2003) found that 65 percent of the large wood pieces and 47 percent of the large wood volume in an Oregon coastal stream originated from upslope sources. Measures that could take advantage of this source of wood include inventorying and mapping unstable headwall areas, protecting them from forestry-related disturbance, permitting natural wood-delivery processes to occur, and allowing late-seral stands to develop in these areas where appropriate (Cissel et al. 1999).

Reducing the effects of roads and passage barriers—Reducing the hydrological and biological effects of forest roads in the NWFP area should improve watershed resilience to the adverse effects of climate change on aquatic ecosystems. Road cuts are known to be a major contributor to accelerated runoff during storms by intercepting subsurface flow and capturing it in ditches, which rapidly deliver water and fine sediment to streams (Wemple and Jones 2003). As the intensity of storms increases with gradual warming and, in some parts of the NWFP area, with greater precipitation, the risk of streambed-mobilizing runoff events will rise as well. Reducing the exacerbating effects of road drainage networks on peak flow in watersheds where roads have been decommissioned could lessen the potential for severe storms to scour eggs and alevins in stream gravels and likewise reduce the intrusion of harmful fine sediment into spawning substrates. In addition, eliminating road-related initiation points for landslides through road decommissioning will help return the frequency of mass wasting in watersheds to more natural levels.

Road corridors can serve as important invasion routes for nonnative species, especially nonnative plants (González-Moreno et al. 2015, Heckman 1999, Menuz and Kettenring 2013), and climate change is likely to favor continued expansion of nuisance and harmful exotic herbaceous species in watersheds (Dale et al. 2001). The effect of invasive plants on riparian ecosystems in federally managed forests has received relatively little study, but some plants (e.g., Asian knotweed, *Polygonum* spp.) are capable of displacing native vegetation (Urgenson et al. 2009) and disrupting the transfer of organic material from streamside vegetation to stream channels. Invasive plant-control programs are costly, and even in riparian zones where treatments have been applied, the long-term reestablishment of native plants has been difficult to achieve (Claeson and Bisson 2013). Therefore, reducing road densities in a watershed and across large areas should help forestall the movement of unwanted nonnative plants into sensitive riparian areas and protect the integrity of native plant assemblages.

Floodplain protection—One of the key tenets of the ACS was that connections between streams and rivers and their associated floodplain and wetland habitats should be protected and, if necessary, restored (Reeves et al. 2006). In valleys where rivers are unconstrained and riparian forests are well developed, off-channel habitats such as braided streams, oxbow lakes, springs, and other floodplain features provide important seasonal rearing habitats for a wide variety of aquatic and terrestrial species and are considered to be among the most biophysically complex and diverse systems on Earth (Bayley 1995). Additionally, they can be important areas of carbon storage (Sutfin et al. 2016). Flood pulses that redistribute sediment and organic matter create a dynamic mosaic of physical habitat features on floodplains (Junk et al. 1989, Stanford et al. 2005), which support diverse and productive biological communities. In forested regions of the Pacific Northwest, flood-induced channel migration creates a variety of aquatic habitat patches that differ in age and connectivity with the main channel, from connected side channels that reside within the active flood zone to disconnected side channels that become connected only during larger flood events.

Flood-induced erosion and deposition of substrate also create dynamic and heterogeneous plant communities. Early-successional species such as alder, willow, and cottonwood are generally found on newly deposited sediments, whereas mixed-species (deciduous and coniferous) mature forests and old-growth coniferous forests are found on older and more stable floodplain surfaces (Naiman et al. 2010). This spatial heterogeneity can also create highly complex and spatially structured food webs (Bellmore et al. 2013), which may be important for mediating the strength of predator-prey interactions and promoting biodiversity and resilience (Bellmore et al. 2015)

In the context of large-scale environmental stressors such as climate change, intact floodplains may be hubs of ecological resilience. The biological and physical diversity found across floodplains may promote ecological resilience in river networks via at least two pathways. First, enhanced species diversity in floodplains may provide functional redundancy within species guilds, whereby individual species extirpations may not significantly reduce ecological function (e.g., primary/secondary production, nutrient cycling) until some critical threshold is exceeded (Walker 1992). Second, the physical heterogeneity or spatial complexity found across floodplains may provide critical refugia for individual species (Boughton and Pike 2013, Sloat et al. 2017). For example, groundwater upwelling in floodplain springbrooks can provide cold-water thermal refugia when main-channel waters exceed thermal optimums for a particular species (Ebersole et al. 2003, Torgersen et al. 1999). Unfortunately, many river-floodplain systems have been severely altered by human disturbance, which has constrained the physical processes that create and maintain habitat heterogeneity in floodplains (Tockner and Stanford 2002), and the associated resilience these habitats may provide. Although active restoration efforts are frequently targeted at recreating specific floodplain habitats (e.g., side channels), the reestablishment of natural channel-forming processes (Beechie et al. 2013), such as the "natural flow regime" (Poff et al. 1997), may be most successful at restoring the biophysical complexity of floodplains throughout the stream network over the long term and help negate potential effects of climate change.

Winners and losers—

Climate change is projected to lead to changes in the distribution and abundance of native fishes and a host of other aquatic-riparian organisms in the NWFP area. Some species will be adversely affected by climate-mediated shifts in environmental conditions; others may actually benefit from the changes. Whether conditions will become more or less favorable for a particular species depends on physiological requirements, life-history and migratory patterns, habitat preferences, shifts in aquatic-community composition, and geographic location within the region covered by the NWFP. In general, we expect that fishes that prefer warm water and benefit from alterations in aquatic food webs and hydrologic regimes that accompany climate change will likely increase in abundance and expand their ranges. Other native fishes that prefer cool water will likely suffer losses from recently established predators and competitors; elements of their habitats that are needed at different points in their life cycles will likely decrease in abundance; and their ranges will either contract or shift northward. Population fragmentation in cool-water fishes is also likely to increase as favorable thermal conditions retreat to higher elevations, and smaller populations may suffer reduced genetic variability that threatens long-term survival (Kovach et al. 2015).

For anadromous species, survival and growth at sea will depend on how climate change alters upwelling patterns, plankton blooms, forage-fish populations, predator abundance, and other potentially limiting variables. In the fisheries management community, there is no clear consensus on whether freshwater or marine environments are "more important" to regulating the abundance of Pacific salmon, but it has become apparent that both ecosystems can exert a strong influence on run size, and that there are many uncertainties about how these two ecosystems interact to govern population viability and resilience.

In the NWFP area, climate change will lead to freshwater alterations that will be more or less favorable for some fish species relative to others. In figure 7-19, we list life-history strategies of fish that could increase vulnerability to the types of habitat change discussed earlier in this chapter. These include inflexible habitat specialization; extended freshwater rearing (1 year or more); low movement and spawning stray rates; potential for extended exposure to high water temperatures in their preferred habitats; and autumn spawning, placing them at risk of exposure to flow extremes. We also list life-history and habitat requirements that are likely to fare better in future climates. These include being able to use many different habitat types (habitat generalist); an abbreviated period in fresh water prior to seaward migration; high movement and spawning stray rates; either brief exposure to high water temperatures or a tolerance of prolonged elevated temperatures; and spring spawning that occurs after peak winter flows. Fishes are then arrayed along a risk scale, ranging from those we believe to be less vulnerable to harm from climate change to those that may be moderately vulnerable, and finally to those that may be at high risk of long-term harm. No species possesses all life-history attributes that are well adapted to thriving under predicted climate regimes, just as no species possesses only attributes that are ill-adapted to all projected future conditions. However, based on what is known about climate-related trends in freshwater habitats and on detailed knowledge of the life-history requirements of native Pacific Northwest fishes, we suggest that there will be winners and losers among fish assemblages. To some extent, the NWFP addresses many of the habitat changes likely to be associated

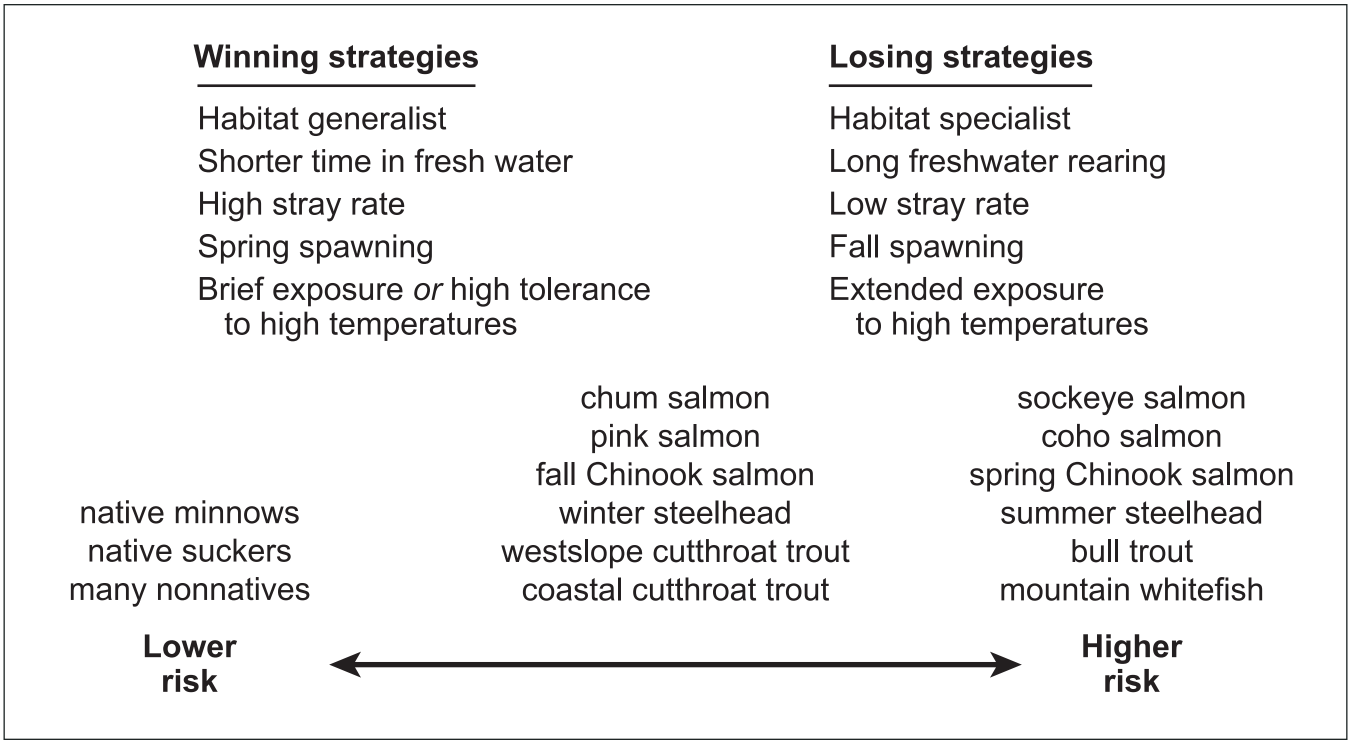

Figure 7-19—Life cycle and habitat-preference strategies of freshwater fishes that are considered in this report to be favored (“winning”) and disfavored (“losing”) in future climates of the Northwest Forest Plan area. Beneath the lists of winning and losing strategies is a grouping of fishes along a gradient of low to high risk from climate effects. These groupings, which are somewhat subjective, are based on current knowledge of each species’ life histories, spawning and rearing locations in watersheds, and residence time in fresh water.

with climate-related alterations in federally managed forests by creating and maintaining functional riparian areas within a watershed and focusing on road removal. However, some changes (e.g., trends in marine conditions) will not be materially affected by NWFP implementation.

The geographical distribution of native fishes and the variation in their life histories, combined with the wide range of effects of climate change on freshwater environments, make it difficult to predict which species will benefit most from NWFP aquatic-habitat protections. In figure 7-20, we divided the NWFP area into four zones: eastern, western, northern, and southern. The western zone includes watersheds draining coastal mountain ranges, whereas the eastern zone includes central lowlands of the NWFP area (Puget Sound, Willamette Valley, and California’s Central Valley) and western drainages of the Cascade Range and Siskiyou Mountains. The northern zone includes all river systems north of the Columbia River; the southern zone includes river systems southward into the Sacramento River. The zones are not mutually exclusive because the northern and southern zones include both eastern and western areas; however, some fishes occur primarily in western coastal systems and others are found primarily in eastern portions of the NWFP area.

Based on different types of improvements to aquatic habitats from implementation of the NWFP that mitigate harmful effects of climate change as discussed above, figure 7-20 lists native salmonids that are likely to benefit in some way from the framework and standards and guidelines introduced by the NWFP. A few of the fishes (e.g., Chinook and coho salmon, steelhead [anadromous *O. mykiss*], and coastal cutthroat trout [*O. clarkii clarkii*]) are found throughout the NWFP area and therefore occur on each list; others (e.g., westslope cutthroat trout, *O. clarkii lewisi*) are limited to relatively small regions of the NWFP area. Figure 7-20 does not include nonnative species or nonsalmonids. In general, nonsalmonids (e.g., native minnows and suckers) are likely to benefit from climate warming (although see

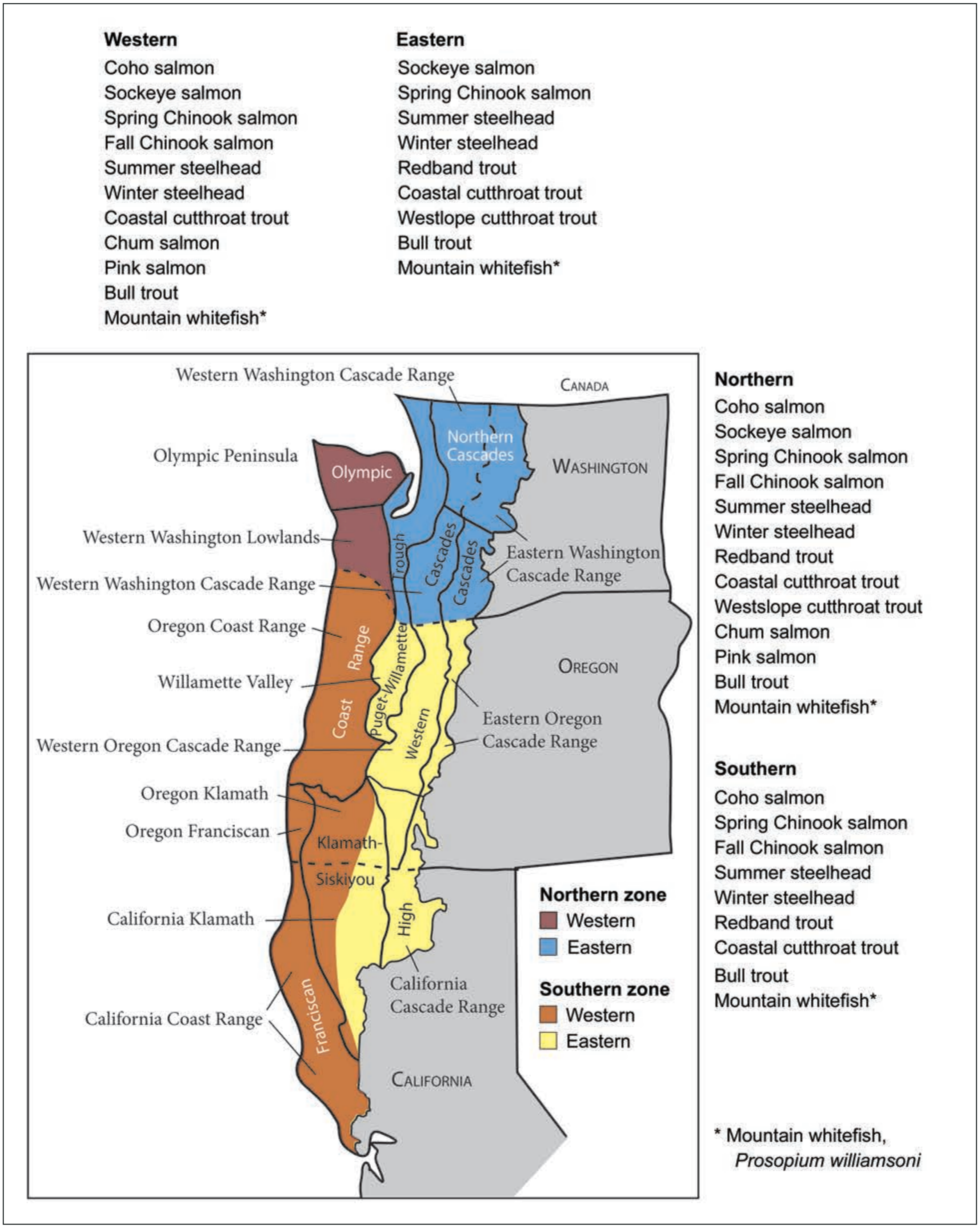

Figure 7-20—Native salmonid fishes in the Northwest Forest Plan area that are likely to benefit in some way from environmental protections from the harmful effects of climate change, grouped by different geographical zones (see text).

Moyle et al. [2013], who suggested that this may not be true in California) and may or may not respond to NWFP aquatic-habitat improvements such as fish-passage barrier removal. Nonnative salmonids (e.g., introduced chars—brook and lake trout, *Salvelinus fontinalis* and *S. namaycush*) will probably be adversely affected by climate change, but also may or may not benefit from NWFP actions. Other introduced species, especially warmwater fishes (e.g., sunfishes and basses, Centrarchidae and *Micropterus* spp.) will likely become more abundant and may increase the risk of predation, competition, and exotic disease exposure to native fishes. However, restoration of riparian habitats may reduce water temperatures and restrict expansion of these fish (Lawrence et al. 2014). Also, the effects of hatchery fish may reduce the potential of wild populations to respond to climate change (Quiñones et al. 2014a, 2014b).

Climate refugia can also be projected for amphibian species (Shoo et al. 2011), with myriad ecological consequences. For lentic-breeding amphibians in the NWFP area, higher-elevation-adapted Cascades frogs (*R. cascadae*) may be faced with shifts in their breeding-habitat conditions. In addition, they may encounter novel interactions with species associated with warmer, lower elevation habitats, such as native northern red-legged frogs (*Rana aurora*), which may spread to higher elevations with altered climate. The low- to mid-elevation-adapted red-legged frogs may in turn encounter invasive American bullfrogs (*Lithobates catesbeianus*), which now occur at warm, low elevations. Similarly, because mountain streamflows are projected to change, torrent salamanders (*Rhyacotriton* spp.) associated with intermittent streams, could have a truncated active season, retreating below ground as small streams dry earlier in the season, possibly affecting survival and reproduction.[9] They may also move downstream and be faced with new interactions with larger predatory salamanders or fish in perennial reaches. If they migrate downstream, their over-ridge dispersal to new watersheds may be affected, as distances between flowing water bodies increase. Hence their populations could become more isolated and vulnerable to stochastic events. For terrestrial-breeding salamanders, we can project the consequence of warmer, drier conditions by examining the distribution of current species in the drier portion of the Northwest; these are species for which climate change has already occurred. Optimal habitat for the Siskiyou Mountains salamander (*Plethodon stormi*) is modeled to occur on the shaded side of mountain ridges and in cooler riparian areas in the dry and warm southern Oregon landscape (Suzuki et al. 2008), and the black salamander (*Aneides flavipunctatus*) appears to become a riparian associate in dry portions of its range (Nauman and Olson 2004). Hence for cool, moisture-dependent species, riparian areas and north-facing slopes with hill shading may become more important with projected changes in climate. Alternatively, as for torrent salamanders, their activity pattern may be altered, with reduced surface activities during dry times and possible consequences for survival. Range shifts for temperature- and moisture-dependent species have also been projected for pathogens of aquatic organisms, such as the amphibian chytrid fungus (*Batrachochytrium dendrobatidis*), which is predicted to increase in occurrence probability in the NWFP area with climate change (Xie et al. 2016).

Implementation of the NWFP represented a significant change in the approach to protection and management of freshwater habitats in federal forests of the Pacific Northwest. Although not directed at mitigating the negative effects of climate change on native aquatic organisms at its outset, the protections provided under the standards and guidelines of the NWFP will benefit populations of native coldwater fishes throughout their life cycles and will help maintain the diverse mosaic of habitat types on the landscape that is essential for population resilience (Beechie et al. 2013, Bisson et al. 2009). However, although many aquatic and riparian habitats in federal forests are likely to retain favorable conditions for aquatic-riparian biota or to slowly improve as watershed-restoration actions are undertaken, it is important to recognize that federally managed forests are usually embedded in a landscape that includes many different types of landowners and uses, and that the standard of environmental protection for other lands is quite different from ACS-based standards and guidelines of the NWFP (Reeves et al. 2016a). Climate-related changes

[9] Unpublished data. On file with: Deanna Olson, Forestry Sciences Laboratory, 3200 SW Jefferson Way, Corvallis, OR 97331.

in aquatic and riparian habitats on nonfederal lands may be much less favorable for native aquatic organisms and more favorable for a variety of nonnative species.

As the biological communities of whole river systems are transformed under a changing climate, there will be a continuing need to monitor the role that federal forests play in conserving native aquatic organisms in the NWFP area. It will be critical for planners to identify vulnerabilities to climate change, and to incorporate approaches that allow management adjustments as the effects of climate change become apparent (Joyce et al. 2009). Because of the nature of environmental variability, the inevitability of novelty and surprise, and the range of management objectives and situations across the NWFP area, no single approach will fit all situations. A range of management options could include practices focused on mitigating or negating the effects of climate change by building resistance and resilience into current ecosystems, and on managing for change by enabling ecosystems and associated biota to adapt to climate change (Joyce et al. 2009, Perry et al. 2015). Better and more widespread implementation of already known practices that reduce the effects of existing stressors represents an important "no-regrets" strategy (Joyce et al. 2009). These management opportunities will require consideration of the Forest Service's adaptive capacity, including availability of personnel with the expertise to conduct required technical analyses, and being able to work cooperatively with the public and other federal agencies to develop and implement the resulting management strategies.

The marine environment is likely to be a major challenge for Pacific salmon in the NWFP area. The predicted effects of climate change on the oceans, including acidification and increased temperatures, and their potential ecological consequences, reduced survival and size of returning adult fish, were described earlier. Pacific salmon have survived climate shifts in the past (Waples et al. 2009) and likely have the ability to persist in many areas of their current range even under more pessimistic climate change scenarios. Salmonid populations exhibit large genetic and phenotypic diversity relative to many other bony fishes (Crozier et al. 2008, Schindler et al. 2010, Waples 1991) and can adapt to changing conditions rapidly (Healey and Prince 1995, Quinn et al. 2001). This diversity has allowed for persistence in highly dynamic and ecologically diverse environments in the past (Greene et al. 2009, Moore et al. 2014, Waples et al. 2009) and will be a key to future survival (Copeland and Vendetti 2009, Mangel 1994). However, we note that Gienapp et al. (2008) cautioned that our knowledge about the role of genetic variation and the ability of natural populations to respond adaptively to current and future environmental change is limited, and that assuming that adaptation can or will happen is risky because of the uncertain rate and extent of climate change, effects of invasive species, and altered ecological processes. The challenge to managers will be to conserve natural environmental complexity in space and time so it can provide the physical template for maintaining genotypic and phenotypic diversity in populations that are currently strong, or to restore environmental complexity where it is currently compromised.

Research Needs, Uncertainties, Information Gaps, and Limitations

The scientific basis of the ACS is still sound and is supported by new science produced since its inception by FEMAT in 1993. However, we have learned much about relationships of riparian vegetation to stream habitats and environments that has refined and modified some hypotheses that were used to develop the ACS in the early 1990s. A major knowledge gain has related to the behavior of aquatic and riparian ecosystems in space and time. At the time the ACS was developed, it was assumed that these systems were relatively stable through time. However, recent science is suggesting that these systems may be very dynamic in space and time, similar to terrestrial systems, and that aquatic organisms are adapted to this dynamism. Implementing this perspective in management actions will be challenging. It is not consistent with many current regulatory approaches, which require aquatic and riparian ecosystems to meet a given standard. Also, a dynamic perspective could be incorporated into the requirements for range of natural variability and all lands consideration of the 2012 planning rule, but will likely require close coordination between managers and researchers.

Emerging science also suggests that the absence of disturbance and management in upland terrestrial ecosystems, primarily fire, may be affecting vegetation, and combined with climate change, is likely altering these ecosystems (see chapters 2 and 3). The same trends are likely occurring in riparian and aquatic ecosystems in a manner that is not fully understood at present; this could be a useful subject for research conducted in an adaptive-management context to provide information to managers, regulators, and policymakers in a timely manner.

Climate change is expected to affect aquatic and riparian ecosystems throughout the NWFP area, though with much uncertainty. Effects will likely differ widely within and among watersheds and geographic areas, necessitating the development of new approaches to identify this variation and help craft strategies and programs for mitigation and adaptation. Much of the focus has been on individual species. Research that focuses on understanding potential effects over the life history of species and how effects may cascade through life-history stages, as well as consideration of community-level effects, is critical. Understanding the effects on water quantity and quality is also important, particularly across spatial scales within watersheds, among watersheds, and across seasons and years. It is likely that aquatic and associated terrestrial ecosystems will change in uncertain, and maybe unpredictable, ways under a changing climate, and that this change will vary widely across the NWFP area. Having the capacity to do the needed analysis will also be critical for the involved agencies to successfully meet this challenge in a timely and effective manner, particularly in an era when budgets and personnel for federal land -management agencies are declining (see chapter 8). Thus, development of cost-effective and scientifically sound analysis procedures performed with close collaboration between research and management is key to addressing this need.

The contribution of federal lands to the conservation and recovery of ESA-listed fish continues to be important. However, federal lands alone are likely to be insufficient in geographic scope to reach the comprehensive goals of the NWFP relative to recovery of listed fish, particularly many evolutionarily significant units of Pacific salmon, as originally expected by FEMAT (1993) and the record of decision (USDA and USDI 1994a). Although the geomorphic setting of streams on federal lands may be as capable as originally expected of providing sufficient favorable habitat, particularly for salmon, streams on state and private lands may have a much greater potential to provide habitat in many watersheds. Thus, it will be important to work closely with adjoining landowners and other interested parties to develop more comprehensive efforts across species ranges. The development of incentive programs is likely to be important to build partnerships for fish-habitat management across land ownerships. Developing an understanding of the variation in the capacity of watersheds to provide favorable conditions for fish and other aquatic biota could be critical to the success of such programs.

Monitoring the effectiveness of the ACS will continue to be important. Some meaningful uncertainties remain regarding the aquatic-riparian monitoring approaches, especially relative to whether they are capable of capturing the effects of the ACS on a wide range of ecological processes and species of aquatic and riparian ecosystems. Research is needed to test the ecological validity of individual metrics and different ways of combining metrics to represent different components of complex and diverse aquatic and riparian ecosystems and communities. It would, therefore, be prudent to compare alternative approaches in the face of the new understanding about the behavior of aquatic and riparian ecosystems in time and space and the yet-to-be-understood effects of disturbance or lack of disturbance, climate change, and novel ecosystems. A related research need is to better understand the relationship of the productivity of aquatic biota, which include organisms other than salmonids, in the context of different upland vegetation and in-channel successional stages or restoration treatments. This type of information can feed into watershed assessments to better ensure that the effects of the ACS are captured more comprehensively relative to the biota that are a key ecosystem service of aquatic-riparian ecosystems. In particular, we lack information about the amount, pattern, and type of restoration activities that have occurred in upland and riparian forests. Implementation monitoring has not been adequate to enable a sufficient understanding of the consequences of restoration actions (or lack of actions), especially relative to how they may have altered aquatic ecosystems in space and time.

Roads and their effects will continue to be a major issue in the NWFP area. Both research on road effects and the continued development of analysis tools such as Geomorphic Roads Analysis and Inventory Package (Black et al. 2012) are important. In particular, understanding the consequences of focusing on small segments rather than the entire network should be a priority. The same is true for effects of culverts on ecological processes and the movement of aquatic biota. These are current priorities given the uncertainties of climate change. Also, understanding how to balance fire management, recreation, and other needs against potential negative aspects of roads will require a concerted cooperative effort of managers and physical, biological, and social scientists.

A key uncertainty that has emerged from our analysis is how to understand and assess the effects of "no-action" management options and tradeoffs of managing for one factor (e.g., water temperature or wood recruitment) on other ecological processes or attributes. The assumption has been that focusing on one concern would not influence other processes or attributes, and that taking no action was synonymous with having no effect. However, these assumptions are questionable and deserve increased consideration and focus by researchers.

Several other topics relating to the components of the ACS merit further research. Watershed analysis could be reexamined so that it is conducted more efficiently and considers the appropriate spatial scales, including a smaller watershed of interest and its context within a larger basin. The larger scale context is particularly relevant for effective landscape-scale planning. In addition, no formal evaluation of the potential effectiveness of the network of key watersheds was conducted during development of the NWFP, nor has such an evaluation been attempted since it was implemented. New concepts, tools, and emerging understandings about aquatic ecosystems are now available to better assess and increase the potential effectiveness of key watersheds. Our understanding of aquatic ecosystems is incomplete (though evolving) at this time, but because there could be significant implications for the productivity of these systems, they will continue to be a major focus of research.

Conclusions and Management Considerations

The goal of the ACS was to maintain and restore aquatic-riparian ecosystems on federal lands within the range of the northern spotted owl. A review of monitoring efforts and the pertinent scientific literature suggests that (1) aquatic ecosystems in the NWFP area are likely improving as expected, albeit slowly; (2) the fundamental tenets and ecological framework of the ACS are sound, and we are gaining more explicit understanding of several components that over time will have important implications for future management; and (3) opportunities exist for implementing parts of the ACS differently while continuing to achieve its goals. The third finding is particularly applicable to the riparian-reserve component of the ACS, where more active management may help to address potential concerns about the effects of the lack of natural disturbance (primarily wildfire), and climate change.

The following is a detailed summary of our main findings and conclusions. We also note to which guiding questions the conclusion applies.

Guiding Questions

1. Is the scientific foundation for the ACS valid, or does the science developed since 1993 suggest potential changes or adjustments that could be made to the ACS?
2. What is the basis of trends observed in the ACS monitoring program, and what are the limitations, uncertainties, and research needs related to monitoring?
3. What is known about variation of characteristics of unmanaged streams and riparian ecosystems in relation to the stream networks across the NWFP area?
4. What has been learned about the effects of riparian vegetation on stream habitat and environment?
5. What effects have human activities had on stream and riparian ecosystems?
6. What is the scientific basis for restoration management in riparian reserves, and how does restoration relate to the ecological goals of the ACS?
7. What is the capacity of federal lands in the NFWP area to contribute water for a suite of economic, recreational, and ecological uses?

8. What are the potential effects of climate change on aquatic ecosystems in the NWFP area, and are they adequately addressed by the ACS?

Science Foundation for the ACS (Question 1)

The scientific foundation of the ACS is generally sound.

1. It is a coarse-filter approach designed to protect and restore ecological processes that create and maintain favorable habitat conditions for native anadromous salmonids. This assumes that if conditions are favorable for these organisms, then they should be suitable for other aquatic and riparian associated organisms.
   a. Verifying these assumptions could be a research priority.
   b. There is growing scientific support for larger scale ecological processes acting at small-to-large watershed scales affecting salmonid habitats and populations; these include landslides delivering sediment and wood, canopy closure, and hill-shading effects on aquatic-riparian temperatures, and the contribution of headwaters to downstream conditions and populations.
   c. The ecological process and species-habitat emphasis areas of the ACS are supported, but since 1993 additional factors have come to the forefront.
      i. More aquatic species have been considered for listing as threatened and endangered, some requiring more focused attention than the regional scale of the ACS, and consideration of threats on a case-by-case basis.
      ii. Aquatic invasives have emerged as an elevated concern because of their effects on native species.
      iii. Anthropogenic disturbances from timber-harvest activities, including road building and maintenance, remain key concerns for aquatic-riparian ecosystems, but new concerns about the extent and severity of wildfire and climate change have emerged as research and monitoring priorities.
      iv. Reliance on federal lands alone cannot address the conservation need to maintain or restore well-distributed populations of all aquatic-riparian species; key salmonid habitats rely on nonfederal lands, and fragmented federal land ownerships affect aquatic-riparian-terrestrial habitat connectivity for organisms dependent upon aquatic-riparian ecosystems.
2. The scientific foundation for the riparian reserve network is valid. The riparian reserve network was intended to identify the outer boundary of the aquatic/riparian ecosystem.
   a. Since 1993, new science supports riparian buffers to maintain aquatic-riparian processes, habitat conditions, and species.
   b. Our ecological knowledge about non-fish-bearing streams has increased tremendously since 1993, and the approach for protecting them is supported.
   c. However, there are suggestions that the second site-potential tree-height on fish-bearing streams may not be required to maintain microclimatic conditions within the first tree-height.
   d. There are potential options available to move away from fixed-width riparian buffers toward riparian management that considers the variability in ecological context within the stream network and specifies management depending on ecological importance and risk.
   e. Passive restoration approaches of riparian forests in streamside buffers have dominated management choices; active restoration might be acceptable in some locations and could accelerate achievement of goals such as growth of large trees to supply key pieces of large wood in the future.
   f. Although science has addressed reach-scale effects of riparian reserves, research on effects of larger scale management activities (e.g., small to large watersheds) is becoming a new research priority.
   g. Implementation, effectiveness, and validation monitoring of NWFP riparian reserves has not formally occurred, and is an emerging priority.

3. The use and structure of the key watershed network are supported by recent science.
    a. There is emerging evidence that the key watersheds do not have the capacity to support and provide favorable habitat for ESA-listed fish to the extent that was originally assumed.
    b. Also, the assumption that habitat conditions in old-growth forests are the most favorable for native salmonids is being questioned.
    c. A review of the key watershed network and the criteria for selecting watersheds would be useful and timely.
4. Watershed analysis remains an important process for developing and assessing management options.
    a. New analytical tools and processes are available that could be used to improve these analyses and make them more cost effective; this is a research priority relative to individual watershed analysis as well as assessment of multiple watersheds across the region that may have differing contexts.
    b. The ability of the Forest Service and other federal land managers to conduct such analyses may be limited by a declining workforce and technical competencey; see chapter 8 for more detailed discussion.
5. A tremendous amount of effort has been directed at restoring degraded watersheds and the associated aquatic and riparian ecosystems.
    a. The vast majority of this effort has been directed toward fish-bearing streams. More effort could be directed at the non-fish-bearing portions of the stream network, which will be important to addressing potential effects of climate change.
    b. Implementation, effectiveness, and validation monitoring is needed to assess restoration activities and contribute to adaptive-management processes.

Monitoring of the ACS (Question 2)

The AREMP results suggest that the condition of aquatic and riparian ecosystems in the NWFP area is improving, albeit slowly, as was originally expected owing to the extensive amount of degradation and lengthy time needed for recovery.

1. The primary reasons for improvement are likely a reduction in the extent of roads, primarily in key watersheds, and an increase in the number of large trees in the riparian reserve.
2. Regionally, there is a signature of wildfire interacting with AREMP restoration criteria in some places in the NWFP area. The ecological significance of this interaction is unclear and merits examination.
3. Assessing watershed condition is inherently challenging, and this synthesis has highlighted a number of areas for further research and management focus:
    a. Use of multiple independent measures of watershed attributes makes it difficult to assess the overall condition of a watershed.
    b. Development of aquatic-riparian monitoring programs requires a clear articulation of which biota and associated functional characteristics of habitats and ecosystems are being considered, tying these to our understanding of patterns of change over space and time, and how they are likely to be altered as a result of the actions of interest.
        i. It is important to clearly describe the ecological context of aquatic-riparian monitoring, for example, to determine to what extent AREMP should focus on environmental parameters that measure habitat for native salmonids or on other aquatic and riparian-dependent organisms.
        ii. Within a dynamic aquatic-riparian ecosystem framework, change is anticipated, but a challenge for monitoring is to assess alterations in conditions that may reflect restoration or other trajectories of patterns in response to a variety of human actions and other events.
    c. A key consideration in development of reference distributions for comparison with current conditions is including the entire natural range of conditions that an ecosystem can experience (natural range of variability). This is critical to be able to evaluate the implications of change.
        i. Reference conditions that are too narrowly or broadly defined can skew the interpretation of monitoring results and introduce uncertainty

into the process. This is an active area of research for the NWFP area: Are there neighborhood, provincial, or regional patterns to consider? We suggest further exploration of the use of reference conditions and their potential utility for diverse analytical approaches, including consideration of how to use them in concert with state-transition models and the potential development of novel conditions in the future.

d. Refinement of the objectives and approaches of aquatic-riparian monitoring programs, including AREMP, is anticipated as our understanding of these ecological systems improve and new analytical tools are developed. Advances in watershed-condition assessment procedures will be important to ensure the validity and reduce the uncertainty of future results and their implications for management.

Aquatic and Riparian Ecosystems (Questions 3–6)

1. Unaltered aquatic and riparian ecosystems likely exhibit a wide range of conditions in space and time, locally and across the NWFP area, depending to a large degree on the magnitude and frequency of the associated disturbance regime. (See chapter 3 for more details.)
   a. Headwater streams tend to be dominated primarily by conifers much of the time.
      i. The biological processing of vegetation that falls into the stream (allochthonous material) is a primary energy source for downstream fish-bearing streams.
   b. In the middle parts of the stream network, the riparian zone is composed of a mixture of conifers and deciduous hardwoods.
      i. Hardwoods are important sources of high-quality allochthonous material important for system productivity.
      ii. Hardwoods are scarce in many areas because of the conversion of riparian areas to conifer-dominated plantations. There may be important implications to system productivity that need to be explored.
2. Human impacts have extensively altered riparian ecosystems.
   a. An estimated 30 to 50 percent of the riparian reserve has been converted to single-species plantations, primarily conifer, as a result of past management that harvested trees to the edge of the streams throughout the network. In headwater streams that have experienced increased rates of landsliding, riparian zones are frequently dominated by alder.
   b. The trajectory of riparian and aquatic ecosystems has been altered as a result, reducing ecological variability across the area of the NWFP.
   c. Additionally, fire exclusion (see chapter 3) and climate change are likely altering aquatic and riparian ecosystems in ways that are not fully recognized or appreciated at this time.
3. Restoration activities in riparian reserves have been limited because of concerns about potential negative effects, particularly increased water temperatures and decreased wood-delivery potential, and lack of trust of the Forest Service (see chapter 12).
   a. Restoration activities have primarily been restricted to fish-bearing streams.
      i. Assessment of these activities has been extremely limited, so it is not possible to quantify the effects.
      ii. More active management may be needed.
      iii. The question of whether the increased risk is sufficiently offset by the long-term gains realized from active restoration or other activities within portions of the riparian buffers is a key research need.
   b. Passive restoration has been the dominant policy in riparian reserves.
   c. This approach assumes that "no activity equals no effect." However, this assumption is questionable, and "no activity" may actually compromise or eliminate key ecological processes such as development of the largest trees.

4. Non-fish-bearing streams have received little attention in terms of restoration.
    a. These streams can be important sources of large wood for streams lower in the network. Improving stand conditions is critical to maintaining this important ecological function.

Water Contributions From Federal Lands (Question 7)

The capacity of federal lands in the NWFP area to contribute water for a suite of purposes varies widely among forests, ranging from less than 20 percent of the total flow in some basins to more than 40 percent in others.

Climate Change (Question 8)

The primary effects of climate change in the NWFP area will be increased water temperatures, decreased streamflows in summer, and increased winter streamflows. The extent of these effects will vary widely depending on location and local topographic features.

1. The ACS has the potential to meet these challenges, but it will take a focused effort to do so, including:
    b. Conducting local-scale analyses.
    c. Considering "all lands."
    d. Shifting the focus of management and restoration from increasing population sizes to increasing the life-history diversity of aquatic and riparian organisms.
    e. Recognizing that there will be "winners" and "losers"—because of their inherent capacity to adapt, some organisms will increase while others are likely to decrease.
2. With regard to anadromous fish, changes in ocean conditions (water temperature, acidification, and timing of upwelling), which are beyond the capacity of the federal land-management agencies to influence, may exert a stronger influence on populations than changes in freshwater ecosystems.

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Appendix 1: Aquatic-Riparian Invasive Species of the Northwest Forest Plan Area

Deanna H. Olson and Rebecca L. Flitcroft[1]

Invasive species are generally considered novel species that are not native to established systems, and their introductions are harmful ecologically (Vitousek et al. 1997) or economically (Pimentel et al. 2000). Nuisance-species lists have been developed for various jurisdictions, including species that both have been or potentially could be introduced to an area with subsequent adverse effects. Priority aquatic-riparian invasive species (ARIS) include those that have the potential to greatly alter food webs or ecosystem structure, economic interests such as fisheries, and recreation opportunities or human safety—for example, by fouling waterways or affecting water transportation. Priority invasive species include pathogens that can trigger disease die-offs, predators that may restructure native communities via trophic cascades, ecosystem engineers that alter physical or biological habitat conditions, and macroinvertebrates and plants that may produce population booms in systems, altering their ecosystem structure or function.

ARIS were not raised as a priority concern during development of the Aquatic Conservation Strategy (ACS) for the Northwest Forest Plan (NWFP, or Plan) in 1993–1994. As described in the 10 ACS objectives (USDA and USDI 1994a), the focus at the time was to maintain and restore watershed, landscape, riparian, and aquatic habitat conditions to which species, populations, and communities are uniquely adapted—hence emphasis was placed on native species. More explicitly, ACS objective 10 refers to the maintenance and restoration of habitat to support well-distributed populations of **native** plant, invertebrate, and vertebrate riparian-dependent species. Since 1994, ARIS concerns have intensified, and several state and federal agency groups with species jurisdictions overlapping the range of the NWFP have been addressing ARIS. In particular, modifications to the Aquatic-Riparian Effectiveness Monitoring Program (AREMP) now address ARIS during the program's annual monitoring efforts. Herein, we provide an overview of ARIS that are priorities for natural resource managers in the NWFP area, highlight key science findings of recent research, and describe the development of invasive species monitoring programs.

Priority Aquatic Invasive Species

Overall, across the Plan area, we identified 63 species and species groups as top regional aquatic-riparian invasive or nuisance-species priorities (table 7-10). Of these, 31 (49 percent) species or species groups were designated as "high concern" and inventoried by AREMP in 2016. Our broader top-priority list of 63 taxa was derived from lists compiled by state government departments in the region, interagency collaborative groups such as state invasive species councils, regional U.S. Forest Service personnel, or other entities identifying nuisance species or emerging infectious diseases. Specifically, our 63 priority taxa include those aquatic-riparian species on Oregon's "100 Worst List" (OISC 2015), Washington's "50 Priority Species" list (WISP 2009), a focal species list for U.S. Forest Service Pacific Northwest Region (Region 6) lands (Flitcroft et al. 2016b; S. Bautista, pers. comm.[2]), and the AREMP list (Raggon 2017). We recognize that top priorities identified by California and the U.S. Forest Service Pacific Southwest Region include other aquatic-riparian taxa, but upon inspection, species identified only in California and not by these other sources appeared to be of lesser immediate concern in northwestern California forests in the Plan area. We acknowledge that some other important California invasive species may merit consideration if our list were to be refined further. Lastly, some pathogens were included here because of their national and international priority status from other entities (Auliya et al. 2016, Bern Convention 2015, Conservation Institute 2013, OIE 2017, Schloegel et al. 2010, USFWS 2016). Note that priority species differ between

[1] **Deanna H. Olson** is a research ecologist and **Rebecca L. Flitcroft** is a research fish biologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331.

[2] Bautista, S. 2017. Personal communication. Pesticide use & invasive plant coordinator, U.S. Forest Service, 1220 SW Third Ave., Portland, OR 97204, sbautista@fs.fed.us.

Table 7-10—Aquatic invasive species of concern in the Pacific Northwest states of Oregon and Washington and within the administrative boundaries of the U.S. Forest Service Pacific Northwest Region

Scientific name	Common name	Oregon	Washington	Pacific Northwest Region	AREMP
Pathogens and parasites:					
Phytophthora alni, *P. kernoviae*, *P. pluvialis*, *P. lateralis*; *P. ramorum*	Alder root rot; *Phytophthora* taxon C; needle cast of Douglas-fir, Port Orford cedar root disease, sudden oak death	✓		✓	
Batrachochytrium dendrobatidis, *B. salamandrivorans*	Amphibian chytrid fungi (*Bd*, *Bsal*)				
Bothriocephalus acheilognathi	Asian tapeworm	✓			
Orthomyxoviridae isavirus	Infectious salmon anemia virus (ISAV)	✓			
Ranavirus	Ranavirus				
Rhabdovirus SVCV	Spring viremia of carp virus (SVCV)		✓		
Novirhabdovirus spp.	Viral hemorrhagic septicemia virus (VHSV)	✓	✓		
Myxobolus cerebralis	Whirling disease	✓			
Aquatic plants:					
Lagarosiphon major	African waterweed or African elodea	✓		✓	
Phragmites australis	Common reed	✓	✓		✓
Potamogeton crispus	Curly-leaf pondweed			✓	✓
Butomus umbellatus	Flowering rush	✓		✓	✓
Salvinia molesta	Giant salvinia	✓			✓
Arundo donax	Giant reed				✓
Hydrilla verticillata	Hydrilla, water thyme	✓	✓	✓	✓
Myriophyllum spp. including *M. spicatum, M. aquaticum*	Milfoils: Eurasian, parrotfeather		✓	✓	✓
Lythrum salicaria, Lysimachia vulgaris	Purple loosestrife, garden yellow loosestrife		✓	✓	✓
Phalaris arundinacea; P. arundinacea var. *picta*	Reed canary grass; ribbongrass			✓	
Didymosphenia geminata	Rock snot (Didymo)	✓		✓	✓
Chondrilla juncea	Rush skeletonweed		✓	✓	
Spartina spp. including *S. alterniflora, S. densiflora*	Spartina (cordgrass)	✓	✓		
Prymnesium parvum, Cylindrospermopsis raciborskii	Toxic algae (golden, toxic cyanobacteria)	✓			
Trapa natans	Water chestnut (European)	✓	✓		

Table 7-10—Aquatic invasive species of concern in the Pacific Northwest states of Oregon and Washington and within the administrative boundaries of the U.S. Forest Service Pacific Northwest Region (continued)

Scientific name	Common name	Oregon	Washington	Pacific Northwest Region	AREMP
Ludwigia spp.	Water primrose			✓	✓
Egeria densa; Elodea nuttallii, E. canadensis, E. canadensis × E. nuttallii hybrid	Brazilian elodea, western waterweed (*Elodea*)		✓		✓
Iris pseudacorus	Paleyellow iris			✓	✓
Nymphoides peltata	Yellow floating heart	✓		✓	✓
Riparian-terrestrial plants:					
Hedera helix	English ivy			✓	✓
Alliaria petiolata	Garlic mustard		✓		✓
Geranium robertianum, G. lucidum	geraniums (Herb-Robert, shining)			✓	✓
Heracleum mantegazzianum	Giant hogweed	✓	✓		✓
Rubus ulmifolius	Himalayan blackberry		✓	✓	✓
Fallopia japonica var. *japonica; Polygonum bohemicum*	Knotweeds (Japanese, Bohemian)		✓	✓	✓
Pueraria lobata	Kudzu	✓	✓		✓
Clematis vitalba	Old man's beard			✓	✓
Hieracium aurantiacum	Orange hawkweed				✓
Potentilla recta	Sulphur cinquefoil			✓	
Tamarix spp.	Tamarix (salt cedar)		✓	✓	✓
Lamiastrum galeobdolon	Yellow archangel				✓
Aquatic invertebrates:					
Potamocorbula amurensis	Asian clam	✓		✓	✓
Radix auricularia	Big-eared radix			✓	✓
Eriocheir sinensis	Chinese mitten crab	✓	✓		
Cipangopaludina chinensis	Chinese mystery snail			✓	✓
Orconectes spp., *Orconectes virilis, Procambarus* spp.	Crayfish (red swamp, rusty, ringed, virile, marbled, signal, northern)		✓	✓	✓
Carcinus maenas	European green crab		✓		
Potamopyrgus antipodarum	New Zealand mud snail		✓	✓	✓
Philine auriformis	New Zealand sea slug	✓			
Bythotrephes longimanus [*cederstroemi*], *Cercopagis pengoi*	Waterfleas	✓			
Dreissena polymorpha, D. rostriformis bugensis	Zebra and quagga mussels	✓	✓	✓	✓

Table 7-10—Aquatic invasive species of concern in the Pacific Northwest states of Oregon and Washington and within the administrative boundaries of the U.S. Forest Service Pacific Northwest Region (continued)

Scientific name	Common name	Oregon	Washington	Pacific Northwest Region	AREMP
Aquatic vertebrates:					
Lithobates catesbeianus (*Rana catesbeiana*)	American bullfrog		✓	✓	✓
Hypophthalmichthys spp., *Mylopharyngodon piceus*	Asian carp, black carp	✓	✓		
Salmo salar	Atlantic salmon	✓	✓		
Didemnum vexillum	*Didemnum* tunicate		✓		
Chelydra serpentina serpentina	Eastern snapping turtle	✓			
Neogobius melanostomas, Rhinogobius brunneus, Tridentiger bifasciatus	Goby	✓			
Noteigonus crysoleucas	Golden shiner	✓			
Esox spp.	Muskellunge/northern pike	✓			
Gymnocephalus cernuus	Ruffe	✓			
Channa spp.	Snakehead	✓	✓		
Dorosoma petenense	Threadfin shad (yellow tails)	✓			
Riparian-terrestrial vertebrates:					
Sus scrofa	Feral swine	✓	✓	✓	✓
Cygnus olor	Mute swan	✓			
Myocaster coypus	Nutria		✓	✓	✓

Note: Three aquatic pathogens (ranavirus, *Batrachochytrium* spp.) are included in this table owing to other national and international priority status (Auliya et al. 2016, Bern Convention 2015, Conservation Institute 2013, OIE 2016, Schloegel et al. 2010, USFWS 2016). Some species clustering within rows was conducted. "✓" denotes priority species from authority listed (above), not occurrence of species within jurisdiction.

Source: Flitcroft et al. 2016b; Bautista, S., personal communication (see footnote 2 on page 585); and Aquatic-Riparian Effectiveness Monitoring Program (AREMP) of the Northwest Forest Plan (Raggon 2017).

lists created by different jurisdictions or entities because of their variable selection criteria or jurisdiction-specific habitats and issues. A species listed as a priority for one jurisdiction and not another may have established populations and be of concern in both areas, yet because of different perspectives not be considered a top priority everywhere. Hence, the broader species list may be important to consider as regionally representative taxa of ecological or economic concern from an all-lands perspective across the Plan area. A few estuarine species are included and may be relevant to consider here, because tidally influenced areas are critical ecosystems interfacing with the coastal forest land base. Other primarily marine-associated species are not included here.

Altogether, as potentially representative of the Plan area, Northwest taxa identified as regional ARIS priorities fall into six categories (table 7-10): 8 pathogens; 19 aquatic plants; 12 riparian-terrestrial plants; 10 aquatic invertebrates; 11 aquatic vertebrates; and 3 riparian-terrestrial vertebrates. Specifically for the Plan area, AREMP's 31 invasive taxa fall into 5 categories: 13 aquatic plants; 11 riparian-terrestrial plants; 6 aquatic invertebrates; 1 aquatic vertebrate; and 2 riparian-terrestrial vertebrates.

Taxonomic Summaries

Pathogens and Parasites

Pathogens and parasites are considered invasive when their spread has been documented coincident with devastating disease effects on host species. There is heightened concern for disease-causing pathogens and parasites affecting sensitive host taxonomic groups that provide important ecosystem services (goods and services that people desire) (Blahna et al. 2017, Penaluna et al. 2016). These host taxa include culturally and economically important species such as salmonid fishes; species with broad distributions that may be central to ecosystem structural integrity and biodiversity such as Douglas-fir (*Pseudotsuga menziesii*) and alder (*Alnus* spp.); and those diseases with multiple host taxa that could affect several native species, with consequences for the organization of wild, native communities, such as the fungi that cause amphibian chytridiomycosis.

Northwest aquatic-riparian pathogens of key concern are viruses and fungi; parasites include cnidarian and cestode worms. Aquatic invasive pathogen species infect vertebrates, for example: (1) cnidarian myxosporean parasites (*Myxobolus cerebalis*) cause whirling disease in salmonid fishes (first described in Germany); (2) Asian tapeworms infect cyprinid fishes in their native range in Asia; (3) viral hemorrhagic septicemia virus (VHSV) infects salmonids, historically known from Europe; (4) ranavirus is considered an emerging infectious disease of fishes, turtles, and amphibians; and (5) chytrid fungi of the genus *Batrachochytrium* can cause the emerging infectious disease chytridiomycosis in amphibians. Riparian pathogens of key concern are fungi of the genus *Phytophthora* (table 7-10) that infect trees typical of riparian zones, such as alder, Douglas-fir, and Port Orford cedar (*Chaemaecyparis lawsoniana*).

The World Organization of Animal Health (OIE) lists species as notifiable because of the extent of their effects, the availability of diagnostic tests for detection, and the role of humans in disease spread. The United States is one of 180 member nations of OIE, hence OIE listing is relevant for consideration here. For pathogens identified here as top ARIS priorities in Oregon, Washington, and Alaska, three are OIE notifiable (OIE 2017): VHSV, ranavirus, and *B. dendrobatidis* (*Bd*). *Bd* is also listed by the Conservation Institute (2013) on their world list of the Top 100 Invasive Species. A second amphibian chytrid fungus included on our Top 60 list, *B. salamandrivorans* (*Bsal*), was recently described in Europe (Martel et al. 2013), and early challenge experiments found numerous North American taxa to be vulnerable to disease effects, with rapid mortality after infection (Martel et al. 2014). The Bern Convention (2015) and others (Auliya et al. 2016) have endorsed legislation to forestall the spread of *Bsal*, and an interim rule to the U.S. Lacey Act (USFWS 2016) has listed host salamander species that may be susceptible to *Bsal* infection as injurious, hence restricting their transportation among jurisdictions. *Bsal* risk models (Richgels et al. 2016, Yap et al. 2015) show Oregon and Washington to be extremely vulnerable to *Bsal* introduction owing to the presence of susceptable host amphibian taxa such as the rough-skinned newt (*Taricha granulosa*), suitable *Bsal* habitat conditions, and proximity to U.S. ports of entry. The pet industry has placed a moratorium on some salamander trade imports to the United States, significantly forestalling the transmission of this pathogen.

Aquatic Plants

The 19 aquatic invasive plants of concern (table 7-10) include two algae, a diatom (rock snot or Didymo), multiple species of submerged aquatic plants (e.g., *Elodea*, *Hydrilla*, milfoils [*Myriophyllum* spp.]), emergent plants (e.g., reeds, cordgrass [*Spartina* spp.], loosestrife [*Lysimachia* spp.], rushes, *Salvinia*, reed canarygrass [*Phalaris arundinacea*], paleyellow iris [*Iris pseudacorus*], water primrose [*Ludwigia* spp.], and floating plants (e.g., curly-leaf pondweed [*Potamogeton crispus*], water chestnut [*Trapa natans*], yellow floating heart [*Nymphoides peltata*]). Once established, these taxa may affect ecosystems, water quality, human health, navigation, and recreation. Emergent plants can dominate wetland and floodplain areas, outcompeting or displacing native species, thereby reducing biodiversity and altering ecosystem functions. Toxic algae are a health concern for native vertebrates and humans because they create powerful toxins known to kill fish, ducks, geese, marine mammals, and other wildlife (Edwards 1999). The diatom commonly called rock snot (Didymo) is native to the Pacific Northwest but is included on priority invasive species lists owing to a change in its growth habits in the mid-1980s (Bothwell et al. 2014), becoming more prolific in its distribution and affecting recreational experiences and activities. Some Northwest ARIS plants were initially brought to the region by the aquarium trade (the elodeas) or for ornamental use (reed canary grass), and then spread to other areas. Further, established populations may be spread by waterfowl as they move from one location to another, or by human vectors (e.g., boats and fishing gear/tackle).

Riparian-Terrestrial Plants

The 12 invasive riparian plants listed (table 7-10) are problematic in both upland and riparian environments. Species such as Himalayan blackberry (*Rubus armeniacus*), Japanese knotweed (*Fallopia japonica* var. *japonica*), and giant hogweed (*Heracleum mantegazzianum*) tend to shade out smaller native plants, reducing plant diversity and altering habitat and food resources for native wildlife. For example, Japanese knotweed (native to Europe and Asia) and giant hogweed (native to the Caucasus region of Eurasia) can grow as tall as 15 to 20 ft (4.5 to 6 m) and spread rapidly. Japanese knotweed is known globally as one of the world's most destructive invasive species because its large underground root system can damage structures, walls, and architectural sites, and reduce stream-channel capacity. Giant hogweed is considered a public-health hazard because it causes a phototoxic reaction when skin is exposed to sap and ultraviolet radiation. Species in the genus *Tamarix* are riparian shrubs or small trees that are aggressively invasive and well known in the Southwestern United States. These riparian trees are known to decrease streamflows, lower biodiversity, and create salinization issues, among other problems. Some of the listed invasive riparian plants were imported to the Northwest as ornamentals and have become invasive (e.g., English ivy [*Hedera helix*] and old man's beard [*Clematis vitabla*], native to the United Kingdom; garlic mustard [*Alliaria petiolate*], native to Europe and Asia). Garlic mustard was initially introduced to the east coast of North America as a medicinal herb, but it has spread through forest understories, where it competes with native species.

Aquatic Invertebrates

The 10 invertebrates on the northwest aquatic-riparian invasive species list (table 7-10) include several mollusks (Asian clam [*Potamocorbula amurensis*], big-eared radix [*Radix auricularia*], Chinese mystery snail [*Cipangopaludina chinensis*), New Zealand mud snail [*Potamopyrgus antipodarum*), New Zealand sea slug [*Philine auriformis*), zebra mussel [*Dreissena polymorpha*), quagga mussel [*D. rostriformis bugensis*]), and crustaceans (crayfish and crab species; waterfleas). Mollusks may spread rapidly and attain large population sizes that displace native species. These taxa can deplete prey resources rapidly, affecting foundation levels of food webs (algae, phytoplankton) in aquatic systems. Along with abundant populations come abundant waste products—in some systems, the tissues or waste products of zebra mussels may accumulate contaminants to 300,000 times the level available in the habitat they occupy, with subsequent effects on their environment, including their predators (Snyder et al. 1997). Another concern is that large numbers of some mollusks can foul human structures. Introductions of some species are likely tied to inadvertent human transmission, such as in ship ballast water or on boats or fishing gear (e.g., zebra/quagga mussels, waterfleas, green crabs). Deliberate introduction and consequent escape of some species is also associated with food and medical markets, biological supplies for education, and the aquarium and bait trade (Chinese mystery snails, crayfish, mitten crabs).

Aquatic Vertebrates

One frog (American bullfrog [*Lithobates catesbeianus*]), one turtle, eight fishes, and a tunicate (*Didemnum*) are included in the priority aquatic-riparian invasive species list (table 7-10). These taxa are strongly tied to human introductions. For example, American bullfrogs are native to the Eastern United States and were brought to the West to be farmed for food and out of nostalgia for their calls. Bullfrogs are carriers of the amphibian chytrid fungus *Bd* but do not always exhibit disease symptoms and hence may serve as a reservoir species of the pathogen, another invasive species of concern. Additional concerns surrounding bullfrog introductions include alterations of the native ecosystem via food-web changes, an issue associated with the snapping turtle (*Chelydra serpentina*) as well.

The invasive fishes include a mix of species introduced for human food, as bait for recreational fisheries, or from the aquarium or ornamental industry. Atlantic salmon (*Salmo salar*) are native to the North Atlantic Ocean, where they are anadromous, occurring in the ocean and returning to spawn in rivers. Farms in Washington and British Columbia are thought to be the origin of Atlantic salmon found elsewhere in the Northwest. Concerns arise in conjunction with their potential competition with native salmonids, pollution from the farms, and the potential for farm-raised animals to carry pathogens to native stocks. Gobies are of Asian origin, occurring in fresh and brackish water. They are thought to have been introduced in ballast water, and may compete with or prey upon native species. Golden shiners (*Noteigonus crysoleucas*) are from the Eastern United States and are pond-cultured fishes that are also used as bait. Where numerous, golden shiners may result in displacement of native species.

Didemnum vexillum is commonly called the carpet sea squirt, or ascidian. It is a colonial tunicate in the chordate phylum, hence is included here together with vertebrates—a sister chordate lineage. It seems to be native to Japan, and has been detected along the Washington coast since 2009, in two Oregon bays since 2010, and near Sitka, Alaska, in 2010. It is a fouling organism in marine and estuarine systems that grows rapidly to cover vast surfaces as mats, displacing native biota and encrusting dock pilings and aquatic equipment. It can be introduced in ballast water, or may hitchhike on the hulls of boats or on commercial shellfish stock or equipment.

Riparian-Terrestrial Vertebrates

The category of terrestrial vertebrates is the smallest, with only three species (table 7-10), but these can have extensive aquatic-riparian effects, ecologically and socioeconomically. Feral swine are escaped domestic pigs with rooting behavior that degrades waterway habitat, provides an invasion pathway for nonnative plants, and causes damage to agricultural crops and lands. The mute swan was introduced from New York for aesthetic enjoyment. These aggressive, large (2- to 30-lb [0.9- to 14-kg]) birds may consume significant quantities of aquatic plants, competing with native birds for food and habitat. Nutria (*Myocastor coypus*) were initially brought to the Pacific Northwest for fur farming in the 1920s. After the collapse of this element of the fur industry, escaped and released animals subsequently spread throughout the region. Nutria burrow into the banks of streams and agricultural canals, destabilizing natural stream systems and human agricultural infrastructure, and they consume vegetable crops.

Research and Development, Monitoring, and Management

Research and Development

Invasive-species disturbance ecology has developed conceptually in the past few decades. Aquatic-riparian ecosystems, like their terrestrial counterparts, are heterogeneous in space and time, occurring in multiple states within an ecosystem domain (e.g., Penaluna et al. 2016). This domain is highly resilient to many natural disturbances, yet larger disturbances can push an ecosystem beyond its "tipping point" to a new domain, a novel ecosystem. Novel ecosystems (e.g., Hobbs et al. 2009) are developing on our planet from a variety of disturbances, including the effects of invasive species. As discussed above, invaders may engineer habitat structures and functions, or become key players in food webs and trophic cascades, altering the native community and ecosystem. Biotic homogenization may result when the variety of initial states of ecosystems becomes equalized as a result of domination of invasive species over natives (e.g., McKinney and Lockwood 1999, Olden et al. 2004). "The New Normal" is a pragmatic description of today's ecological systems that seem to be undergoing irrevocable change, a newly developing status quo (Marris 2010). However, it may be premature to characterize such changes as irrevocable, because there are many examples of restoration successes (e.g., Murcia et al. 2014). Nevertheless, without preempting invasions, vigilance at the early stages of invasion, and concerted, often-continuous restoration efforts, transformation to a novel ecosystem can occur.

These concepts are playing out with aquatic invasive species globally. As cases of ARIS are analyzed, costs to native biodiversity are being claimed. For example, the introductions of the European brown trout (*Salmo trutta*) into South America (Soto et al. 2006) and New Zealand (Townsend 1996), and the eastern mosquitofish (*Gambusia holbrooki*) into Australia (Hamer et al. 2002), have caused major reductions in native fishes. Similar adverse effects on native amphibians and other ecosystem components have been documented by fish-stocking practices (reviews: Dunham et al. 2004, Kats and Ferrer 2003). Despite regionwide efforts to control ARIS spread, some species are recognized as requiring continuous management, or the efficacy of control methods is low. As a result, some invasive species (e.g., bullfrogs, New Zealand mud snails, Himalayan blackberry) seem fully established in some watersheds; the specter of a pragmatic New Normal with diminished native aquatic biodiversity in forests may be realized, owing to our lack of capacity to effectively control invasions everywhere. Furthermore, a clear conflict exists between maintenance of native biodiversity and pursuit of high-value recreational fisheries through nonnative fish-stocking programs.

Nevertheless, restoration tools are being applied to maintain habitats for key native species despite nearby invasive species occurrences (Biebighauser 2011). The solution appears to be purposeful management of the multistate ecosystem across landscapes and regions beyond that which has thus far occurred, in order to designate both wild and nonwild states, in which some places retain a semblance of pristine native ecosystems, whereas in other places different ecosystem services (e.g., fishing experiences) can be fostered. This managed multistate condition is likely part of our regional, if not global, future.

In the Plan area, limited research on ARIS has been conducted recently; several examples of case studies or syntheses follow. First, in a study of invasive fishes in the Willamette River, Oregon, LaVigne et al. (2008) documented an increase in invasive fish diversity and abundance since the 1940s. They also noted the significant contribution to overall fish biomass in the river contributed by the top three most common invasive fishes (smallmouth bass [*Micropterus dolomieu*], largemouth bass [*M. salmoides*], and common carp [*Cyprinus carpio*]). They argued for increased river monitoring and the use of double-pass electrofishing as a means of fish capture and eradication. Carey et al. (2011) assessed the threat to native salmonids posed by smallmouth bass. They described the tension between conservation of native salmon and angling opportunities provided by invasive warm-water fishes, such as smallmouth bass. They argued for more specific management that targeted locations for native fishes only, and others in which invasive species would be allowed to enhance angling opportunities. This notion supports the wild versus nonwild ecosystem-management approach described above.

Sanderson et al. (2009) completed a comprehensive assessment of the potential effect of invasive species on Pacific salmon in the Pacific Northwest. They found that invasive species may pose an even greater threat to salmonid persistence in the region than the four traditional factors generally thought to affect abundance and survival of native salmonids (habitat alteration, harvest, hatcheries, and the hydrosystem). They considered invasive-species management to be a significant component of salmonid-recovery planning.

Yamada and Gillespie (2008) described how initial assessments of the effects of European green crab (*Carcinus maenas*) invasion in the Pacific Northwest (in 1989), which predicted that the crabs would naturally die out, have been proven incorrect. Instead, they found that changing environmental conditions and coastal currents stemming from El Niño cycles have resulted in shifting habitat characteristics amenable to the crab, promoting its spread. They concluded that management for crab eradication is a more pressing issue than first thought.

Pearl et al. (2013) also showed that invasive crayfish in the Pacific Northwest displace native crayfish. In their work in the Rogue, Umpqua, and Willamette/Columbia River basins, they found that invasive crayfish (in particular, *Procambarus clarkia*) tended to be associated with anthropogenic effects on streams, and that these crayfish appeared to have a negative effect on occupancy of native crayfish. They argued that there is still time to control invasive nonnative crayfish, but that the window of opportunity for management to have a meaningful effect is closing.

Claeson and Bisson (2013) conducted a study of the efficacy of invasive knotweed removal by herbicidal application, and effects on the riparian plant community in western Washington. They found that sites where knotweed had been removed, followed by passive restoration, had more nonnative species and vegetative cover than reference (no knotweed) sites, and reference sites had more native species. This finding was especially true for riparian areas along larger streams in their sample, as riparian areas along smaller 2^{nd}- to 3^{rd}-order channels had primarily native plant-species assemblages. They suggested active restoration to control secondary invaders, such as replanting native species. Also, they proposed that effectiveness monitoring of invasive species control projects could help to refine and improve restoration approaches.

Kinziger et al. (2014) described establishment pathways of an introduced fish from a nearby source area to two coastal rivers of northern California. Using genetic techniques, they reported that the Eel River invasion of Sacramento pikeminnow (*Ptychocheilus grandis*) likely was the result of only three or four founding individuals, whereas the Elk River invasion likely came from seven founders. This reflects an astounding adaptive capacity for rapid invasion, and highlights the threat posed by such close-range invaders. This species is not included on our priority list (table 7-10).

In a study of western Oregon wetlands, Rowe and Garcia (2014) reported that native anuran amphibians were negatively associated with invasive plant cover, nonnative fish presence, and invasive bullfrog counts. More generally, Bucciarelli et al. (2014) conducted a comprehensive review of the effects of nonnative species on amphibians and broader ecosystem services, painting a complex picture of negative and potentially positive effects. Their conclusion points to the need for additional research on the interactions of native and nonnative species in many ecosystems.

Globally, invasive species experts are using Web-portal technologies to expedite communication among multiple stakeholders, including natural resource management communities, research, and the public sector. Web-portal information can be used to address scientific hypotheses, aid decisionmaking regarding surveillance priorities, and support local-to-regional management actions. To aid communication about emerging invasive pathogens, for example, the Pacific Northwest (PNW) Research Station has partnered with disease and bioinformatics experts internationally to create online data and mapping portals for ranavirus (https://mantle.io/grrs) and the amphibian chytrid fungus *Bd* (Olson et al. 2013) (https://www.Bd-maps.net). The online *Bd* database has been used in subsequent research (e.g., Grant et al. 2016, Xie et al. 2016). For land-management applications, the *Bd* point-locality and watershed-scale occurrence maps have been used during firefighting for decisions about which water sources might be used for water draws and whether water disinfection procedures may be necessary (NWCG 2017). A new portal is being populated now with data on both chytrid fungi, *Bd* and *Bsal*, including both planned and completed research and monitoring reports (www.amphibiandisease.org). In addition, EDDMapS (Center for Invasive Species and Ecosystem Health 2017) is a new, national, real-time tracking system for invasive species that employs global positioning system (GPS)-based mobile applications technology to allow users to report invasive species occurrences.

Monitoring and Management

Northwest Forest Plan implementation has required ACS monitoring, conducted by AREMP, with adjustments and modifications over time to address new knowledge and aquatic priorities. AREMP assessments for invasive species began in 2007 during annual field surveys at watersheds across the NWFP area (Gruendike and Lanigan 2008). The initial focus was on 13 species of primary concern for Northwest national forest waterways, with an additional 14 species considered of secondary concern (27 species total). The number of species assessed during annual sampling of watersheds in the Plan area has since fluctuated between 23 and 41 species, with 38 total species (i.e., 31 species groups in table 7-10) being included in the 2017 survey season. Survey methods have also been modified as needed, examining streams and adjacent banks within the bankfull width of the channel during summer low-flow periods. Surveys now include subsampling for benthic snails, mussels, crayfish, and ARIS plants. Few invasive species have been detected annually (table 7-11), with Himalayan blackberry being the most common species reported. Because the design of the AREMP surveys revisits watersheds every 8 years, some of the detections do not represent

Table 7-11—Invasive species detections by the Aquatic-Riparian Effectiveness Monitoring Program (AREMP) of the Northwest Forest Plan, 2007–2016

Year	Watersheds surveyed	Sites surveyed	Number of invasive species detections	Species detected (number of detections)	Reference
2007	31	149	7	Himalayan blackberry (7)	Gruendike and Lanigan 2008
2008	31	167	17	Himalayan blackberry (15) reed canary grass (2)	Gruendike and Lanigan 2009
2009	28	189	17	Himalayan blackberry (14) ringed crayfish (2) Japanese knotweed (1)	Andersen and Lanigan 2010
2010	28	185	7	Himalayan blackberry (4) reed canary grass (2) Robert geranium (1) Also reported common mullein (*Verbascum thapsus*) from the Region 6 invasive species list	Raggon and Lanigan 2011
2011	29	184	15	Himalayan blackberry (14) English ivy (1)	Raggon and Lanigan 2012a
2012	28	177	10	Himalayan blackberry (9) ringed crayfish (1)	Raggon and Lanigan 2012b
2013	28	187	4	Himalayan blackberry (2) English ivy (1) ringed crayfish (1)	Raggon and Lanigan 2013
2014	27	157	10	Himalayan blackberry (9) herb Robert, geranium (1)	Raggon 2014
2015	34	177	18	Himalayan blackberry (17) parrotfeather watermilfoil (1)	Pennell and Raggon 2016
2016	25	140	10	Himalayan blackberry(10)	Raggon 2017
Overall totals	289	1,712	125	8 species total	
Unique totals	225	1,376			

Note: Ten-year overall totals do not represent unique watersheds and sites, as some resampling among years was conducted as per the AREMP design. Totals of unique watersheds and sites sampled are also provided.

sampling of unique watersheds or sites. Taking unique sites and watersheds into consideration, overall, only 125 invasive species detections of 8 species have occurred across 1,376 unique sites sampled in 225 unique watersheds for the 10 years spanning 2007 to 2016.[3 4]

ARIS monitoring is also a priority for the Aquatic Invasive Species Network (AISN) (AISN 2017). Initiated by the U.S. Geological Survey and Washington State University in 2010 as the Columbia River Basin Aquatic Invasive Species group (CRBAIS 2011), the network integrates federal, state, academic, and tribal organizations over the area of the Columbia River basin, which includes parts of seven states and British Columbia, Canada, and is roughly the size of France. This region overlaps the NWFP area, in watersheds along the western Washington-Oregon border. AISN objectives are to develop an integrated monitoring

[3] Hirsch, C. 2017. Personal communication. Fish Program Manager, Siuslaw National Forest, Corvallis, OR 97331, chirsch@fs.fed.us

[4] Unpublished data. On file with: Aquatic and Riparian Effectiveness Monitoring Program, 3200 SW Jefferson Way, Corvallis, OR 97331.

and information system, coordinate early-detection efforts, assess invasion pathways, and contribute to an evaluation of the effects of climate change on native and nonnative biota (CRBAIS 2011). Zebra and quagga mussels have been the main taxonomic emphasis; the 2016 map of monitoring sites shows no occurrences of zebra and quagga mussels in the NWFP area (AISN 2017).

In 2012, Forest Service Region 6 developed the Regional Aquatic Invasive Species Strategy and Management Plan (USDA FS 2012b). Its three goals were to (1) prevent new introductions of ARIS into waters and riparian areas of the region; (2) limit the spread of established populations of ARIS into uninfested waters; and (3) provide a cooperative environment that encourages coordinated activities among all affected parties throughout the region. The strategy to achieve these goals is multifaceted, including educational and training programs; implementation of biosecurity protocols (e.g., equipment use and cleaning, inspections); mapping of known invasive species occurrences to inform decisions for water draws for firefighting; coordination of inventory and monitoring efforts; and advance knowledge for eradication procedures. The 2012 list of focal species in this document includes 26 species and species groups listed in table 7-10; known species occurrences were mapped in 2012 (USDA FS 2012b).

As part of the Region 6 ARIS strategy (USDA FS 2012b), surveillance and management is conducted by the joint Region 6 and PNW Research Station dive team.[5] Four specific incidences of invasive species establishment in the NWFP area have been addressed by the dive team in recent years. First, yellow floating heart infestation at a lake in Rogue River–Siskiyou National Forest, Oregon, was evaluated, and control measures were applied and monitored for efficacy. The plants were pulled out, and the area covered by a geotech-style (hardware weed-control) cloth; after 3 years, the area has remained clear of the plant. Second, Eurasian water milfoil was detected in Coldwater Lake at the Mount St. Helens National Volcanic Monument, Washington. The plants were pulled out by the dive team and the lake has been monitored for 2 years. Third, in an estuary adjacent to the Siuslaw National Forest, an invasive tunicate was found. The dive team continues to monitor this situation, and, as yet, no control measures have been implemented. Fourth, the dive team partners with the Siuslaw National Forest to survey for freshwater mussels, work that includes documenting occurrences of the Asian clam. Additional surveillance by this regional dive team occurred in summer 2017 within the Plan area on the Deschutes National Forest, Oregon. The dive team also conducts half-day annual training sessions in aquatic-riparian invasive species identification and management for Region 6 personnel, to be applied as stream field crews conduct stream and lake inventories on the national forests.

Management actions implemented when there are known infestations of invasive species on federal lands in the Plan area differ depending on the species considered. In the best scenario, invasive species are identified when their population is small enough for control to be effective. Early Detection and Rapid Response is considered the cornerstone of effective invasive species management (USDA 2017). In situations in which identification of invasive species occurs before the species becomes overly abundant on the landscape, control techniques may be quite effective, as in the above examples implemented by the regional dive team. Additionally, across this region and elsewhere, biosecurity protocols are in effect for personal disinfection of aquatic field gear to prevent spread of emerging diseases and invasive organisms (e.g., Gray et al. 2017, NWCG 2017). In riparian and upland settings, when invasive species have long been present in the environment and are ubiquitous in landscapes surrounding Forest Service land, plans for complete eradication are less feasible. Instead, measures are taken annually to control spread of invasive species, or with the understanding that additional treatments to combat recolonization will be necessary. This is particularly true of several of the invasive riparian and wetland plant species, including reed canary grass, Himalayan blackberry, and purple loosestrife. Mechanical means of control using masticating machines are combined

[5] Hansen, B. 2017. Personal communication. Ecologist, Pacific Northwest Research Station, Corvallis, OR 97331, bhansen@fs.fed.us

with pesticide applications for the most comprehensive and long-term control of these species.

In addition to invasive species control measures, management actions implemented by Region 6 include development of more effective monitoring frameworks, along with preventative measures to forestall ARIS invasion. To prevent the spread of invasive species, educational programs have been initiated, and biosecurity programs have been implemented. For example, changes have been made to fire equipment contracts that now require equipment such as water tanks to arrive at a fire clean and drained (see ARIS website at https://www.fs.fed.us/r6/fire/aquatic-invasive-species/). A two-pronged ARIS monitoring program has recently been developed by the Region 6 and the PNW Research Station. First, to leverage existing freshwater monitoring programs for ARIS detection, a review was completed of ongoing aquatic habitat monitoring, with particular focus on those programs that assess ARIS risk factors. Results of the evaluation found that wadeable stream sections were adequately represented in monitoring on lands administered by Region 6. However, non-wadeable river sections, lakes, and reservoirs that may be at highest risk for invasion by aquatic species were not well represented in existing survey programs (Flitcroft et al. 2016b). The second element was developed as a followup to this finding—a Pilot Monitoring Project of "big water," began in the summer of 2017. The pilot project will implement multispecies environmental DNA (eDNA) methods to facilitate a consistent and rigorous sampling program. Environmental DNA refers to the residual DNA found in water that is shed by species present in (aquatic species) or near (e.g., tree fungi) the water. Water samples are filtered and then processed in the laboratory, allowing for the identification of DNA from species present in the water sample. Traditionally, eDNA has been used to identify one target species at a time. Techniques being developed by the PNW Research Station in collaboration with Region 6 will allow for up to 48 species to be identified per sample. This approach could provide a breakthrough for ARIS monitoring.

Last, in an attempt to leverage existing resources for ARIS monitoring and mitigation, Region 6 has been able to involve forest law enforcement officers (LEOs) in AIS monitoring. LEOs interact regularly with users of Forest Service lands, making them ideal partners in ARIS monitoring. For LEOs to have authority to inspect vehicles, trailers, and boats, Region 6 completed a National Environmental Policy Act review in 2016 to activate two relevant federal regulations that prohibit the transfer of animal and plant invasive species across National Forest System lands. LEOs in the region are trained on invasive species inspection and identification. This effort parallels invasive species law enforcement at the state level, in which state fish and wildlife agencies or invasive species councils work with state police as the law enforcement entities to help remove illegal alien and invasive species. For example, in Washington state, the 2015 Report to the Legislature (http://wdfw.wa.gov/publications/01697/) reported results from 2011 to 2013, including (1) more than 27,000 boat inspections, with decontamination of 83 boats with aquatic invasive species, of which 19 boats had zebra or quagga mussels, and (2) six new infestations of New Zealand mud snails. The Oregon state "report card" for 2013 (http://www.oregoninvasivespeciescouncil.org/oregons-report-card) similarly reports the results of required boat inspections, including a 73 percent compliance rate, mandatory decontamination of ~4 percent (n = 289) of boats because of the presence of invasive plants or animals, including 17 boats decontaminated for quagga or zebra mussels. It is easy to envision how truncating the transmission pathway along our nation's roadways can be an effective ARIS mitigation.

Future Considerations

Our focus has been on describing those invasive species that have become leading priorities for state or Forest Service management actions in the region of the NWFP, and summarizing recent research and management advances. There is a much longer list of nonnative species detected in western Oregon and Washington that are raising local to widespread concerns. Considerable attention is being paid to novel species in the region, with efforts to prevent introductions of nonnative species into new areas and to understand their potential effects. There are also species that are naturalized to the extent that they are considered long-term, somewhat intractable problems, and that do not appear on state or other types of species lists; this situation explains why some priority species are identified in some Northwest states, but not others.

Other Nonnative Species on the Radar in the Northwest

It is important to note that species priorities change with time as new knowledge or events trigger new concerns. For example, the 2011 earthquake and tsunami in Japan resulted in an alert for alien aquatic species crossing the Pacific Ocean and reaching the eastern Pacific shores of Oregon and Washington. Heightened attention to potential introductions of aquatic nuisance species has occurred, as over 300 nonnative species have been found on debris from Japan that reached North America through the summer of 2016,[6] with more than 100 Japanese marine species drifting across the Pacific on a single dock from Misawa, Japan, to Agate Beach, Oregon (Lam et al. 2015). The potential importance of estuaries for such invasions also supports our rationale for their inclusion here.

Barred owls (*Strix varia*) have naturally dispersed into Oregon and Washington from the south and are being recorded as having ripple effects through western forested ecosystems. In addition to interactions affecting the native northern spotted owl (*S. occidentalis caurina*), barred owls have been found to have a broader prey base, including aquatic prey such as crayfish, amphibians, and fish (Wiens et al. 2014). The effects of barred owls on aquatic ecosystems await further research.

Many nonnative fish species have been released in the Western United States for sports fisheries (Schade and Bonar 2005). Effects on native species have been implicated most frequently for amphibians in the lower 48 states (e.g., Knapp and Matthews 2000). Among nonnative fishes released in Oregon and Washington lakes and rivers are smallmouth bass (*Micropterus dolomieu*) and brook trout (*Salvelinus fontinalis*). Both are predators, and effects on native aquatic prey are a concern. For example, bass are implicated as having adverse effects on state-sensitive species such as the foothill yellow-legged frogs (*Rana boylii*) in Oregon (Paoletti et al. 2011). Nonnative stocked fishes are an example of a conflict between ecosystem services: recreation versus native species. In the NWFP area, there have been increasing efforts to eradicate nonnative fish from wild areas, such as Crater Lake National Park, Oregon. To date, stocking continues at some historically stocked sites in Oregon and Washington, and native vertebrates in these systems appear to be persisting—yet may have declined from historical numbers or distribution. This is an evolving issue, and monitoring may be needed for sensitive native species under additional stressors such as disease.

Numerous additional species could be mentioned here. Newly identified nonnative species can gain quick attention with the hope of rapid eradication, forestalling a new invasive species gaining a foothold in the region. For example, chemical treatment for African clawed frogs (*Xenopus laevis*) was conducted in 2016 at a pond in Lacy, Washington, (WDFW 2016). The clawed frogs were eradicated, and surveillance is ongoing to continue efforts as needed. The role of human releases of nonnative species into the wild focuses attention on how these animals enter the region, to state laws and their enforcement for alien species generally, and to the pet trade more specifically.

Climate Change Projections

Climate factors (temperature and precipitation regimes) strongly affect seasonal conditions in upslope, riparian, and freshwater environments. As with native species, invasive species survival is also tied to these same parameters, and projected climate change can likewise affect them. Hence, the distributions of both native and invasive species are likely to synchronously respond to changing conditions. Effects on some species have not yet been modeled, but for many species, the effects of climate change on invasions can be assessed. For example, American bullfrogs require water temperatures greater than 20 to 21 °C (68 to 70 °F) for breeding (Hayes and Jennings 2005), and suitable breeding sites are projected to be found at higher latitudes and altitudes in the future. Similarly, a northward expansion of the relatively cold-water-adapted amphibian chytrid fungus *Bd* has been projected with a variety of climate

[6] Chan, S. 2017. Personal communication. Extension Watersheds and Aquatic Invasive Species. Oregon Sea Grant, Oregon State University, samuel.chan@oregonstate.edu.

futures (Xie et al. 2016). Temperature and precipitation often constrain the range of many invasive plants and limit their successful establishment. With climate change, new habitat may become available, enabling plants to survive outside their historical ranges and expand beyond their current range. For plants, disturbances such as wildfire or logging can provide a "fast-track" for changes in plant communities or even type conversion. For aquatic-dependent species, coldwater refugia are now being considered as localized areas that may be used to more practically protect native species and assemblages from the projected increase in biotic homogenization that is occurring from climate change effects and warm-water species invasions. Finally, climate-related drought and flooding events are also associated with invasive species dispersal; these effects merit additional consideration for the Northwest and elsewhere.

Research and Monitoring Priorities

Despite their increasing recognition as a potentially dominant force in restructuring ecosystems, relatively few research studies have been conducted on Northwest ARIS; their effects on the composition, function, or processes of ecosytems; ecosystem services valued by people; and mitigation efficacies. As evidenced by the above selected studies, support is growing for the importance of invasive species in altering native ecosystems. For example, Sanderson et al. (2009) considered invasive species more important for native salmonids than four other leading concerns combined, including habitat alteration and overexploitation from fishing pressures (harvest).

Several areas stand out as potentially meriting additional research attention. First, aquatic-riparian pathogens and parasites appear underrepresented on Forest Service regional lists of invasive concern species. None are included in AREMP annual surveys, and only tree fungi are included in the Region 6 watch list. Recognition of pathogens and parasites as taxa for regional monitoring could enable their early detection and help forestall invasions. New eDNA techniques could aid in this regard, as detection of cryptic invaders such as pathogens and parasites may otherwise require significant time commitment or costly laboratory analyses applied after disease events are large enough to be easily detectable. Second, only one study summarized above (Claeson and Bisson 2013) addressed effectiveness of invasive species mitigation approaches with a scientific study design. This is a topic that deserves research for all categories of invasive species in table 7-10, and likely a species-by-species comparison of approaches is needed. For example, field intervention strategies for novel species such as *Bsal* have never been attempted, and foreknowledge of fungicidal or other approaches could be vital to control spread. Nevertheless, trial of some invasive species control methods is ongoing via case-by-case management actions with monitoring, like those being conducted by the regional dive team. Although this adds significantly to our knowledge, it is critical to apply the rigor of hypothesis testing with a scientific design. Lastly, the notion of managing for wild and nonwild ecosystems has been broached, but several questions arise about how this might be developed into an effective long-term strategy. For example, relative to federal lands of the NWFP area, if reserved land use allocations are desired to be wild, can that goal be effectively achieved relative to aquatic-riparian ecosystems given that streams often are contiguous across wild and nonwild areas, potentially promoting invasive species dispersal? Furthermore, can forest restoration practices aid in forestalling nonnative species introductions, or altering the existing heterogeneity within the aquatic ecosystem to avoid crossing "tipping points" to establishment of a novel ecosystem domain (Penaluna et al. 2016)?

Appendix 2: Influence of Climate Change on Life Stages of Pacific Salmon

Peter A. Bisson, Gordon H. Reeves, Nate Mantua, and Steven M. Wondzell[1]

Adults

The species of anadromous Pacific salmonids found in the Northwest Forest Plan (NWFP) area and their freshwater and marine residence times are shown in table 7-8. The freshwater environment is used for both growth and reproduction; the marine environment is used for growth and the initiation of sexual maturity. Depending on species, fish may spend from 1 to 5 or more years in the eastern Pacific Ocean before returning to fresh water to spawn. An exception is coastal cutthroat trout (*Oncorhynchus clarkii*), which generally make limited forays into nearshore areas and typically do not range more than 65 mi (100 km) from natal rivers (Trotter 1989). Owing to marine heterogeneity, the disparate migration patterns of various stocks, and the widely varying amount of time spent at sea, the influences of climate change on survival and growth of different populations of salmon in the ocean will differ.

Although the specific effects of climate change on marine survival and growth of salmon will depend on the location of their natal rivers and their movements at sea, some trends seem to be common to populations along the Pacific Coast. Possibly as a result of decreasing pH and increasing temperature, salmon are becoming smaller and sometimes younger upon return to fresh water, and exhibit reduced marine survival rates. The size of returning adults of most Pacific salmon species has generally trended downward over the past three decades of the 20th century (Bigler et al. 1996), although there have been multiyear periods when both sizes and abundances have increased (Helle et al. 2007). Some populations of sockeye salmon in Bristol Bay, Alaska, have returned to spawn at a younger age in the second half of the 20th century (Hodgeson et al. 2006, Robards and Quinn 2002).

In the past 69 years, the size of the largest fish caught in a Juneau, Alaska, fishing derby for Chinook salmon (*O. tshawytscha*) has declined (fig. 7-21). Although the origin of these salmon is not known with certainty, it is possible that some originated from rivers in the NWFP area, as migratory routes for some Pacific Northwest Chinook salmon

[1] **Peter Bisson** is a research fish ecologist (retired), U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 3625 93rd Ave. SW, Olympia, WA 98512; **Gordon H. Reeves** is a research fish ecologist and **Steven M. Wondzell** is a research geologist, U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, 3200 SW Jefferson Way, Corvallis, OR 97331; **Nate Mantua** is a landscape ecologist, U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, 110 McAllister Way, Santa Cruz, CA 95060.

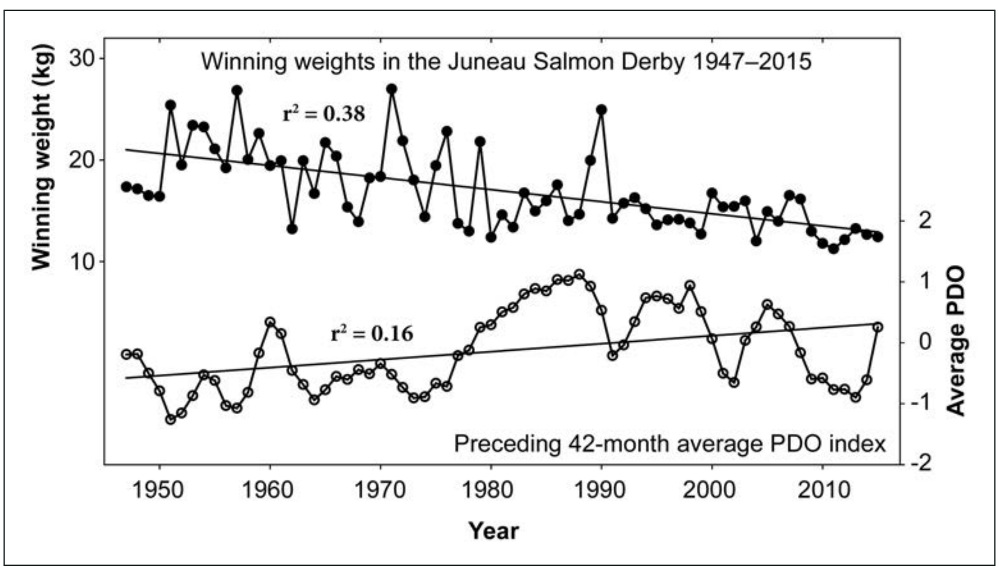

Figure 7-21—Winning weights of Juneau's Golden North Salmon Derby from 1947 through 2015 and the preceding 42-month average Pacific Decadal Oscillation (PDO) index. Positive deviations in the PDO index occur in warmer-than-average PDO cycles, and negative deviations occur in cooler cycles. See also Fagen (1988) and Reid et al. (2016).

stocks include southeast Alaska. There are many possible explanations for the observed declines in fish size, but several previously published examinations of adult salmon sizes from either commercial fishing records (Helle et al. 2007) or Alaskan fishing derbies (Fagen 1988) attributed at least some of the decline to increased competition, owing to large numbers of hatchery-produced salmon (Bigler et al. 1996, Francis and Hare 1997). However, such relationships are not simple. Helle et al. (2007) analyzed data for different species and stocks from northern Alaska to Oregon and concluded that adult body size resulted from both density-dependent factors (competition) and density-independent factors (environmental conditions). Long-term trends in body size observed over time in a Juneau, Alaska, fishing derby are weakly correlated with the gradually warming 42-month average Pacific Decadal Oscillation (PDO) index observed prior to when the fish were caught (fig. 7-21), suggesting a linkage between ocean conditions and fish size that portends future size declines under a warming climate. The relationship between gradual warming and shifts in the frequency and intensity of PDO fluctuations is unclear, but significant PDO regime shifts can signal major changes in the Earth's biophysical systems (Reid et al. 2016).

Decreases in adult body size resulting from changing environmental conditions in the ocean could also lead to reduced reproductive success. In Pacific salmon, both the number of eggs (Hankin and McKelvey 1985, Healey and Heard 1984) and egg size (Quinn and Vøllestad 2003) are directly related to the weight of adult females. Reproductive capacity of populations could decline if females have fewer eggs (McElhany et al. 2000). Egg size, primarily related to yolk reserve, can also be an adaptation to the environment in which eggs develop. Fish that spawn in warmer areas tend to have larger eggs compared to those from cooler areas because the efficiency of yolk conversion to body tissue is reduced at higher temperatures (Fleming and Gross 1990). The survival and body mass at hatching of eggs incubating at warmer future temperatures could therefore be compromised if egg size does not increase as well.

Food webs in aquatic and riparian ecosystems are supported by the influx of marine-derived nutrients from returning adult salmonids (Bilby et al. 1996, Schindler et al. 2003). The productivity of many streams and rivers within the range of Pacific salmon is influenced by the quantity of marine-derived nutrients from salmon carcasses (Gende et al. 2004, Helfield and Naiman 2001, Willson et al. 2004). A reduction in the size and number of returning adult salmon could compromise the capacity of freshwater ecosystems to produce new salmon, with carryover effects on the wide variety of aquatic and terrestrial organisms that may also benefit from the consumption of eggs during the spawning period (Cederholm et al. 2001, Garner et al. 2009). The growth of juvenile salmon during the spawning season is important for their overwinter survival (Lang et al. 2006). Energy derived from eggs consumed by returning adults can also allow for longer migrations and extended spawning times (Copeland and Venditti 2009); thus fewer, smaller eggs could diminish this potential energy source.

According to climate change predictions for most rivers in the NWFP area, returning adult salmon will face warmer temperatures and lower flows if migrations take place in summer. Some species and life-history types, such as stream-type ("spring") Chinook salmon and summer steelhead in the southern and middle portions of the Pacific Coast range of Pacific salmon, return to fresh water in spring or early-summer months, and hold in rivers and streams for several months before spawning. Adults feed infrequently and usually rest in large pools with cool water. Such pools are not abundant in late summer and early autumn, with coolwater refuges likely to become even less available at those times as climate continues to warm. This circumstance suggests that holding and migrating adults may become increasingly stressed, which will diminish their reproductive potential and increase prespawning mortality. Beechie et al. (2006) believed that the loss of summer prespawn staging habitats in rivers entering Puget Sound, Washington, could result in the replacement of stream-type Chinook salmon by ocean-type Chinook salmon, whose autumn run timing avoids exposure to warm, low-flow summer conditions. For populations undertaking long upstream migrations to spawning grounds, elevated stream temperatures will incur higher metabolic costs and mortality (Rand et al. 2006), and fish that do arrive at spawning grounds may have reduced reproductive capacities (Miller et al. 2011).

Warmer temperatures may also limit gonadal development; Pankhurst et al. (1996) found that female steelhead did not ovulate when temperatures exceeded 70 °F (21 °C). The extirpation of Atlantic salmon in the southern portion of their distributional range is attributed to reproductive failure associated with elevated water temperatures in freshwater spawning areas (McCarthy and Houlihan 1997).

Elevated water temperatures during migration can have indirect effects on returning adults. Returning adults may be more vulnerable to disease and parasites if conditions are warmer in fresh water (Johnson et al. 1996, Ray et al. 2012). However, Stocking et al. (2006) found no relation between water temperature and infection of salmonids with *Ceratomyxa shasta* in the Klamath River, California. Juveniles (Chiaramonte et al. 2016) that are unable to find coolwater holding areas during migration in warmer water may be particularly vulnerable to disease because warm water will favor rapid disease transmission and virulence of warm-adapted pathogens that could lead to fish kills. For example, Miller et al. (2011) presented evidence that elevated temperatures in British Columbia's Fraser River have likely contributed to the virulence of a virus that infects adult sockeye salmon (*O. nerka*) prior to entering the Fraser River, resulting in a high incidence of prespawning mortality.

Rising sea level (IPCC 2007) may affect the reproductive success of species that spawn close to tidewater, particularly some pink (*O. gorbuscha*) and chum (*O. keta*) salmon populations. For small populations that spawn in streams just above the high-tide level, elevated sea levels could reduce the available spawning habitat if suitable spawning sites upstream are inaccessible.

The development and persistence of less favorable ocean conditions could potentially influence the degree of anadromy in populations that possess both anadromous and nonanadromous (fully freshwater-resident) life cycle options. Steelhead, the anadromous form of *O. mykiss*, persist at least in part because there is a fitness advantage associated with migrating to the ocean to feed and returning to fresh water to spawn (Quinn and Myers 2004). If this advantage is reduced or lost, residency could increase in populations, assuming that changes in the freshwater environment are suitable for the persistence of the freshwater life-history variant of rainbow trout (Benjamin et al. 2013, Rosenberger et al. 2015, Sloat and Reeves 2014). Other Pacific Coast populations of *O. mykiss* maintain primarily resident populations in locations where the marine environment is believed to be unfavorable for survival and growth, as in southern California (Behnke 2002).

Eggs and Alevins

Eggs and developing embryos will likely be affected by two different aspects of climate change—increased temperatures during egg incubation and altered hydrographs. Under some climate scenarios, winter temperatures are predicted to increase at faster rates than are summer temperatures for Alaska (IPCC 2007), whereas the opposite is true for the more southerly NWFP region (Mote and Salathé 2010).

Most research on climate effects on native fish has focused on the potential for elevated summer temperatures (e.g., Crozier and Zabel 2006, Isaak et al. 2010). However, the effect of elevated winter temperatures may be as, and perhaps even more, pronounced and ecologically significant than increases in summer temperatures. Increased winter temperatures in the NWFP area will result in more precipitation falling as rain rather than snow. Watersheds that historically developed a seasonal snowpack will experience a trend from snow to rain, resulting in more rapid runoff in winter and early spring when snow usually falls, and lower late-spring and early-summer flows owing to reduced snowmelt (Hamlet and Lettenmaier 2007, Hamlet et al. 2005, Tague and Grant 2009). In Washington state's transitional drainage systems that historically possessed both autumn/winter and spring/summer runoff peaks, the shift to a rain-dominant hydrograph is expected to be the most dramatic. Substantial increases are anticipated in the magnitude and frequency of extremely high-flow events in winter, coupled with substantial reductions in summer low flows (e.g., Elsner et al. 2010, Mantua et al. 2010). However, because snowpack will be reduced, rivers with snowmelt-dominated hydrographs could likely see a reduction in the magnitude of high flows during spring runoff. Loukas and Quick (1999) predicted that floods in the snowmelt-dominated continental portions of British Columbia will decrease in magnitude by 7 percent and in volume by 38 percent, and occur as many as 20 days earlier, as a result of the snow-to-rain transition. In coastal areas, Loukas and Quick (1999) projected that there would be little change in the timing of floods, but that, on average, peak-flow magnitude (+14 percent), flood volume (+94 percent), frequency (+11 percent), and duration (+44 percent) would all increase.

High-flow events will influence egg and alevin survival, depending on the depth of the redd, the size of the female, and the location of spawning in the stream network. Eggs in shallower redds will be more susceptible to being scoured than will those in deeper redds, and smaller salmon often excavate shallower redds than larger salmon (van den Berghe and Gross 1989). It has been speculated that increased peak flows during the incubation period could result in decreased survival of eggs and embryos in populations exposed to hydrologic regimes that have become more prone to gravel-mobilizing flows (Battin et al. 2007)

Potential effects of hydrographs altered by climate change are likely to differ among species and life-history forms. In most drainages of the NWFP area, scour is likely to increase the most in small streams or in confined, steep rivers, affecting fish such as bull trout (*Salvelinus confluentus*) that spawn in the late autumn and early winter when the most severe storms tend to occur along the northwestern Pacific Coast (Isaak et al. 2012). Fish spawning in lower gradient, unconfined areas, such as coho (*O. kisutch*), Chinook, pink, and chum salmon, could be less affected. Studies that have examined potential effects of increased flows on streambed scour (Battin et al. 2007, Leppi et al. 2014, Shanley and Albert 2014) assumed a uniform relationship between flood magnitudes and the vulnerability of salmon populations and their habitat. However, the geographic range of Pacific salmon is characterized by exceptional topographic complexity and watershed dynamism (Montgomery 1999), which can generate considerable diversity in watershed- and stream reach-scale responses of habitat to flood disturbance (Buffington 2012, Montgomery and MacDonald 2002). Thus, effects of increased flows are unlikely to be similar among watersheds or even among reaches within stream networks.

Previous research has demonstrated that stream-channel response potential varies according to position within the dendritic structure of stream networks (Benda et al. 2004), variation in valley and reach-scale confinement (Coulthard et al. 2000, Montgomery and Buffington 1997), and differences among species in their use of habitats created by this physiographical complexity (Goode et al. 2013). In terms of management, floodplain connectivity may ameliorate the effects of future increases in discharge on streambed dynamics. Floodplain connectivity in unconfined reaches provides a “stress release valve” (McKean and Tonina 2013) that limits vulnerability of salmon spawning habitat even in large floods with return intervals of decades to centuries (Goode et al. 2013, Lapointe et al. 2000, McKean and Tonina 2013). In this regard, maintaining or restoring connectivity between streams and adjacent floodplains will mitigate near-term responses to increased flood magnitudes. Additionally, maintaining or restoring channel complexity and hydraulic roughness from large wood may further mitigate the effect of higher flows on salmon spawning habitat (Montgomery et al. 1996, Sloat et al. 2017).

The rate of development of eggs and the size of fish at emergence is related to water temperature. Egg development depends on the accumulation of degree days (Neuheimer and Taggart 2007). Even slight increases in temperature can accelerate rate of development and ultimately result in earlier time of emergence from the gravel (McCullough 1999) (fig. 7-22). Accelerated development leads to smaller

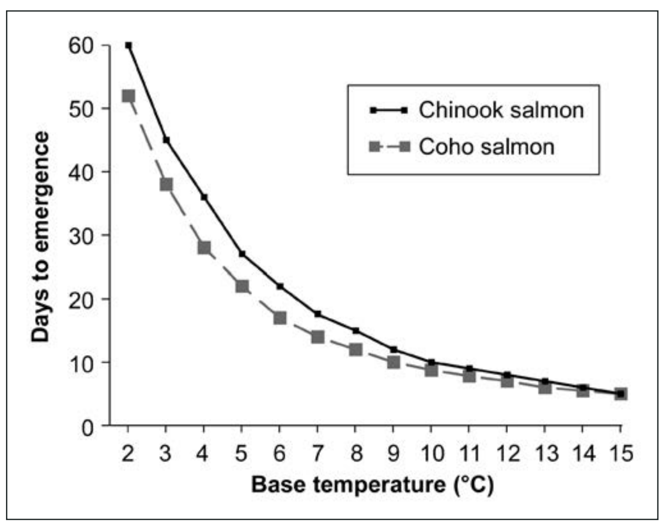

Figure 7-22—Changes in time of emergence of Chinook and coho salmon as a result of a 1 °C-increment increase in water temperature during egg development. From McCullough 1999.

individuals at emergence because metabolic costs decrease the efficiency of yolk use (Beacham and Murray 1990, Elliott and Hurley 1998). Upon emergence, smaller fish are more susceptible to displacement at higher flows. Some fish species may be more influenced by thermal shifts during incubation than others; Beacham and Murray (1990) suggested that coho salmon are adapted for cool water temperatures during development and could experience poorer survival under warming climate scenarios.

There are important ecological implications of climate-related changes in the time and size of fish at emergence. Earlier emergence can result in an extended growing season, a benefit that can lead to increased fitness. Holtby (1988) found that an increase of 1.3 °F (0.7 °C) in winter water temperatures following timber harvest in Carnation Creek on the west coast of Vancouver Island, British Columbia, resulted in coho salmon emerging 6 weeks earlier. Size at age increased because of the extended growing season, resulting in more fish completing their freshwater-rearing life history in one year rather than two. Coho salmon in Carnation Creek also smolted and moved to sea about 2 weeks earlier following timber harvest (which raised stream temperatures); however, marine survival declined, possibly as a result of the decoupling of the timing of smolt migration from marine plankton blooms (Holtby and Scrivener 1989). Similarly, warmer winter temperatures increased the length of the growing season of recently emerged sockeye salmon in southwest Alaska. Like coho salmon in Carnation Creek, sockeye salmon grew faster, and more underwent smolt transformation at age 1+ during warm periods rather than at age 2+ in cooler periods (Schindler et al. 2005). However, age-1+ smolts were smaller than age-2+ smolts and were expected to have decreased marine survival.

Juveniles

Juvenile Pacific salmon (defined here as recently emerged fry up to, but not including, smolts) face a number of challenges from the potential effects of climate change. These challenges will include elevated temperatures and altered streamflows, both of which can affect physical and biological aspects of stream habitats. The type and extent of flow effects will differ depending on the time of emergence. For example, fish emerging in the late winter and early spring may experience high flows caused by earlier snowmelt. The consequences of a changing hydrograph will depend to a large degree on the geomorphic setting in which spawning and emergence occurs. In some settings, increased flooding could improve use of floodplain habitats when fish in wide, geomorphically unconstrained channels have access to habitats where floodplain vegetation is intact and secondary channels are available.

Low-gradient streams and rivers can be important areas for postemergent and seasonal growth (Brown and Hartman 1988, Moore and Gregory 1988, Peterson 1982a), and marginal areas with reduced water velocities provide refuge against downstream displacement. Fry that emerge at a smaller size if water temperature is warmer can potentially overcome their size disadvantage by gaining an early start on the growing season (Holtby 1988). Juvenile salmonids in rain-dominated hydrographic regimes often move into the lower reaches of the channel network or into off-channel habitats in autumn to seek refuge from unfavorable water velocities in the main channel (Ebersole et al. 2006, Everest 1975, Peterson 1982b, Solazzi et al. 2000). In high-elevation snowfall-dominated drainage systems, however, climate warming might not significantly increase mid-winter flood flows and facilitate access to floodplain habitats if precipitation still falls as snow.

Under several climate scenarios, the onset of the low-flow period is expected to occur up to 4 to 6 weeks earlier in most areas as a result of warming (Hamlet and Lettenmaier 2007, Hamlet et al. 2005, Tague and Grant 2009). An extended period of low discharge over the dry season would likely decrease the amount of habitat suitable to juvenile salmonids, and this effect could be most pronounced in small to mid-sized streams (Stewart et al. 2005), resulting in some reaches that formerly held surface flows throughout the year becoming intermittent or even drying completely. As noted by Battin et al. (2007), flow reductions in headwater areas during the dry season could force resident fishes downstream in the stream network, as well as compromise their ability to cope with drought, by reducing the network of connected, perennially flowing channels. Additionally, the downstream displacement of headwater-rearing fish will expose them to warmer temperatures than those to which they are adapted, and possibly to harmful biological interactions with native and nonnative species inhabiting the lower watershed.

The consequences of climate-induced changes in low flows for juvenile salmonids such as Chinook salmon and steelhead that often rear in rivers are likely similar to those in smaller streams, although the risk of river reaches becoming intermittent is less because drainage areas are larger. Mantua et al. (2010) found widespread declines in summer discharge for many rivers in Washington state under climatic warming scenarios. Likewise, Luce and Holden (2009) examined hydrographic records from drainage systems throughout the Pacific Northwest and found that summer flows in all types of hydrologic regimes have been declining, thus providing increasingly smaller rearing areas to river-dwelling species.

In addition to lower flows, elevated summer water temperatures will likely have strong ecological effects on juvenile Pacific salmon, with the direction and magnitude of influence varying geographically, by species, and by life-history type. Water temperature influences the metabolism, food consumption, and growth of an individual (Brett et al. 1969, Warren and Davis 1967, Wurtsbaugh and Davis 1977). Age and size of individuals also influence thermal effects; younger and smaller fish are most susceptible to thermal extremes (Brett 1952) and to short-term thermal variation (Elliott 1994). There is a temperature range in which an individual performs best given a certain level of food resources, and beyond that range, metabolic costs increase such that growth declines (Warren 1971). Increased temperature could potentially affect juvenile salmonids in opposing ways (Li et al. 1994). Warmer water could enhance primary and secondary aquatic production, leading to greater food availability; however, if the increased metabolic demands of warmer temperatures reduce food-conversion efficiency or if the organisms benefiting from warmer temperatures are not preferred food items, the net effect of warming could be reduced growth (Bisson and Davis 1976). In southern portions of a species' range, elevated temperatures could reduce the suitability of rearing areas for juveniles during the summer as temperatures exceed the point at which gains resulting from increased aquatic production are offset by physiological costs, resulting in reduced summer growth rates (Marine and Cech 2004). In contrast, growth rates of juveniles in more northern areas could increase if projected temperature changes stimulate aquatic productivity while remaining within the preferred physiological range for the species.

If the net effects of elevated temperatures resulting from climate change in southern areas reduce summer growth (Isaak et al. 2010, Royer and Minshall 1997, Scarnecchia and Bergersen 1987), juveniles will be smaller entering the winter (ISAB 2007), and overwinter survival may decrease (Quinn and Petersen 1996). However, thermal increases may be beneficial for growth during other seasons if abundant food is present. Sogard et al. (2010) found that juvenile steelhead on the central coast of California attained the most growth in the spring and autumn, and that juvenile coho salmon grew in the winter in coastal Oregon (Ebersole et al. 2006, 2009).

Outcomes of interactions between salmonids and nonsalmonids can be influenced by changing water temperatures. Rearing salmonids tend to outcompete nonsalmonids for food resources and preferred feeding areas at cooler temperatures, whereas nonsalmonids have the advantage at warmer temperatures (Petersen and Kitchell 2001, Reeves et al. 1987). The susceptibility of juvenile salmonids to disease could also increase at warmer temperatures and could be compounded by the presence of competitors that are less susceptible to the pathogens infecting salmon and trout (Reeves et al. 1987). Additionally, warmer temperatures could lead to increased predation from nonnative warmwater fish (ISAB 2007, Petersen and Kitchell 2001). The aggregate results of these indirect effects are likely to be changes in the structure and composition of fish communities in the affected stream systems (ISAB 2012), particularly in the southern portions of the NWFP area where the potential for interaction with warmwater species is greatest owing to widespread introduction and proliferation of nonnative warmwater fishes.

The effects of climate change on rearing habitats for juvenile salmon at the local level will depend, to some degree, on the geomorphic features of a particular location.

Crozier and Zabel (2006) suggested that two climate-influenced factors—stream temperature and flow—could affect habitat in different ways: narrow, confined streams were predicted to be more responsive to flow changes, and geomorphically unconfined streams would be more sensitive to temperature changes. In addition, the future quantity and quality of freshwater rearing habitat of Pacific salmon may also be influenced by predicted increases in the magnitude and frequency of large disturbances. Climate change scenarios predict an increase in exceptional flood events caused by transitions from snow to rain, accelerated glacial melt, wildfires, and forest pathogen outbreaks (Dale et al. 2001, Hamlet and Lettenmaier 2007). Frequent large floods promote landsliding and stream sedimentation in many areas (Miller et al. 2003). The effects of floods and associated erosion events on freshwater habitat will differ depending on the geomorphic setting, the magnitude and legacy of the event, the interval between succeeding disturbances, and the extent to which the affected ecosystem has been altered by past human activities (Reeves et al. 1995, Rieman et al. 2006).

Increased disturbance frequency and severity can have short-term negative consequences for fish populations, including substrate scour and fine-sediment intrusion that reduces egg and alevin survival and macroinvertebrate abundance in confined channels, displacement of juveniles downstream, and loss of surface flow in summer in reaches where porous material has been deposited in the channel. However, in functionally intact systems there is a strong potential for aquatic habitat complexity to improve with flooding because floodplain linkages can be reestablished and large wood will be recruited to the channel network (Bisson et al. 2009). Long-term changes could be favorable to rearing salmon if the cumulative effects of climate change on water temperature, fine-sediment levels, and surface flows remain within limits tolerable to juvenile salmon or exceed those thresholds only for a short duration.

Population productivity after large disturbances will also be enhanced by the presence of adjacent fish populations that provide sources of colonizers to help initiate recovery and that add to the phenotypic and genetic diversity of affected populations (Schtickzelle and Quinn 2007). But it is also possible that in greatly altered watersheds, where the cumulative harmful effects of climate change exceed environmental tolerance limits, the damage caused by large-scale disturbances will be too great, and if there are no nearby populations to provide new colonists, local population extirpation will occur.

Lakes are important rearing habitats for sockeye salmon and will also be affected by climate change, although there are relatively few drainage systems in the NWFP area that support sockeye salmon runs. Potential effects will vary greatly depending on the location and features of the lake, but a primary effect will be the magnitude and seasonality of warming, with epilimnetic water and the timing of spring and autumn turnover experiencing the greatest changes (Stefan et al. 2001). Slight warming of deep lakes could lead to increased sockeye growth rates if temperatures stimulate primary and secondary production without significantly affecting the availability of cooler water during periods when the epilimnion becomes too warm for efficient metabolism. This benefit could be offset during the growing season by a reduction in the delivery of inorganic nutrients and dissolved organic carbon from terrestrial systems as a result of decreased spring and summer flows. Reduced inputs of nutrients and dissolved organic carbon from the surrounding watershed could result in diminished algal production, which would result in deeper light penetration and additional warming of the lake (Schindler et al. 1990).

The productivity of zooplankton, the principal food of juvenile sockeye salmon in lakes, will be affected by climate change, but whether or not the changes are beneficial will depend on ambient thermal and hydrologic regimes. In Alaska, warming temperatures have resulted in earlier ice melt, greater densities of zooplankton, and increasing sockeye growth rates (Schindler et al. 2005). In contrast, earlier onset of spring in western Washington's Lake Washington has advanced lake stratification by 20 days in recent years, resulting in earlier diatom blooms and a decline in cladocerans (*Daphnia* spp.), important prey species for juvenile sockeye rearing in the lake (Winder and Schindler 2004).

Smolts

Anadromous salmonids typically undergo the smolting process and move to the ocean in spring, although seaward migrations of some salmon stocks occur throughout the year. Water temperature, day length, and changes in flow are the principal cues influencing the timing of parr-smolt transformations. Environmental signals affecting smolting can be divided into regulating and controlling factors (Byrne et al. 2004). Regulating factors act on juvenile salmon before the migration and influence the physiological aspects of smolting. Controlling factors operate during migration and affect the speed of downstream movement. Water temperature and day length appear to be key regulating factors (Jonsson and Jonsson 2009). Day length is not influenced by climate change, but increased temperature will affect the onset of smoltification. For Pacific salmon, elevated winter temperatures can result in earlier migration times of smolts. Chinook salmon have been observed to migrate earlier in warmer years than in cooler years (Achord et al. 2007, Roper and Scarnecchia 1999), but Jonsson and Jonsson (2009) cite a suite of other studies on Atlantic salmon, brown trout (*Salmo trutta*), and steelhead in which water temperatures did not affect the timing of smolt migration. Under certain conditions, elevated temperatures may even inhibit parr-smolt transformation. Adams et al. (1973) found that smolting in steelhead held at 59 °F (15 °C) or warmer led to reductions of ATPase activity needed to initiate the smolt transformation process. Thus, the effect of altered temperature on timing of smolt migration remains unpredictable and likely will vary widely across populations.

To a large extent, streamflow determines the rate at which smolts move downstream (Connor et al. 2003, Smith et al. 2002). Climate model projections of stream runoff (Snover et al. 2003, Tague and Grant 2009) suggest that the onset of the low-flow period will occur 4 to 6 weeks earlier over much of the NWFP area in the next century. Projections of the annual cycle of elevated flows from melting snow for more northerly areas are not currently available, but we assume that they will be similar. The consequences of altered flows are likely to be population-specific, with the timing and smolt survival rates of those populations that tend to migrate later or are required to move long distances likely to be the most affected by climate change.

The survival of smolts entering the ocean depends on a number of factors (Pearcy 1992). Larger smolts tend to have higher survival rates than do smaller fish (Holtby and Scrivener 1989, Quinn and Peterson 1996, Slaney 1988), possibly because they are better able to avoid predation. The size of an individual at smolting is influenced by its size at the beginning of the previous winter. Brown and Hartman (1988) found that stream and groundwater warming caused by logging in a coastal Vancouver Island watershed resulted in increased overwinter growth of presmolt coho salmon, and Holtby and Scrivener (1989) suggested that this growth advantage led to higher smolt-to-adult return rates through improved ocean survival.

Conditions in marine nearshore areas at the time of ocean entry are known to strongly influence ocean survival (Rechisky et al. 2009). In the coastal area influenced by the California current—primarily the southern half of the distributional range of many Pacific salmon species—potential changes in the timing and intensity of upwelling have important implications for smolts (Barth et al. 2007). Cold, nutrient-rich waters are pushed into nearshore areas by northerly winds in the late spring and early summer, producing favorable conditions for plankton production (Nickelson 1986, Scheuerell and Williams 2005). Under one climate change scenario, upwelling is projected to intensify but occur later in the summer (Snyder et al. 2003), decoupling the timing of smolt migration relative to plankton blooms for early-entry salmon smolts.

The abundance of predators in nearshore areas can also influence marine survival of smolts (Pearcy 1992). Coho salmon from Carnation Creek on the west coast of Vancouver Island, British Columbia, entered the ocean about 2 weeks earlier as a result of increased growth as juveniles (Holtby 1988), but survival declined compared to the timing of pre-logging smolt migration. It was believed that predation by mackerel (*Scomber japonicus*) and hake (*Merluccius productus*) contributed to the decline, as both species moved into Barkley Sound during periods of warm sea-surface temperatures. Elevated ocean temperatures could also result in the expansion of subtropical predators such as the Humboldt squid (*Dosidicus gigas*) into Pacific Northwest waters, further increasing predation pressure on salmon smolts (Christensen and Trites 2011, ISAB 2007).

Nearshore conditions in northern portions of the NWFP area will also be influenced by climate change. In some locations, melting glaciers could increase iron levels in nearshore areas (Westerlund and Ohman 1991). Iron levels are often considered limiting to primary production in the North Pacific, and increased iron levels in freshwater plumes could potentially enhance marine food webs (Rose et al. 2005) and thus improve growth and survival of young salmon. The projected effects of climate change on the ocean ecology of Pacific salmon will therefore result from the combined influences of several factors, notably predation, food resource abundance, and both intra- and interspecific competition.

Scientific and common names of plant species identified in this report

Scientific name	Common name
Abies amabilis (Douglas ex Loudon) Douglas ex Forbes	Pacific silver fir
Abies concolor (Gord. & Glend.) Lindl. ex Hildebr.	White fir
Abies grandis (Douglas ex D. Don) Lindl.	Grand fir
Abies lasiocarpa (Hook.) Nutt.	Subalpine pine
Abies magnifica A. Murray bis	California red fir
Abies procera Rehder	Noble fir
Acer circinatum Pursh	Vine maple
Acer macrophyllum Pursh	Bigleaf maple
Achlys triphylla (Sm.) DC.	Sweet after death
Adenocaulon bicolor Hook.	American trailplant
Alliaria petiolata (M. Bieb.) Cavara & Grande	Garlic mustard
Alnus rubra Bong.	Red alder
Amelanchier alnifolia (Nutt.) Nutt. ex M. Roem.	Saskatoon serviceberry
Anemone oregana A. Gray	Blue windflower
Apocynum cannabinum L.	Dogbane
Arbutus menziesii Pursh)	Madrone
Arceuthobium M. Bieb.	Dwarf mistletoe
Arceuthobium occidentale Engelm.	Gray pine dwarf mistletoe
Arceuthobium tsugense Rosendahl	Hemlock dwarf mistletoe
Arctostaphylos nevadensis A. Gray	Pinemat manzanita
Brachypodium sylvaticum (Huds.) P. Beauv.	False brome
Brodiaea coronaria (Salisb.) Engl.	Cluster-lilies
Callitropsis nootkatensis (D. Don) Oerst. ex D.P. Little	Alaska yellow-cedar
Calocedrus decurrens (Torr.) Florin	Incense cedar
Cannabis L.	Marijuana
Carex barbarae Dewey and *C. obnupta* L.H. Bailey	Sedges
Centaurea solstitialis L.	Yellow starthistle
Chamaecyparis lawsoniana (A. Murray bis) Parl.	Port Orford cedar
Chimaphila menziesii (R. Br. ex D. Don) Spreng.	Little prince’s pine
Chimaphila umbellata (L.) W.P.C. Barton	Pipsissewa
Clematis vitalba L.	Old man’s beard
Clintonia uniflora Menzies ex Schult. & Schult. f.) Kunth	Bride’s bonnet
Coptis laciniata A. Gray	Oregon goldthread
Corylus cornuta Marshall var. *californica* (A. DC.) Sharp	California hazel
Cornus canadensis L.	Bunchberry dogwood
Cytisus scoparius (L.) Link	Scotch broom
Disporum hookeri (Torr.) G. Nicholson var. *hookeri*	Drops-of-gold
Fallopia japonica (Houtt.) Ronse Decr. var. *japonica*	Japanese knotweed
Gaultheria ovatifolia A. Gray	Western teaberry
Gaultheria shallon Pursh	Salal

Scientific name	Common name
Gentiana douglasiana Bong.	Swamp gentian
Geranium lucidum L.	Shining geranium
Geranium robertianum L.	Robert geranium
Goodyera oblongifolia Raf.	Western rattlesnake plantain
Hedera helix L.	English ivy
Heracleum mantegazzianum Sommier & Levier	Giant hogweed
Hesperocyparis sargentii (Jeps.) Bartel	Sargent's cypress
Hieracium aurantiacum L.	Orange hawkweed
Ilex aquifolium L.	English holly
Iris pseudacorus L.	Paleyellow iris
Juniperus occidentalis Hook.	Western juniper
Lamiastrum galeobdolon (L.) Ehrend. & Polatschek	Yellow archangel
Lilium occidentale Purdy	Western lily
Linnaea borealis L.	Twinflower
Lithocarpus densiflorus (Hook. & Arn.) Rehder	Tanoak
Lonicera hispidula Pursh	Honeysuckle
Lupinus albicaulis Douglas	Sickle-keeled lupine
Lycopodium clavatum L.	Running clubmoss
Lythrum salicaria L.	Purple loosestrife
Mahonia nervosa (Pursh) Nutt.	Cascade barberry
Malus fusca (Raf.) C.K. Schneid.	Pacific crabapple
Notholithocarpus densiflorus (Hook. & Arn.) P.S. Manos, C.H. Cannon, & S.H. Oh	Tanoak
Notholithocarpus densiflorus (Hook. & Arn.) P.S. Manos, C.H. Cannon, & S.H. Oh var. *echinoides* (R.Br. ter) P.S. Manos, C.H. Cannon & S.H. Oh	Shrub form of tanoak
Nuphar polysepala (Engelm.)	Yellow pond lily
Nymphoides peltata (S.G. Gmel.) Kuntze	Yellow floating heart
Osmorhiza chilensis Hook. & Arn.	Sweetcicely
Phalaris arundinacea L.	Reed canarygrass
Picea engelmannii Parry ex Engelm.	Engelmann spruce
Picea sitchensis (Bong.) Carrière	Sitka spruce
Pinus albicaulis Engelm.	Whitebark pine
Pinus attenuata Lemmon	Knobcone pine
Pinus contorta Douglas ex Loudon	Lodgepole pine
Pinus contorta Douglas ex Loudon var. *contorta*	Beach pine, shore pine
Pinus jeffreyi Balf.	Jeffrey pine
Pinus lambertiana Douglas	Sugar pine
Pinus monticola Douglas ex D. Don)	Western white pine
Pinus ponderosa Lawson & C. Lawson	Ponderosa pine
Populus trichocarpa L. ssp. *trichocarpa* (Torr. & A. Gray ex Hook) Brayshaw	Black cottonwood
Potamogeton crispus L.	Curly pondweed
Potentilla recta L.	Sulphur cinquefoil

Scientific name	Common name
Prunus emarginata (Douglas ex Hook. D. Dietr.)	Bitter cherry
Pseudotsuga menziesii (Mirb.) Franco	Douglas-fir
Pteridium aquilinum (L. Kuhn)	Brackenfern
Pueraria montana (Lour.) Merr. var. *lobata* (Willd.) Maesen & S.M. Almeida ex Sanjappa & Predeep	Kudzu
Pyrola asarifolia Sweet	American wintergreen
Quercus agrifolia Née var. *oxyadenia* (Torr.) J.T. Howell	Coastal live oak
Quercus berberidifolia Liebm.	Scrub oak
Quercus chrysolepis Liebm.	Canyon live oak
Quercus douglasii Hook. & Arn.	Blue oak
Quercus garryana Douglas ex hook.	Oregon white oak
Quercus kelloggi Newberry	California black oak
Quercus lobata Née	Valley oak
Rhamnus purshiana (DC.) A. Gray	Cascara
Rhododendron groenlandicum Oeder	Bog Labrador tea
Rhododendron macrophyllum D. Don ex G. Don	Pacific rhododendron
Ribes lacustre (Pers.) Poir.	Prickly currant
Rubus armeniacus Focke	Himalayan blackberry
Salix exigua Nutt.	Sandbar willow
Senecio bolanderi A. Gray	Bolander's ragwort
Sequoia sempervirens (Lamb. ex D. Don) Endl.	Redwood
Smilacina stellata (L.) Desf.	Starry false Solomon's seal
Synthyris reniformis (Douglas ex Benth.) Benth.	Snowqueen
Taxus brevifolia Nutt.	Pacific yew
Thuja plicata Donn ex D. Don	Western redcedar
Tiarella trifoliate L.	Threeleaf foamflower
Trapa natans L.	Water chestnut
Trillium ovatum Pursh	Pacific trillium
Tsuga heterophylla (Raf.) Sarg.	Western hemlock
Tsuga mertensiana (Bong.) Carrière	Mountain hemlock
Typha latifolia L.	Cattails
Umbellularia californica (Hook. & Arn.) Nutt.	California bay laurel
Vaccinium alaskaense Howell	Alaska blueberry
Vaccinium membranaceum Douglas ex Torr.	Thinleaf huckleberry, big huckleberry
Vaccinium ovatum Pursh	Evergreen huckleberry
Vaccinium oxycoccos L.	Small cranberry
Vaccinium parvifolium Sm.	Red huckleberry
Vancouveria hexandra (Hook.) C. Morren & Decne.	White insideout flower
Xerophyllum tenax (Pursh) Nutt.	Beargrass

Glossary

This glossary is provided to help readers understand various terms used in the Northwest Forest Plan (NWFP) science synthesis. Sources include the Forest Service Handbook (FSH), the Code of Federal Regulations (CFR), executive orders, the Federal Register (FR), and various scientific publications (see "Glossary Literature Cited"). The authors have added working definitions of terms used in the synthesis and its source materials, especially when formal definitions may be lacking or when they differ across sources.

active management—Direct interventions to achieve desired outcomes, which may include harvesting and planting of vegetation and the intentional use of fire, among other activities (Carey 2003).

adaptive capacity—The ability of ecosystems and social systems to respond to, cope with, or adapt to disturbances and stressors, including environmental change, to maintain options for future generations (FSH 1909.12.5).

adaptive management—A structured, cyclical process for planning and decisionmaking in the face of uncertainty and changing conditions with feedback from monitoring, which includes using the planning process to actively test assumptions, track relevant conditions over time, and measure management effectiveness (FSH 1909.12.5). Additionally, adaptive management includes iterative decisionmaking, through which results are evaluated and actions are adjusted based on what has been learned.

adaptive management area (AMA)—A portion of the federal land area within the NWFP area that was specifically allocated for scientific monitoring and research to explore new forestry methods and other activities related to meeting the goals and objectives of the Plan. Ten AMAs were established in the NWFP area, covering about 1.5 million ac (600 000 ha), or 6 percent of the planning area (Stankey et al. 2003).

alien species—Any species, including its seeds, eggs, spores, or other biological material capable of propagating that species, that is not native to a particular ecosystem (Executive Order 13112). The term is synonymous with exotic species, nonindigenous, and nonnative species (see also "invasive species").

allochthonous inputs—Material, specifically food resources, that originates from outside a stream, typically in the form of leaf litter.

amenity communities—Communities located near lands with high amenity values.

amenity migration—Movement of people based on the draw of natural or cultural amenities (Gosnell and Abrams 2011).

amenity value—A noncommodity or "unpriced" value of a place or environment, typically encompassing aesthetic, social, cultural, and recreational values.

ancestral lands (of American Indian tribes)—Lands that historically were inhabited by the ancestors of American Indian tribes.

annual species review—A procedure established under the NWFP in which panels of managers and biologists evaluate new scientific and monitoring information on species to potentially support the recommendation of changes in their conservation status.

Anthropocene—The current period (or geological epoch) in which humans have become a dominant influence on the Earth's climate and environment, generally dating from the period of rapid growth in industrialization, population, and global trade and transportation in the early 1800s (Steffen et al. 2007).

Aquatic Conservation Strategy (ACS) —A regional strategy applied to aquatic and riparian ecosystems across the area covered by the NWFP) (Espy and Babbit 1994) (see chapter 7 for more details).

at-risk species—Federally recognized threatened, endangered, proposed, and candidate species and species of conservation concern. These species are considered at risk of low viability as a result of changing environmental conditions or human-caused stressors.

best management practices (BMPs) (for water quality)—Methods, measures, or practices used to reduce or eliminate the introduction of pollutants and other detrimental impacts to water quality, including but not limited to structural and nonstructural controls and to operation and maintenance procedures.

biodiversity—In general, the variety of life forms and their processes and ecological functions, at all levels of biological organization from genes to populations, species, assemblages, communities, and ecosystems.

breeding inhibition—Prevention of reproduction in healthy adult individuals.

bryophytes—Mosses and liverworts.

canopy cover—The downward vertical projection from the outside profile of the canopy (crown) of a plant measured in percentage of land area covered.

carrying capacity—The maximum population size a specific environment can sustain.

ceded areas—Lands that particular tribes ceded to the United States government by treaties, which have been catalogued in the Library of Congress.

climate adaptation—Management actions to reduce vulnerabilities to climate change and related disturbances.

climate change—Changes in average weather conditions (including temperature, precipitation, and risk of certain types of severe weather events) that persist over multiple decades or longer, and that result from both natural factors and human activities such as increased emissions of greenhouse gases (U.S. Global Change Research Program 2017).

coarse filter—A conservation approach that focuses on conserving ecosystems, in contrast to a "fine filter" approach that focuses on conserving specific species. These two approaches are generally viewed as complementary, with fine-filtered strategies tailored to fit particular species that "fall through the pores" of the coarse filter (Hunter 2005). See also "mesofilter."

co-management—Two or more entities, each having legally established management responsibilities, working collaboratively to achieve mutually agreed upon, compatible objectives to protect, conserve, use, enhance, or restore natural and cultural resources (81 FR 4638).

collaborative management—Two or more entities working together to actively protect, conserve, use, enhance, or restore natural and cultural resources (81 FR 4638).

collaboration or collaborative process—A structured manner in which a collection of people with diverse interests share knowledge, ideas, and resources, while working together in an inclusive and cooperative manner toward a common purpose (FSH 1909.12.05).

community (plant and animal)—A naturally occurring assemblage of plant and animal species living within a defined area or habitat (36 CFR 219.19).

community forest—A general definition is forest land that is managed by local communities to provide local benefits (Teitelbaum et al. 2006). The federal government has specifically defined community forest as "forest land owned in fee simple by an eligible entity [local government, nonprofit organization, or federally recognized tribe] that provides public access and is managed to provide community benefits pursuant to a community forest plan" (36 CFR 230.2).

community of place or place-based community—A group of people who are bound together because of where they reside, work, visit, or otherwise spend a continuous portion of their time.

community resilience—The capacity of a community to return to its initial function and structure when initially altered under disturbance.

community resistance—The capacity of a community to withstand a disturbance without changing its function and structure.

composition—The biological elements within the various levels of biological organization, from genes and species to communities and ecosystems (FSM 2020).

congeneric—Organisms that belong to the same taxonomic genus, usually belonging to different species.

connectivity (of habitats)—Environmental conditions that exist at several spatial and temporal scales that provide landscape linkages that permit (a) the exchange of flow, sediments, and nutrients; (b) genetic interchange of genes among individuals between populations; and (c) the long-distance range shifts of species, such as in response to climate change (36 CFR 219.19).

consultation (tribal)—A formal government-to-government process that enables American Indian tribes and Alaska Native Corporations to provide meaningful, timely input, and, as appropriate, exchange views, information, and recommendations on proposed policies or actions that may affect their rights or interests prior to a decision. Consultation is a unique form of communication characterized by trust and respect (FSM 1509.05).

corticosterone—A steroid hormone produced by many species of animals, often as the result of stress.

cryptogam—An organism that reproduces by spores and that does not produce true flowers and seeds; includes fungi, algae, lichens, mosses, liverworts, and ferns.

cultural keystone species—A species that significantly shapes the cultural identity of a people, as reflected in diet, materials, medicine, or spiritual practice (Garibaldi and Turner 2004).

cultural services—A type of ecosystem service that includes the nonmaterial benefits that people obtain from ecosystems through spiritual enrichment, cognitive development, reflection, recreation, and aesthetic experiences (Sarukhán and Whyte 2005).

desired conditions—A description of specific social, economic, or ecological characteristics toward which management of the land and resources should be directed.

disturbance regime—A description of the characteristic types of disturbance on a given landscape; the frequency, severity, and size distribution of these characteristic disturbance types and their interactions (36 CFR 219.19).

disturbance—Any relatively discrete event in time that disrupts ecosystem, watershed, community, or species population structure or function, and that changes resources, substrate availability, or the physical environment (36 CFR 219.19).

dynamic reserves—A conservation approach in which protected areas are relocated following changes in environmental conditions, especially owing to disturbance.

early-seral vegetation—Vegetation conditions in the early stages of succession following an event that removes the forest canopy (e.g., timber harvest, wildfire, windstorm), on sites that are capable of developing a closed canopy (Swanson et al. 2014). A nonforest or "pre-forest" condition occurs first, followed by an "early-seral forest" as young shade-intolerant trees form a closed canopy.

ecocultural resources—Valued elements of the biophysical environment, including plants, fungi, wildlife, water, and places, and the social and cultural relationships of people with those elements.

ecological conditions—The biological and physical environment that can affect the diversity of plant and animal communities, the persistence of native species, invasibility, and productive capacity of ecological systems. Ecological conditions include habitat and other influences on species and the environment. Examples of ecological conditions include the abundance and distribution of aquatic and terrestrial habitats, connectivity, roads and other structural developments, human uses, and occurrence of other species (36 CFR 219.19).

ecological forestry—A ecosystem management approach designed to achieve multiple objectives that may include conservation goals and sustainable forest management and which emphasizes disturbance-based management and retention of "legacy" elements such as old trees and dead wood (Franklin et al. 2007).

ecological integrity—The quality or condition of an ecosystem when its dominant ecological characteristics (e.g., composition, structure, function, connectivity, and species composition and diversity) occur within the natural range of variation and can withstand and recover from most perturbations imposed by natural environmental dynamics or human influence (36 CFR 219.19).

ecological keystone species—A species whose ecological functions have extensive and disproportionately large effects on ecosystems relative to its abundance (Power et al. 1996).

ecological sustainability—The capability of ecosystems to maintain ecological integrity (36 CFR 219.19).

economic sustainability—The capability of society to produce and consume or otherwise benefit from goods and services, including contributions to jobs and market and nonmarket benefits (36 CFR 219.19).

ecoregion—A geographic area containing distinctive ecological assemblages, topographic and climatic gradients, and historical land uses.

ecosystem—A spatially explicit, relatively homogeneous unit of the Earth that includes all interacting organisms and elements of the abiotic environment within its boundaries (36 CFR 219.19).

ecosystem diversity—The variety and relative extent of ecosystems (36 CFR 219.19).

ecosystem integrity—See "ecological integrity."

ecosystem management—Management across broad spatial and long temporal scales for a suite of goals, including maintaining populations of multiple species and ecosystem services.

ecosystem services—Benefits that people obtain from ecosystems (see also "provisioning services," "regulating services," "supporting services," and "cultural services").

ectomycorrhizal fungi—Fungal species that form symbiotic relationships with vascular plants through roots, typically aiding their uptake of nutrients. Although other mycorrhizal fungi penetrate their host's cell walls, ectomycorrhizal fungi do not.

endangered species—Any species or subspecies that the Secretary of the Interior or the Secretary of Commerce has deemed in danger of extinction throughout all or a significant portion of its range (16 U.S.C. Section 1532).

endemic—Native and restricted to a specific geographical area.

El Niño Southern Oscillation (ENSO)—A band of anomalously warm ocean water temperatures that occasionally develops off the western coast of South America and can cause climatic changes across the Pacific Ocean. The extremes of this climate pattern's oscillations cause extreme weather (such as floods and droughts) in many regions of the world.

environmental DNA (eDNA)—Genetic material (DNA) contained within small biological and tissue fragments that can be collected from aquatic, terrestrial, and even atmospheric environments, linked to an individual species, and used to indicate the presence of that species.

environmental justice populations—Groups of people who have low incomes or who identify themselves as African American, Asian or Pacific Islander, American Indian or Alaskan Native, or of Hispanic origin.

ephemeral stream—A stream that flows only in direct response to precipitation in the immediate locality (watershed or catchment basin), and whose channel is at all other times above the zone of saturation.

epicormic—Literally, "of a shoot or branch," this term implies growth from a previously dormant bud on the trunk or a limb of a tree.

epiphyte—A plant or plant ally (including mosses and lichens) that grows on the surface of another plant such as a tree, but is not a parasite.

even-aged stand—A stand of trees composed of a single age class (36 CFR 219.19).

fecundity—The reproductive rate of an organism or population.

federally recognized Indian tribe—An Indian tribe or Alaska Native Corporation, band, nation, pueblo, village, or community that the Secretary of the Interior acknowledges to exist as an Indian tribe under the Federally Recognized Indian Tribe List Act of 1994, 25 U.S.C. 479a (36 CFR 219.19).

fine filter—A conservation approach that focuses on conserving individual species in contrast to a "coarse filter" approach that focuses on conserving ecosystems; these approaches are generally viewed as complementary with fine-filtered strategies tailored to fit particular species that "fall through the pores" of the coarse filter (Hunter 2005). See also "mesofilter."

fire-dependent vegetation types—A vegetative community that evolved with fire as a necessary contributor to its vitality and to the renewal of habitat for its member species.

fire exclusion—Curtailment of wildland fire because of deliberate suppression of ignitions, as well as unintentional effects of human activities such as intensive grazing that removes grasses and other fuels that carry fire (Keane et al. 2002).

fire intensity—The amount of energy or heat release during fire.

fire regime—A characterization of long-term patterns of fire in a given ecosystem over a specified and relatively long period of time, based on multiple attributes, including frequency, severity, extent, spatial complexity, and seasonality of fire occurrence.

fire regime, low frequency, high severity—A fire regime with long return intervals (>200 years) and high levels of vegetation mortality (e.g., ~70 percent basal area mortality in forested ecosystems), often occurring in large patches (>10,000 ac [4047 ha]) (see chapter 3 for more details).

fire regime, moderate frequency, mixed severity—A fire regime with moderate return intervals between 50 and 200 years and mixtures of low, moderate, and high severity; high-severity patches would have been common and frequently large (>1,000 ac [>405 ha]) (see chapter 3 for more details).

fire regime, very frequent, low severity—A fire regime with short return intervals (5 to 25 years) dominated by surface fires that result in low levels of vegetation mortality (e.g., <20 percent basal area mortality in forested ecosystems), with high-severity fire generally limited to small patches (<2.5 ac [1 ha]) (see chapter 3 for more details).

fire regime, frequent, mixed severity—A fire regime with return intervals between 15 and 50 years that burns with a mosaic of low-, moderate-, and high-severity patches (Perry et al. 2011) (see chapter 3 for more details).

fire rotation—Length of time expected for a specific amount of land to burn (some parts might burn more than once or some not at all) based upon the study of past fire records in a large landscape (Turner and Romme 1994).

fire severity—The magnitude of the effects of fire on ecosystem components, including vegetation or soils.

fire suppression—The human act of extinguishing wildfires (Keane et al. 2002).

floodplain restoration—Ecological restoration of a stream or river's floodplain, which may involve setback or removal of levees or other structural constraints.

focal species—A small set of species whose status is assumed to infer the integrity of the larger ecological system to which it belongs, and thus to provide meaningful information regarding the effectiveness of a resource management plan in maintaining or restoring the ecological conditions to maintain the broader diversity of plant and animal communities in the NWPF area. Focal species would be commonly selected on the basis of their functional role in ecosystems (36 CFR 219.19).

food web—Interconnecting chains between organisms in an ecological community based upon what they consume.

Forest Ecosystem Management Assessment Team (FEMAT)—An interdisciplinary team that included expert ecological and social scientists, analysts, and managers assembled in 1993 by President Bill Clinton to develop options for ecosystem management of federal forests within the range of the northern spotted owl (FEMAT 1993).

forest fragmentation—The patterns of dispersion and connectivity of nonhomogeneous forest cover (Riitters et al. 2002). See also "landscape fragmentation" and "habitat fragmentation" for specific meanings related to habitat loss and isolation.

frequency distribution—A depiction, often appearing in the form of a curve or graph, of the abundance of possible values of a variable. In this synthesis report, we speak of the frequency of wildfire patches of various sizes.

fuels (wildland)—Combustible material in wildland areas, including live and dead plant biomass such as trees, shrub, grass, leaves, litter, snags, and logs.

fuels management—Manipulation of wildland fuels through mechanical, chemical, biological, or manual means, or by fire, in support of land management objectives to control or mitigate the effects of future wildland fire.

function (ecological)—Ecological processes, such as energy flow; nutrient cycling and retention; soil development and retention; predation and herbivory; and natural disturbances such as wind, fire, and floods that sustain composition and structure (FSM 2020). See also "key ecological function."

future range of variation (FRV)—The natural fluctuation of pattern components of healthy ecosystems that might occur in the future, primarily affected by climate change, human infrastructure, invasive species, and other anticipated disturbances.

gaps (forest)—Small openings in a forest canopy that are naturally formed when one or a few canopy trees die (Yamamoto 2000).

genotype—The genetic makeup of an individual organism.

glucocorticoid—A class of steroid hormones produced by many species of animals, often as the result of stress.

goals (in land management plans)—Broad statements of intent, other than desired conditions, that do not include expected completion dates (36 CFR part 219.7(e)(2)).

guideline—A constraint on project and activity decision-making that allows for departure from its terms, so long as the purpose of the guideline is met (36 CFR section 219.15(d)(3)). Guidelines are established to help achieve or maintain a desired condition or conditions, to avoid or mitigate undesirable effects, or to meet applicable legal requirements.

habitat—An area with the environmental conditions and resources that are necessary for occupancy by a species and for individuals of that species to survive and reproduce.

habitat fragmentation—Discontinuity in the spatial distribution of resources and conditions present in an area at a given scale that affects occupancy, reproduction, and survival in a particular species (see "landscape fragmentation").

heterogeneity (forest)—Diversity, often applied to variation in forest structure within stands in two dimensions: horizontal (e.g., single trees, clumps of trees, and gaps of no trees), and vertical (e.g., vegetation at different heights from the forest floor to the top of the forest canopy), or across large landscapes (North et al. 2009).

hierarchy theory—A theory that describes ecosystems at multiple levels of organization (e.g., organisms, populations, and communities) in a nested hierarchy.

high-severity burn patch—A contiguous area of high-severity or stand-replacing fire.

historical range of variation (HRV)—Past fluctuation or range of conditions in the pattern of components of ecosystems over a specified period of time.

hybrid ecosystem—An ecosystem that has been modified from a historical state such that it has novel attributes while retaining some original characteristics (see "novel ecosystem").

hybrid—Offspring resulting from the breeding of two different species.

inbreeding depression—Reduced fitness in a population that occurs as the result of breeding between related individuals, leading to increased homogeneity and simplification of the gene pool.

in-channel restoration—Ecological restoration of the channel of a stream or river, often through placement of materials (rocks and wood) or other structural modifications.

individuals, clumps, and openings (ICO) method—A method that incorporates reference spatial pattern targets based upon individual trees, clumps of trees, and canopy openings into silvicultural prescriptions and tree-marking guidelines (Churchill et al. 2013).

Interagency Special Status and Sensitive Species Program (ISSSSP)—A federal agency program, established under the U.S. Forest Service Pacific Northwest Region and Bureau of Land Management Oregon/Washington state office. The ISSSSP superseded the Survey and Manage standards and guidelines under the NWFP and also addresses other species of conservation focus, coordinates development and revision of management recommendations and survey protocols, coordinates data management between the agencies, develops summaries of species biology, and conducts other tasks.

intermittent stream—A stream or reach of stream channel that flows, in its natural condition, only during certain times of the year or in several years, and is characterized by interspersed, permanent surface water areas containing aquatic flora and fauna adapted to the relatively harsh environmental conditions found in these types of environments.

invasive species—An alien species (or subspecies) whose deliberate, accidental, or self-introduction is likely to cause economic or environmental harm or harm to human health (Executive Order 13112).

key ecological function—The main behaviors performed by an organism that can influence environmental conditions or habitats of other species.

key watersheds—Watersheds that are expected to serve as refugia for aquatic organisms, particularly in the short term, for at-risk fish populations that have the greatest potential for restoration, or to provide sources of high-quality water.

land and resource management plan (Forest Service)—A document or set of documents that provides management direction for an administrative unit of the National Forest System (FSH 1909.12.5).

landform—A specific geomorphic feature on the surface of the Earth, such as a mountain, plateau, canyon, or valley.

landscape—A defined area irrespective of ownership or other artificial boundaries, such as a spatial mosaic of terrestrial and aquatic ecosystems, landforms, and plant communities, repeated in similar form throughout such a defined area (36 CFR 219.19).

landscape fragmentation—Breaking up of continuous habitats into patches as a result of human land use and thereby generating habitat loss, isolation, and edge effects (see "habitat fragmentation").

landscape genetics—An interdisciplinary field of study that combines population genetics and landscape ecology to explore how genetic relatedness among individuals and subpopulations of a species is influenced by landscape-level conditions.

landscape hierarchy—Organization of land areas based upon a hierarchy of nested geographic (i.e., different-sized) units, which provides a guide for defining the functional components of a system and how components at different scales are related to one another.

late-successional forest—Forests that have developed after long periods of time (typically at least 100 to 200 years) following major disturbances, and that contain a major component of shade-tolerant tree species that can regenerate beneath a canopy and eventually grow into the canopy in which small canopy gaps occur (see chapter 3 for more details). Note that FEMAT (1993) and the NWFP also applied this term to older (at least 80 years) forest types, including both old-growth and mature forests, regardless of the shade tolerance of the dominant tree species (e.g., 90-year-old forests dominated by Douglas-fir were termed late successional).

leading edge—The boundary of a species' range at which the population is geographically expanding through colonization of new sites.

legacy trees—Individual trees that survive a major disturbance and persist as components of early-seral stands (Franklin 1990).

legacies (biological)—Live trees, seed and seedling banks, remnant populations and individuals, snags, large soil aggregates, hyphal mats, logs, uprooted trees, and other biotic features that survive a major disturbance and persist as components of early-seral stands (Franklin 1990, Franklin et al. 2002).

lentic—Still-water environments, including lakes, ponds, and wet meadows.

longitudinal studies—Studies that include repeated observations on the same response variable over time.

lotic—Freshwater environments with running water, including rivers, streams, and springs.

low-income population—A community or a group of individuals living in geographic proximity to one another, or a set of individuals, such as migrant workers or American Indians, who meet the standards for low income and experience common conditions of environmental exposure or effect (CEQ 1997).

managing wildfire for resource objectives—Managing wildfires to promote multiple objectives such as reducing fire danger or restoring forest health and ecological processes rather than attempting full suppression. The terms "managed wildfire" or "resource objective wildfire" have also been used to describe such events (Long et al. 2017). However, fire managers note that many unplanned ignitions are managed using a combination of tactics, including direct suppression, indirect containment, monitoring of fire spread, and even accelerating fire spread, across their perimeters and over their full duration. Therefore, terms that separate "managed" wildfires from fully "suppressed" wildfires do not convey that complexity. (See "Use of wildland fire," which also includes prescribed burning).

matrix—Federal and other lands outside of specifically designated reserve areas, particularly the late-successional reserves under the NWFP, that are managed for timber production and other objectives.

mature forest—An older forest stage (>80 years) prior to old-growth in which trees begin attaining maximum heights and developing some characteristic, for example, 80 to 200 years in the case of old-growth Douglas-fir/western hemlock forests, often (but not always) including big trees (>50 cm diameter at breast height), establishment of late-seral species (i.e., shade-tolerant trees), and initiation of decadence in early species (i.e., shade-intolerant trees).

mesofilter—A conservation approach that "focuses on conserving critical elements of ecosystems that are important to many species, especially those likely to be overlooked by fine-filter approaches, such as invertebrates, fungi, and nonvascular plants" (Hunter 2005).

meta-analysis—A study that combines the results of multiple studies.

minority population—A readily identifiable group of people living in geographic proximity with a population that is at least 50 percent minority; or, an identifiable group that has a meaningfully greater minority population than the adjacent geographic areas, or may also be a geographically dispersed/transient set of individuals such as migrant workers or Americans Indians (CEQ 1997).

mitigation (climate change)—Efforts to reduce anthropogenic alteration of climate, in particular by increasing carbon sequestration.

monitoring—A systematic process of collecting information to track implementation (implementation monitoring), to evaluate effects of actions or changes in conditions or relationships (effectiveness monitoring), or to test underlying assumptions (validation monitoring) (see 36 CFR 219.19).

mosaic—The contiguous spatial arrangement of elements within an area. In regions, this is typically the upland vegetation patches, large urban areas, large bodies of water, and large areas of barren ground or rock. However, regional mosaics can also be described in terms of land ownership, habitat patches, land use patches, or other elements. For landscapes, this is typically the spatial arrangement of landscape elements.

multiaged stands—Forest stands having two or more age classes of trees; this includes stands resulting from variable-retention silvicultural systems or other traditionally even-aged systems that leave residual or reserve (legacy) trees.

multiple use—The management of all the various renewable surface resources of the National Forest System so that they are used in the combination that will best meet the needs of the American people; making the most judicious use of the land for some or all of these resources or related services over areas large enough to provide sufficient latitude for periodic adjustments in use to conform to changing needs and conditions; that some land will be used for less than all of the resources; and harmonious and coordinated management of the various resources, each with the other, without impairment of the productivity of the land, with consideration being given to the relative values of the various resources, and not necessarily the combination of uses that will give the greatest dollar return or the greatest unit output, consistent with the Multiple-Use Sustained-Yield Act of 1960 (16 U.S.C. 528–531) (36 CFR 219.19).

natal site—Location of birth.

native knowledge—A way of knowing or understanding the world, including traditional ecological, and social knowledge of the environment derived from multiple generations of indigenous peoples' interactions, observations, and experiences with their ecological systems. This knowledge is accumulated over successive generations and is expressed through oral traditions, ceremonies, stories, dances, songs, art, and other means within a cultural context (36 CFR 219.19).

native species—A species historically or currently present in a particular ecosystem as a result of natural migratory or evolutionary processes and not as a result of an accidental or deliberate introduction or invasion into that ecosystem (see 36 CFR 219.19).

natural range of variation (NRV)—The variation of ecological characteristics and processes over specified scales of time and space that are appropriate for a given management application (FSH 1909.12.5).

nested hierarchy—The name given to the hierarchical structure of groups within groups used to classify organisms.

nontimber forest products (also known as "special forest products")—Various products from forests that do not include logs from trees but do include bark, berries, boughs, bryophytes, bulbs, burls, Christmas trees, cones, ferns, firewood, forbs, fungi (including mushrooms), grasses, mosses, nuts, pine straw, roots, sedges, seeds, transplants, tree sap, wildflowers, fence material, mine props, posts and poles, shingle and shake bolts, and rails (36 CFR part 223 Subpart G).

novel ecosystem—An ecosystem that has experienced large and potentially irreversibly modifications to abiotic conditions or biotic composition in ways that result in a composition of species, ecological communities, and functions that have never before existed, and that depart from historical analogs (Hobbs et al. 2009). See "hybrid ecosystem" for comparison.

old-growth forest—A forest distinguished by old trees (>200 years) and related structural attributes that often (but not always) include large trees, high biomass of dead wood (i.e., snags, down coarse wood), multiple canopy layers, distinctive species composition and functions, and vertical and horizontal diversity in the tree canopy (see chapter 3). In dry, fire-frequent forests, old growth is characterized by large, old fire-resistant trees and relatively open stands without canopy layering.

palustrine—Inland, nontidal wetlands that may be permanently or temporarily flooded and are characterized by the presence of emergent vegetation such as swamps, marshes, vernal pools, and lakeshores.

passive management—A management approach in which natural processes are allowed to occur without human intervention to reach desired outcomes.

patch—A relatively small area with similar environmental conditions, such as vegetative structure and composition. Sometimes used interchangeably with vegetation or forest stand.

Pacific Decadal Oscillation (**PDO)**—A recurring (approximately decadal-scale) pattern of ocean-atmosphere —a stream or reach of a channel that flows continuously or nearly so throughout the year and whose upper surface is generally lower than the top of the zone of saturation in areas adjacent to the stream.

perennial stream—A stream or reach of a channel that flows continuously or nearly so throughout the year and whose upper surface is generally lower than the top of the zone of saturation in areas adjacent to the stream.

phenotype—Physical manifestation of the genetic makeup of an individual and its interaction with the environment.

place attachment—The "positive bond that develops between groups or individuals and their environment" (Jorgensen and Stedman 2001: 234).

place dependence— "The strength of an individual's subjective attachment to specific places" (Stokols and Shumaker 1982: 157).

place identity—Dimensions of self that define an individual's [or group's] identity in relation to the physical environment through ideas, beliefs, preferences, feelings, values, goals, and behavioral tendencies and skills (Proshansky 1978).

place-based planning—"A process used to involve stakeholders by encouraging them to come together to collectively define place meanings and attachments" (Lowery and Morse 2013: 1423).

plant association—A fine level of classification in a hierarchy of potential vegetation that is defined in terms of a climax-dominant overstory tree species and typical understory herb or shrub species.

population bottleneck—An abrupt decline in the size of a population from an event, which often results in deleterious effects such as reduced genetic diversity and increased probability of local or global extirpation.

potential vegetation type (PVT)—Native, late-successional (or "climax") plant community that reflects the regional climate, and dominant plant species that would occur on a site in absence of disturbances (Pfister and Arno 1980).

poverty rate—A measure of financial income below a threshold that differs by family size and composition.

precautionary principle—A principle that if an action, policy, or decision has a suspected risk of causing harm to the public or to the environment, and there is no scientific consensus that it is not harmful, then the burden of proof that it is not harmful falls on those making that decision. Particular definitions of the principle differ, and some applications use the less formal term, "precautionary approach." Important qualifications associated with many definitions include (1) the perceived harm is likely to be serious, (2) some scientific analysis suggests a significant but uncertain potential for harm, and (3) applications of the principle emphasize generally constraining an activity to mitigate it rather than "resisting" it entirely (Doremus 2007).

prescribed fire—A wildland fire originating from a planned ignition to meet specific objectives identified in a written and approved prescribed fire plan for which National Environmental Policy Act requirements (where applicable) have been met prior to ignition (synonymous with controlled burn).

primary recreation activity—A single activity that caused a recreation visit to a national forest.

probable sale quantity—An estimate of the average amount of timber likely to be awarded for sale for a given area (such as the NWFP area) during a specified period.

provisioning services—A type of ecosystem service that includes clean air and fresh water, energy, food, fuel, forage, wood products or fiber, and minerals.

public participation geographic information system (PPGIS)—Using spatial decisionmaking and mapping tools to produce local knowledge with the goal of including and empowering marginalized populations (Brown and Reed 2009).

public values—Amenity values (scenery, quality of life); environmental quality (clean air, soil, and water); ecological values (biodiversity); public use values (outdoor recreation, education, subsistence use); and spiritual or religious values (cultural ties, tribal history).

record of decision (ROD)—The final decision document that amended the planning documents of 19 national forests and seven Bureau of Land Management districts within the range of the northern spotted owl (the NWFP area) in April 1994 (Espy and Babbit 1994).

recreation opportunity—An opportunity to participate in a specific recreation activity in a particular recreation setting to enjoy desired recreation experiences and other benefits that accrue. Recreation opportunities include non-motorized, motorized, developed, and dispersed recreation on land, water, and in the air (36 CFR 219.19).

redundancy—The presence of multiple occurrences of ecological conditions, including key ecological functions (functional redundancy), such that not all occurrences may be eliminated by a catastrophic event.

refugia—An area that remains less altered by climatic and environmental change (including disturbances such as wind and fire) affecting surrounding regions and that therefore forms a haven for relict fauna and flora.

regalia—Dress and special elements made from a variety of items, including various plant and animal materials, and worn for tribal dances and ceremonies.

regulating services—A type of ecosystem service that includes long-term storage of carbon; climate regulation; water filtration, purification, and storage; soil stabilization; flood and drought control; and disease regulation.

representativeness—The presence of a full array of ecosystem types and successional states, based on the physical environment and characteristic disturbance processes.

reserve—An area of land designated and managed for a special purpose, often to conserve or protect ecosystems, species, or other natural and cultural resources from particular human activities that are detrimental to achieving the goals of the area.

resilience—The capacity of a system to absorb disturbance and reorganize (or return to its previous organization) so as to still retain essentially the same function, structure, identity, and feedbacks (see FSM Chapter 2020 and see also "socioecological resilience"). Definitions emphasize the capacity of a system or its constituent entities to respond or regrow after mortality induced by a disturbance event, although broad definitions of resilience may also encompass "resistance" (see below), under which such mortality may be averted.

resistance—The capacity of a system or an entity to withstand a disturbance event without much change.

restoration economy—Diverse economic activities associated with the restoration of structure or function to terrestrial and aquatic ecosystems (Nielsen-Pincus and Moseley 2013).

restoration, ecological—The process of assisting the recovery of an ecosystem that has been degraded, damaged, or destroyed. Ecological restoration focuses on reestablishing the composition, structure, pattern, and ecological processes necessary to facilitate terrestrial and aquatic ecosystems sustainability, resilience, and health under current and future conditions (36 CFR 219.19).

restoration, functional—Restoration of dynamic abiotic and biotic processes in degraded ecosystems, without necessarily a focus on structural condition and composition.

riparian areas—Three-dimensional ecotones (the transition zone between two adjoining communities) of interaction that include terrestrial and aquatic ecosystems that extend down into the groundwater, up above the canopy, outward across the floodplain, up the near slopes that drain to the water, laterally into the terrestrial ecosystem, and along the water course at variable widths (36 CFR 219.19).

riparian management zone—Portions of a watershed in which riparian-dependent resources receive primary emphasis, and for which plans include Plan components to maintain or restore riparian functions and ecological functions (36 CFR 219.19).

riparian reserves—Reserves established along streams and rivers to protect riparian ecological functions and processes necessary to create and maintain habitat for aquatic and riparian-dependent organisms over time and ensure connectivity within and between watersheds. The Aquatic Conservation Strategy in the NWFP record of decision included standards and guidelines that delineated riparian reserves.

risk—A combination of the probability that a negative outcome will occur and the severity of the subsequent negative consequences (36 CFR 219.19).

rural restructuring—Changes in demographic and economic conditions owing to declines in natural resource production and agriculture (Nelson 2001).

scale—In ecological terms, the extent and resolution in spatial and temporal terms of a phenomenon or analysis, which differs from the definition in cartography regarding the ratio of map distance to Earth surface distance (Jenerette and Wu 2000).

scenic character—A combination of the physical, biological, and cultural images that gives an area its scenic identity and contributes to its sense of place. Scenic character provides a frame of reference from which to determine scenic attractiveness and to measure scenic integrity (36 CFR 219.19).

science synthesis—A narrative review of scientific information from a defined pool of sources that compiles and integrates and interprets findings and describes uncertainty, including the boundaries of what is known and what is not known.

sense of place—The collection of meanings, beliefs, symbols, values, and feelings that individuals or groups associate with a particular locality (Williams and Stewart 1998).

sensitive species—Plant or animal species that receive special conservation attention because of threats to their populations or habitats, but which do not have special status as listed or candidates for listing under the Endangered Species Act.

sensitivity—In ecological contexts, the propensity of communities or populations to change when subject to disturbance, or the opposite of resistance (see "community resistance").

sink population—A population in which reproductive rates are lower than mortality rates but that is maintained by immigration of individuals from outside of that population (see also "source population").

social sustainability—"The capability of society to support the network of relationships, traditions, culture, and activities that connect people to the land and to one another, and support vibrant communities" (36 CFR 219.19). The term is commonly invoked as one of the three parts of a "triple-bottom line" alongside environmental and economic considerations. The concept is an umbrella term for various topics such as quality of life, security, social capital, rights, sense of place, environmental justice, and community resilience, among others discussed in this synthesis.

socioecological resilience—The capacity of socioecological systems (see "socioecological system") to cope with, adapt to, and influence change; to persist and develop in the face of change; and to innovate and transform into new, more desirable configurations in response to disturbance.

socioecological system (or social-ecological system)—A coherent system of biophysical and social factors defined at several spatial, temporal, and organizational scales that regularly interact, continuously adapt, and regulate critical natural, socioeconomic, and cultural resources (Redman et al. 2004); also described as a coupled-human and natural system (Liu et al. 2007).

source population—A population in which reproductive rates exceed those of mortality rates so that the population has the capacity to increase in size. The term is also often used to denote when such a population contributes emigrants (dispersing individuals) that move outside the population, particularly when feeding a sink population.

special forest products—See "nontimber forest products."

special status species—Species that have been listed or proposed for listing as threatened or endangered under the Endangered Species Act.

species of conservation concern—A species, other than federally recognized as a threatened, endangered, proposed, or candidate species, that is known to occur in the NWFP area and for which the regional forester has determined that the best available scientific information indicates substantial concern about the species' capability to persist over the long term in the Plan area (36 CFR 219.9(c)).

stand—A descriptor of a land management unit consisting of a contiguous group of trees sufficiently uniform in age-class distribution, composition, and structure, and growing on a site of sufficiently uniform quality, to be a distinguishable unit.

standard—A mandatory constraint on project and activity decisionmaking, established to help achieve or maintain the desired condition or conditions, to avoid or mitigate undesirable effects, or to meet applicable legal requirements.

stationarity—In statistics, a process that, while randomly determined, is not experiencing a change in the probability of outcomes.

stewardship contract—A contract designed to achieve land management goals while meeting local and rural community needs, including contributing to the sustainability of rural communities and providing a continuing source of local income and employment.

strategic surveys—One type of field survey, specified under the NWFP, designed to fill key information gaps on species distributions and ecologies by which to determine if species should be included under the Plan's Survey and Manage species list.

stressors—Factors that may directly or indirectly degrade or impair ecosystem composition, structure, or ecological process in a manner that may impair its ecological integrity, such as an invasive species, loss of connectivity, or the disruption of a natural disturbance regime (36 CFR 219.19).

structure (ecosystem)—The organization and physical arrangement of biological elements such as snags and down woody debris, vertical and horizontal distribution of vegetation, stream habitat complexity, landscape pattern, and connectivity (FSM 2020).

supporting services—A type of ecosystem service that includes pollination, seed dispersal, soil formation, and nutrient cycling.

Survey and Manage program—A formal part of the NWFP that established protocols for conducting various types of species surveys, identified old-forest-associated species warranting additional consideration for monitoring and protection (see "Survey and Manage species"), and instituted an annual species review procedure that evaluated new scientific and monitoring information on species for potentially recommending changes in their conservation status, including potential removal from the Survey and Manage species list.

Survey and Manage species—A list of species, compiled under the Survey and Manage program of the NWFP, that were deemed to warrant particular attention for monitoring and protection beyond the guidelines for establishing late-successional forest reserves.

sustainability—The capability to meet the needs of the present generation without compromising the ability of future generations to meet their needs (36 CFR 219.19).

sustainable recreation—The set of recreation settings and opportunities in the National Forest System that is ecologically, economically, and socially sustainable for present and future generations (36 CFR 219.19).

sympatric—Two species or populations that share a common geographic range and coexist.

threatened species—Any species that the Secretary of the Interior or the Secretary of Commerce has determined is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range. Threatened species are listed at 50 CFR sections 17.11, 17.12, and 223.102.

timber harvest—The removal of trees for wood fiber use and other multiple-use purposes (36 CFR 219.19).

timber production—The purposeful growing, tending, harvesting, and regeneration of regulated crops of trees to be cut into logs, bolts, or other round sections for industrial or consumer use (36 CFR 219.19).

topo-edaphic—Related to or caused by particular soil conditions, as of texture or drainage, rather than by physiographic or climatic factors within a defined region or area.

traditional ecological knowledge—"A cumulative body of knowledge, practice, and belief, evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes et al. 2000: 1252). See also "native knowledge."

trailing edge—When describing the range of a species, the boundary at which the species' population is geographically contracting through local extinction at occupied sites.

trophic cascade—Changes in the relative populations of producers, herbivores, and carnivores following the addition or removal of top predators and the resulting disruption of the food web.

uncertainty—Amount or degree of confidence as a result of imperfect or incomplete information.

understory—Vegetation growing below the tree canopy in a forest, including shrubs and herbs that grow on the forest floor.

use of wildland fire—Management of either wildfire or prescribed fire to meet resource objectives specified in land or resource management plans (see "Managing wildfire for resource objectives" and "Prescribed fire").

variable-density thinning—The method of thinning some areas within a stand to a different density (including leaving dense, unthinned areas) than other parts of the stand, which is typically done to promote ecological diversity in a relatively uniform stand.

vegetation series (plant community)—The highest level of the fine-scale component (plant associations) of potential vegetation hierarchy based on the dominant plant species that would occur in late-successional conditions in the absence of disturbance.

vegetation type—A general term for a combination or community of plants (including grasses, forbs, shrubs, or trees), typically applied to existing vegetation rather than potential vegetation.

viable population—A group of breeding individuals of a species capable of perpetuating itself over a given time scale.

vital rates—Statistics describing population dynamics such as reproduction, mortality, survival, and recruitment.

watershed—A region or land area drained by a single stream, river, or drainage network; a drainage basin (36 CFR 219.19).

watershed analysis—An analytical process that characterizes watersheds and identifies potential actions for addressing problems and concerns, along with possible management options. It assembles information necessary to determine the ecological characteristics and behavior of the watershed and to develop options to guide management in the watershed, including adjusting riparian reserve boundaries.

watershed condition assessment—A national approach used by the U.S. Forest Service to evaluate condition of hydrologic units based on 12 indicators, each composed of various attributes (USDA FS 2011).

watershed condition—The state of a watershed based on physical and biogeochemical characteristics and processes (36 CFR 219.19).

watershed restoration—Restoration activities that focus on restoring the key ecological processes required to create and maintain favorable environmental conditions for aquatic and riparian-dependent organisms.

well-being—The condition of an individual or group in social, economic, psychological, spiritual, or medical terms.

wilderness—Any area of land designated by Congress as part of the National Wilderness Preservation System that was established by the Wilderness Act of 1964 (16 U.S.C. 1131–1136) (36 CFR 219.19).

wildlife—Undomesticated animal species, including amphibians, reptiles, birds, mammals, fish, and invertebrates or even all biota, that live wild in an area without being introduced by humans.

wildfire—Unplanned ignition of a wildland fire (such as a fire caused by lightning, volcanoes, unauthorized and accidental human-caused fires), and escaped prescribed fires.

wildland-urban interface (WUI)—The line, area, or zone where structures and other human development meet or intermingle with undeveloped wildland or vegetation fuels.

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