American Fisheries Society Symposium 92:279–325, 2022

Beyond Best Management Practices

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Abstract.—In contemporary forest landscapes, aquatic–riparian management approaches are addressing ecological integrity of site-to-landscape components that extend beyond the reach of traditional best management practices (BMPs). In this chapter, we highlight the intersection of BMPs that have guided past priorities with integrated interdisciplinary geomorphic, hydrologic, and biological perspectives of joint aquatic–terrestrial ecosystem management and restoration in forests. Beyond-BMP considerations include adapting prescribed BMPs for broader species and habitat protections and recognizing the need for coordinated stream-to-upland ecosystem restoration, in addition to protection from project-specific actions. Riparian management area (i.e., riparian buffer) designs, site-specific management, and watershed set-asides are beyond-BMP approaches that can be used to address abiotic resources such as light, temperature, nutrients, and down wood, as well as biotic concerns, including imperiled species, their habitats at whole-watershed scales, and the ecological functions and processes to which they are tied. Aquatic–riparian ecosystems are inherently dynamic, and managing for spatial and temporal heterogeneity has emerged as a priority restoration goal. To aid in complex protection and restoration aims across watershed scales, multiforest stakeholder collaborative groups are seeking to ensure delivery of broad ecosystem services (i.e., the range of goods and values desired by people from forests) across watersheds or landscapes, rather than on each project area or land ownership. In this way, beyond-BMP approaches are integrating management of geomorphic, hydrologic, and biological concerns to provide both a sustainable supply chain of wood and a host of other ecosystem services.

Introduction

Forestry best management practices (BMPs; Jackson et al. 2022, this volume) are an efficient approach to target human–forest interactions and avoid potential adverse environmental effects, yet BMPs can vary considerably in scope, from a narrow focus on limiting water quality exceedances to a broad focus on maintaining a suite of physical and chemical conditions that may

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conserve biodiversity across aquatic, riparian, and upland ecosystems. For example, adaptation of existing BMPs for water quality standards may easily address a growing number of aquatic–riparian goods and services provided by forests, such as native species that are becoming recognized as being at risk and habitat conditions that support their persistence. As adaptive management has occurred with time, some contemporary BMPs may more broadly address the maintenance or restoration of the integrity of complex forest–aquatic ecosystems and their multidimensional services. Some of these more holistic approaches may be considered beyond BMPs. Additionally, aquatic–riparian ecosystems are spatially and temporally dynamic (Reeves et al. 2020), yet formulaic BMP approaches may be implemented across broad spatial scales (e.g., statewide prescriptions based on limited site-specific information), possibly contributing to decreased environmental heterogeneity. The research community has broadly acknowledged the need for flexible and adaptive management approaches that will support an extensive array of ecosystem conditions (Messier et al. 2015; Kaushal et al. 2017; Ledesma et al. 2018; Penaluna et al. 2018; Spies et al. 2018a). Although these approaches are more complex to implement compared to highly prescriptive BMPs, they could advance conservation goals for retaining more comprehensive aquatic-ecosystem values and extend to aquatic-riparian restoration practices. Constructing conservation frameworks that are adaptable and address the range of potential future conditions are particularly relevant given a changing climate and increased societal and political challenges associated with water security (i.e., Messier et al. 2015) and next-generation wood-fiber demands (Lowell et al. 2017). In this chapter, we highlight the intersection of BMPs that have guided past priorities with integrated multidisciplinary geomorphic, hydrologic, and biological perspectives (Castro and Thorne 2019) of joint upland–riparian–aquatic ecosystem management and restoration in forests.

BMP Basics: Integrating Clean Water, People, and At-Risk Species

A hallmark of aquatic BMPs in U.S. forests is the focus on selected priority components that may be adversely affected by forest management activities. Common priority components across landscapes often have specific regulatory backing, where state or federal laws require standards to be met (e.g., U.S. Clean Water Act, U.S. Endangered Species Act). These laws may be applied at small spatial scales, for example by regulating a project or site affected by a proposed management action. The result is an explicit, prescriptive pathway to forestall adverse effects tied to those priority components that are implemented during forest-management projects. In some cases, cumulative effects across broader spatial or ecological scales are evaluated, which can broaden the scope of BMPs and integrate priority components from a narrow site perspective with associated ecological processes or functions at a watershed or landscape scale.

Forestry BMPs were originally designed to protect water quality (following the Clean Water Act of 1972; see Loehle et al. 2014). The emphasis on the provision of clean water was initially justified for human health and welfare. More than 50% of the water supply in the contiguous United States and 65% of the supply in the western United States originates on public and private forests (Brown et al. 2008). In fact, source water from national forests and grasslands alone reaches ~25% of the U.S. population (60 million people) nationwide, with a greater reliance in the U.S. West where ~51% of the mean annual water supply originates on federal forests (Ryan and Glasser 2000; Brown et al. 2008). Hence, protection of water quality comes to the foreground for guidance in forested stream or wetland management, especially control of sedimentation and pollution—elements important for water uses, including agriculture, human consumption, aquatic species, and recreation.

More specifically, forestry BMPs developed to minimize effects of forest management activities on water quality typically have focused on water pollution from nonpoint sources (Loehle et al. 2014), causing elevated water temperatures, stream sedimentation, and chemical contamination, particularly from in situ organic matter nutrient release and applied chemicals such as fertilizers and herbicides. Forest activities that prompt water quality BMP considerations include chemical applications (fertilizers, herbicides, pesticides, or fire retardants), drainage alterations, road maintenance and construction, site preparation for forest regeneration, timber harvest and stand improvement activities, tree planting, prescribed fire, wildfire control actions, and vegetation management for wildlife (e.g., see Chapter 1 in North Carolina Forest Service 2006). Forestry BMPs addressing water quality issues often include implementing prescribed widths of forested riparian buffers (also called riparian-management areas or streamside-management zones) and guidance for constructing and maintaining roads, culverts at stream–road intersections, and skid trails.

Today, provision of clean water also is intimately tied to maintenance of imperiled native aquatic species, and hence, primary goals for some contemporary BMPs include protection of both the biophysical integrity and biodiversity of aquatic ecosystems (Penaluna et al. 2017). This transition from human health goals to broader human values (i.e., ecosystem services, the goods and services people value from natural systems, including species; Blahna et al. 2017; Deal et al. 2017) has been iterative. Clean water goals have been recognized to inherently offer some protections for aquatic species via positive influences on their habitat (Warrington et al. 2017). Further, the increased implementation rate of BMPs over time (Ice et al. 2010) and their continual refinement to increase effectiveness has led to more explicit protections for selected aquatic species, for example by tying water temperature standards to fish-habitat requirements (e.g., Loehle et al. 2014). In the United States, increasing concerns over the past three decades for thermal pollution in freshwater systems and effects on native fishes has led to the development of temperature total maximum daily loads (temperature TMDLs; note, there also are TMDLs for nutrients, bacteria, and chemicals) as regulatory guidance for local basins and standards regulated by states (e.g., Wisconsin Department of Natural Resources 2013; Oregon Department of Environmental Quality 2020) and as part of the implementation of the U.S. Clean Water Act (e.g., EPA 2019, 2020). The U.S. Endangered Species Act also focuses on habitat protections for threatened and endangered (T&E) species, which may include retention or restoration of areas with adequate water quality and specific thermal limits of tolerance for aquatic species persistence. National guidance has been developed for achieving complementary goals for water quality and species' habitat conditions by these two U.S. laws in a coordinated fashion (EPA 2001). In forest management applications, this integrated guidance allows for adaptation of BMPs to simultaneously address multiple regulatory concerns. For example, BMPs focused on meeting a critical water temperature threshold for an at-risk coldwater species at a watershed scale can also address site-level protections that forestall temperature changes defined by state legal authority rules. Such BMP consequences may directly or incidentally benefit broader ecosystem services associated with human sustenance, nature experiences, or retention of the integrity of other ecosystem components, structures, or functions.

While initially developed to protect water quality, riparian buffers also have direct or indirect influences on species' habitat characteristics for species associated with aquatic, riparian, or upland areas in forests. In particular, in addition to vegetation cover, riparian buffers also influence (1) microclimate, (2) instream substrate composition, and (3) down-wood structures. Links to these three components can be found in many contemporary BMPs. First, a primary function of riparian buffers is to provide direct shade to maintain coolwater temperatures for coldwater species of concern (e.g., Pacific salmonids, see Table 7.1 in Reeves et al. 2018). An incidental benefit of overstory shading by riparian buffers includes maintaining cool, moist conditions in streamside riparian zones (Anderson et al. 2007), which positively affect numerous riparian-dependent species (Olson et al. 2007; Olson and Burnett 2013). Oregon's Forest Practice Act now designates wider riparian buffers where Pacific salmon *Oncorhynchus* spp., steelhead *O. mykiss*, or Bull Trout *Salvelinus confluentus* occur than in other fish-bearing streams to address composite temperature concerns and other habitat elements (Oregon Department of Forestry 2019). Second, riparian buffers reduce sediment from entering streams or other water bodies. For example, riparian buffers provide erosion control by retaining tree rooting functions for soil integrity, ultimately reducing fine-sediment deposition that can lead to hypoxic or anoxic conditions in the water column or embed cobble substrates. Interstitial spaces in coarse stream substrates are typically used for successful reproduction of fish, some amphibians, and freshwater mollusks and are critical refugia for several at-risk taxa (e.g., amphibians: Nickerson et al. 2003; mussels: Haag and Williams 2014). Third, down-wood inputs to water bodies provide benefits for multiple species by contributing to structural complexity via pool habitat formation, a more varied streamflow environment, lower mean flow velocity, food provision, and refuge cover (FEMAT 1993; Gregory et al. 2003; North American Atlantic and Gulf coastal plain streams: Benke et al. 1985; Gippel 1995; Warren et al. 2002; Benke and Wallace 2003; Dolloff and Warren 2003). Ecological benefits of riparian buffer protections go beyond species-habitat considerations. Their additional roles in retaining the ecological integrity of physical habitat structures, processes, and functions are covered in more detail below.

Any management approach that seeks to extend beyond BMPs could distinguish between priorities for regulatory benchmarks and additional ecological outcomes, yet although BMP approaches are effective for meeting regulatory goals (Warrington et al. 2017; Jackson et al. 2022), their influence on the broader composition, functions, and processes of forested aquatic–riparian ecosystems may be largely uncertain. Ideally, riparian buffer recommendations for at-risk species, biodiversity, and physical and chemical conditions adapt over time as new scientific knowledge refines our understanding of joint buffer and upland forestry effects on their habitat needs (e.g., Pacific Northwest: water temperature in Oregon, Groom et al. 2011; riparian zone down-wood recruitment, Reeves et al. 2003, 2016b; Burton et al. 2016; Arkansas: species, Guzy et al. 2019). However, with regulatory constraints, adaptive management of forestry-BMP regulatory guidance may lag behind the pace of incremental knowledge accrual. Strategically planned applied-science studies to advance knowledge for policy development are useful, especially when results feed into planned periodic synthesis of new information for regulatory updates (Bormann et al. 2017; Olson and Van Horne 2017; Spies et al. 2018b).

Beyond BMPS: Provision of Broad Ecosystem Services

Moving beyond BMPs can integrate effective BMP strategies with a suite of ecosystem services that forested aquatic ecosystems provide for people. These services are many, like puzzle pieces for a large puzzle; looking at the larger picture can help us understand their role and integration. At large spatial scales, forest ecosystem-management approaches often recognize the interactive elements of upland-forest and aquatic–riparian ecosystem components, processes, and functions (Lindenmayer and Franklin 2002; Olson and Van Horne 2017; Franklin et al. 2018; Spies et al. 2018a). In this light, at watershed, landscape, or regional scales, where forest-ecosystem planning is employed, the inherent variability of the joint aquatic–terrestrial system can be addressed as a mix of known historical natural and anthropogenic disturbances and contexts with a series of recognized place or time signatures (Cissel et al. 1998, 1999; Davis et al. 2017; Olson et al. 2017; Reeves and Spies 2017; Reeves et al. 2018; Spies et al. 2018a). For example, historical wildfire signatures were used by Cissel et al. (1998, 1999) to estimate how fire frequency and intensity varied within each watershed. They proposed that this variability can inform heterogeneous patterns of today's forest-management frequency and intensity by providing an analogous upland disturbance type to which ecosystem processes, functions, or components could be resilient (e.g., at lower elevations, historically more-frequent low-intensity fires were matched to density-management harvests conducted at similarly more-frequent time intervals). In their aquatic assessment, they similarly applied a variety of stream–riparian management strategies across a large watershed, with larger areas of riparian protection along main-stem streams and headwaters where numerous ecological processes, functions, and resources align spatially and more active riparian buffer management at intermediate stream reaches where heterogeneity could be managed. In another example, the 1900–2012 time series of northwest forest maps in Davis et al. (2017) showed the extent of the "ghost of land use past" (i.e., wood production activities; see Harding et al. 1998) across the region. Across a century, they show signatures of forest cover changes from timber forests and wildfires to provide a better reference for the scope and magnitude of forest ecosystem heterogeneity from past human and natural disturbances to inform future regional-scale forest-ecosystem management decisions for uplands and streams. Understanding signatures of past disturbances are pivotal for broad landscape planning and can provide insights to the variability of select subcomponents or values of management concern (e.g., western U.S. instream habitats affected by splash dams: Miller 2010; Steel et al. 2017; eastern U.S. stream species affected by forest harvest practices: Surasinghe and Baldwin 2014).

These sorts of composite assessments of forest ecosystem heterogeneity from diverse past disturbances also have been described as contributing to a multistate portfolio of habitat-and-population conditions, with implications for management of multistate forest ecosystems with greater potential for long-term persistence (for forested aquatic systems: Penaluna et al. 2017, 2018). Penaluna et al. (2017, 2018) emphasized that aquatic ecosystems are not static, hence managing for a mosaic of habitat conditions with disturbances providing renewal and change can aid in producing more stable, resilient ecosystems with a resulting portfolio of diversified population characteristics (e.g., aquatic species life history strategies and patterns, age structures, genetics, and behaviors). Penaluna et al. (2018) state,

> [T]he ecological diversity that contributes to long-term resilience in variable environments is referred to as a 'portfolio effect'.... Increased biocomplexity produces temporally stable systems because of complementary or independent dynamics among species, populations, individuals, or genes that perform similar ecosystem functions.

Further, their analogy of the value of diverse ecological portfolios to diversification of economic portfolios for sound monetary investment strategies can be extended: ecological diversity portfolios considered during forest-management planning also can address resilience in delivery of a host of goods and services gained by people from forests, including recreation opportunities and esthetics of natural places, in addition to commodity production, clean water, and native species (e.g., Blahna et al. 2017). Such eco-sociopolitical forest-management portfolios also could address set-asides for other priorities such as research studies that may be designed to contribute to adaptive management decisions (Bormann et al. 2017) and trade-offs among goods and services, which may vary in place, time, or context, such as land ownership (Deal et al. 2017).

This top-down context of a complex integrated ecosystem to its component parts establishes a distinct paradigm for maintenance or restoration of stream ecological integrity in managed forests. The set of ecosystem services that can emerge as priorities for management considerations from this paradigm can differ markedly from historical stream BMPs in managed forests. Some policies are dictating broader inclusion of such ecosystem services while better integrating with state and federal regulations. For example, development of the forest-ecosystem management provisions of the U.S. federal Northwest Forest Plan (NWFP: FEMAT 1993; USDA and USDI 1994) exemplifies a beyond-BMP approach as it was informed by the U.S. Endangered Species Act (ESA) for hundreds of terrestrial and aquatic species closely associated with late-successional and old-growth forest conditions that were considered at risk for ESA listing, but not yet listed as T&E. Further, a broad set of aquatic-specific criteria and procedures were implemented for the NWFP, including watershed analyses, aquatic conservation strategy objectives, and its specific set of standards and guidelines (Reeves et al. 2018). Also, the U.S. Forest Service's National Core BMPs (U.S. Forest Service 2012) updated BMP policy guidance to maintain and restore the chemical, physical, and biological integrity of the nation's waters in or near national forests and grasslands. The National Core BMPs aim to improve multidimensional eco-sociopolitical integrity, including water quality in TMDL-restoration plans for impaired waters, relationships with the U.S. Environmental Protection Agency and state nonpoint source programs and their emerging guidance, National Environmental Policy Act compliance with other federal laws, BMP implementation consistency among administrative units, trust with partners and stakeholders, BMP monitoring, and adaptive management processes (U.S. Forest Service 2012).

As forest ecosystem management approaches are shifting from a focus on static conditions to managing for a heterogeneous set of ecological processes, functions, and components, three broad considerations emerge at the top of priority lists for beyond-BMP considerations. These considerations help identify the specific puzzle pieces on which management actions may focus and the piece-specific, place- and time-specific contexts of high relevance. They include (1) additional attributes that warrant specific management, beyond traditional BMPs to address water quality and imperiled species habitat conditions; (2) a portfolio of dynamic abiotic and biotic conditions within forested aquatic–riparian ecosystems, rather than a one-size-fit all approach; and (3) an integrated approach across multiple conditions, components, and scales (spatial and temporal) for ecosystem integrity across the broader landscape. Spanning all three aspects relative to other aquatic–riparian components, there may be aspects of system structure or composition, processes, or functions that can be considered to retain ecological integrity. These can be local or regional attributes or priorities and might be addressed at the scale of single projects or during watershed- or landscape-scale planning. Both a broader suite of aquatic–riparian dependent species and ecological processes that occur across the gradient from streams to uplands can be considered for management consideration. Some attributes may come to the foreground when forest management is considered simultaneously with other known or potential disturbances or threats (e.g., disease, fuels management to forestall wildfires, and climate change). Analyses of these additional elements may support extension of protections beyond those designed to comply with strict legal thresholds. And, novel site-management or restoration approaches may emerge in the context of each project area or larger landscape planning unit. Overall, the beyond-BMP concept can address legal compliance and an interconnected aquatic–riparian–upland forest ecosystem, including the complexity of its composition and its ecological functions and processes. These beyond-BMP considerations are developed further below by focusing on retention and restoration of abiotic and biotic resources and their integration.

Abiotic Resources

By implementing largely uniform-width, no-entry riparian buffers across broad spatial scales, abiotic resources of managed stream–riparian ecosystems may become increasingly homogenous longitudinally along stream reaches and spatially across watersheds. An exception may occur when buffers are of sufficient width and length to accommodate a full range of natural processes and functions, which may confer considerable variability over time. Abiotic resources naturally exhibit longitudinal, lateral, and vertical variability within the stream network, including patterns of hyporheic hydrologic connectivity, temperature fluctuation, light availability, geomorphology, and biogeochemistry (e.g., Gregory et al. 1991; Montgomery 1999; Naiman et al. 2000). Such variability provides structural and thermal refugia and enhances diversity of basal food resources that fuel stream food webs (Woodward et al. 2010a, 2010b; Bellmore et al. 2015; Nelson et al. 2020). Below are beyond-BMP considerations for diverse abiotic resources: light availability, water temperature, stream flow, nutrients, and down wood.

Light availability.—Streamside forest vegetation structure and associated canopy gaps affect light availability to streams (e.g., Warren et al. 2013, 2016; Bechtold et al. 2017). Currently, many smaller stream systems are experiencing uniformly high levels of riparian forest canopy closure and reduced light availability, largely owing to the reliance on passive restoration of previously harvested riparian forests in subsequent streamside buffer zones (Kaylor and Warren 2017). In some ecosystems, increased shading of smaller streams leads to reduced primary productivity and fish density through bottom-up food web pathways (Kiffney et al. 2014; Kaylor and Warren 2017; Heaston et al. 2018). In coniferous forests of western Oregon, mid-successional riparian stands experienced enhanced shading from 30 to 100 years postharvest (Kaylor and Warren 2017). Yet with enough time, this is expected to change due to tree growth, mortality, floods, fire, and other disturbances. However, if this age range spans landscapes due to past time periods of synchronous harvest, it could signal locations to manage for riparian forest canopy heterogeneity for biocomplexity benefits (Box 1; Figure 1). For example, prey biomass and Coho Salmon *O. kisutch* growth more than doubled in reaches with greater sunlight in the U.S. West (Kiffney et al. 2014), and wetland amphibian diversity was enhanced by opening canopies in the eastern United States (Werner et al. 2007; Skelly et al. 2014)

Beyond-BMP measures may create spatial heterogeneity of additional abiotic attributes such as light availability, as site-specific to landscape-level opportunities are identified. For example, alternative stream buffer configurations such as a variable retention buffer (Figure 1) could provide narrower buffers along the stream reach to address concerns for light availability in exchange for protections in other areas for attributes warranting greater protection, such as groundwater discharge areas. This approach can address multiple resources; for example, it may address biodiversity of vascular plants, bryophytes, aquatic invertebrates, periphyton, and fish; hydrological integrity; water quality; and water temperature (Burton et al. 2013; Kuglerová et al. 2014). Alternatively, purposely manipulating a riparian zone to emulate natural disturbance has been proposed as a tool to support natural processes, enhance heterogeneity within and among watersheds, and promote long-term sustainability of the ecosystem (Kreutzweiser et al. 2012). Conceptually, alternative riparian buffer management options such as creation of streamside riparian canopy gaps or sections of a one-sided buffer (e.g., variation of a zipper buffer, Figure 1) potentially have the capacity to enhance light availability on the stream channel and promote stream productivity, including bottom-up food web responses. Ongoing research is investigating these composite effects (e.g., effects on light, stream temperature, and food webs of 50% canopy cover reduction by thinning along a 100–200-m reach with a before–after–control–impact design in northern California: Roon et al. 2017; Roon and Dunham 2019; also M. Kluber and M. House, Green Diamond Resource Co., unpublished data; D. Roon, Oregon State University, unpublished data; Roon and J. Dunham, U.S. Geological Survey, unpublished data). Any alternative buffer configurations also should consider a broad range of site-specific ecological responses to ensure minimal adverse effects of traditional-BMP criteria (e.g., on target abiotic conditions such as chemical contamination, sedimentation, water temperature, and biotic factors such as imperiled species). Beyond-BMP approaches may target multiple objectives, specifically addressing BMP limitations, and more comprehensively consider spatial and temporal scales, including a more comprehensive understanding of how each abiotic factor interacts with one another, biota, and natural and anthropogenic disturbance regimes.

Water temperature.—Light availability (i.e., solar radiation) is associated with stream temperatures, with temperature variation stemming from stream shading by both riparian–upland forest canopies and topography (e.g., Reeves et al. 2018). As a component of water quality, water temperatures are often considered a key metric of aquatic ecosystem health, with stream temperature TMDLs linked to thermal tolerances of

Box 1. Beyond-Best Management Practices Forested-Stream Management

Beyond-BMP approaches include actions tiered to site or watershed conditions for ecological protection or restoration of elements that are not explicit for regulatory compliance. Beyond-BMP approaches may (1) alter riparian buffer widths with watershed or stream location based on site characteristics such as soil class or a species of interest, (2) enhance spatial heterogeneity along stream reaches, or (3) be tiered to restoration goals. A foundational element is application of riparian buffers to address multiple priorities by designation of alternative buffer widths (Figure 1A) or with zones of management within buffers (Figure 1B). Managed buffers may have streamside interior zones with no disturbance to retain tree rooting strength, overhead shading of streams, and erosion control and outer zones with management for stream or riparian ecosystem restoration goals or light-touch commodity production (Figure 1B). Alternative approaches seek to enhance heterogeneity of instream conditions along the entire length of the stream reach to better mimic natural conditions with zipper designs (Figure 1C), localized canopy gaps, or variable retention buffers (Figure 1D) that offer greater protections in locations of greater ecological significance in exchange for narrower buffers elsewhere along the reach. Low-impact zipper designs (Figure 1C) might include occasional-to-regular patterns of streamside tree management on each side of selected stream reaches. These approaches can address other riparian-forest priorities while providing some water-quality and fish-habitat protections.

Special places within watersheds may have beyond-BMP actions extending riparian buffer frameworks (Figure 2). In addition to implementation of riparian buffers of different widths to buffer spatially dynamic watershed components (e.g., water temperature, water chemistry, and riparian habitats used by integrated biotic communities; Figure 2A, 2B), headwaters may be protected for unstable slopes, habitat for unique headwater biota, and provision of linkage areas between watersheds (Figure 2C–F). Tributary junction protections (Figure 2D) can address nodes of habitat and biotic complexity, in addition to locations of coldwater inputs. Alternative forest management approaches such as dispersed and clumped green tree retention may applied to outer zones of buffers (Figure 1) or in uplands for upland forest habitat protections in linkage areas for species dispersal (Figure 2E–G).

In a western Washington watershed with planned forest management (Figure 3), by overlaying the stream network, priority overland connections from streams and their riparian buffers were identified for possible managed-corridor habitats to aid dispersal of low-mobility species (e.g., amphibians). Conceptually, over-ridge connections to unique large watersheds were considered first by identifying where three large watersheds convene to economize landscape-scale connectivity management (triads, blue triangles, Figure 3; Olson and Burnett 2013). Second, connections

Box 1 continues

Box 1. Continued

across neighboring subwatersheds were considered (blue circles, Figure 3), followed by connections between adjacent subdrainages (yellow circles, Figure 3). This landscape contains remnant patches of late-successional forest identified as potential habitat for northern spotted owls *Strix occidentalis*, an umbrella species of concern in the region (brown hexagons, Figure 3). Linking riparian buffers to these patches connects additional climate microrefugia. Inspection of geographic imagery or local knowledge may expose ecological values of other over-ridge connections (yellow double arrows, Figure 3); here, lower-elevation ridges between adjoining watersheds may facilitate ground movements as least-resistance links relative to how species may perceive the landscape (i.e., lower elevation passes over ridgetops).

aquatic species. In aquatic ecosystems with coldwater-adapted species, thermal maximums are often regulated via specified riparian buffer widths (e.g., Groom et al. 2011), but incorporating new knowledge about spatial dynamics of stream thermal conditions could contribute to considerations beyond traditional BMP approaches (e.g., in rivers: Steel et al. 2017; in small northwest streams: Leach et al. 2017; Reiter et al. 2020). For example, a recent large-scale evaluation of longitudinal variation in riverine temperature regimes challenged the traditional paradigm that temperature increases with downstream distance and then flattens (Fullerton et al. 2015). Instead, stream temperature exhibited multiple patterns and revealed that diverse thermal regimes may provide refugia for aquatic organisms with thermal limits of tolerance (Fullerton et al. 2015), potentially providing a source of aquatic ecosystem resilience in a changing climate. In particular, stream areas with groundwater inputs are affiliated with more stable or cooler water temperatures than in surrounding locations (Leach et al. 2017), providing thermal refugia during extreme seasons and spawning habitat for fish and other species that require cool temperatures (Baxter and Hauer 2000; Kuglerová et al. 2014). Groundwater inputs also may be less sensitive to temperature variability and climate warming (Luce et al. 2014).

As water temperature in forested stream ecosystems may relate directly to native biota, there are growing concerns about how thermal conditions will interact with forest management and climate change projections (e.g., Reeves et al. 2016a, 2018). Hydromapping can be a useful tool to remotely identify groundwater discharge areas along a stream reach and incorporate these dynamics into temperature modeling efforts and riparian management strategies (Laudon et al. 2016). Mapping shading based on topography and tree canopies (height, live crown) along a stream reach can further aid in determining where placement of riparian vegetation will maximize shade on the stream surface and thus limit temperature exceedances (e.g., Reeves et al. 2016a, 2018; also, see TerrainWorks: http://terrainworks.com). Topographic shade mapping also would help with effective placement of canopy gaps for patch augmentation of light.

Streamflow.—Considering factors affecting streamflow conditions is part of con-

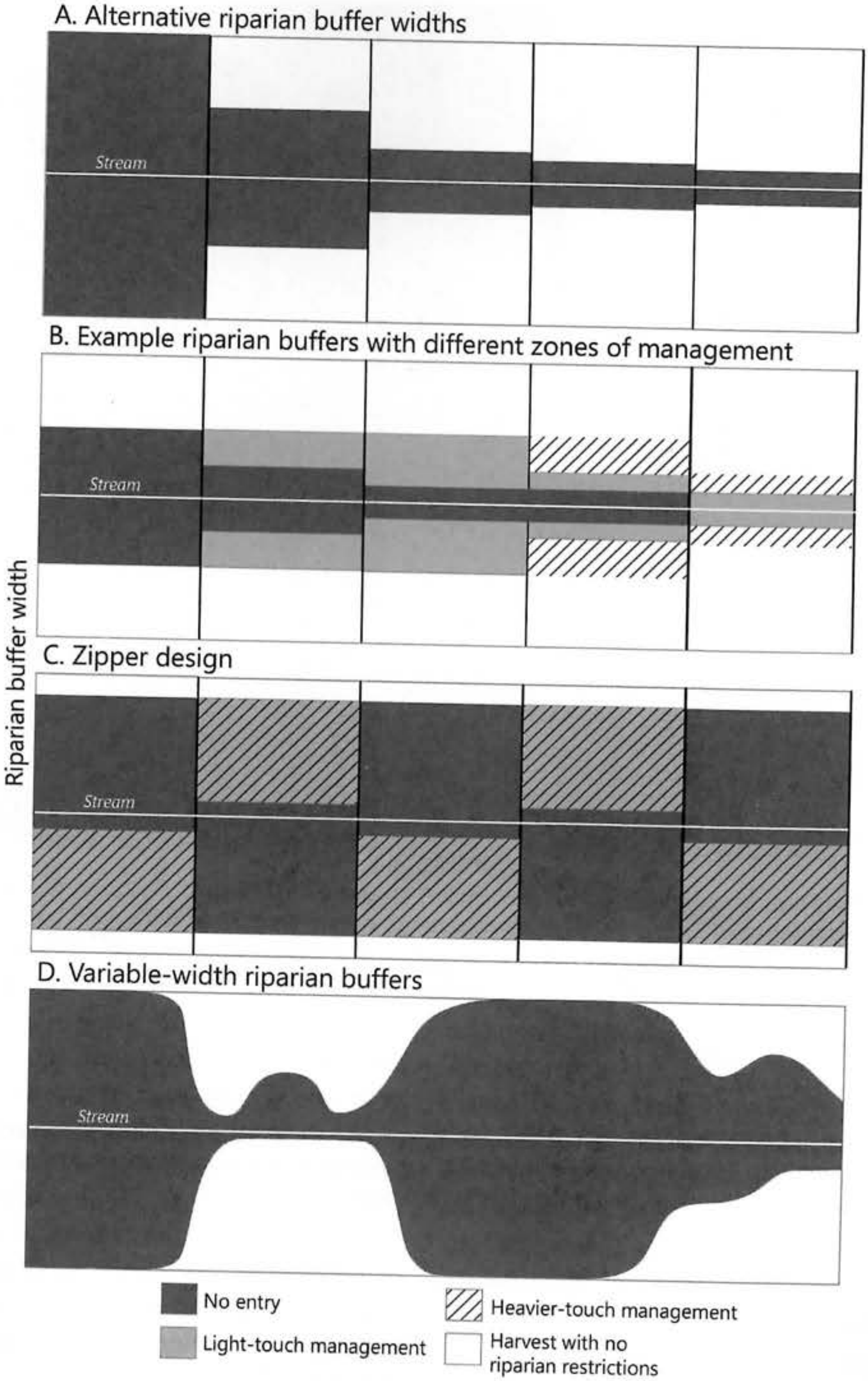

Figure 1. Beyond-BMP riparian buffer designs to address local to watershed scale goods and services to protect or restore aquatic–riparian ecological conditions, functions, and processes and to promote heterogeneity across watershed to landscape scales: **(A)** Different widths of riparian buffers, **(B)** zones of management within buffers, **(C)** light- or heavy-touch management areas on opposite sides of forested streams, and **(D)** variable-width riparian buffers to tier protection or restoration to site conditions. Further explanation in Box 1.

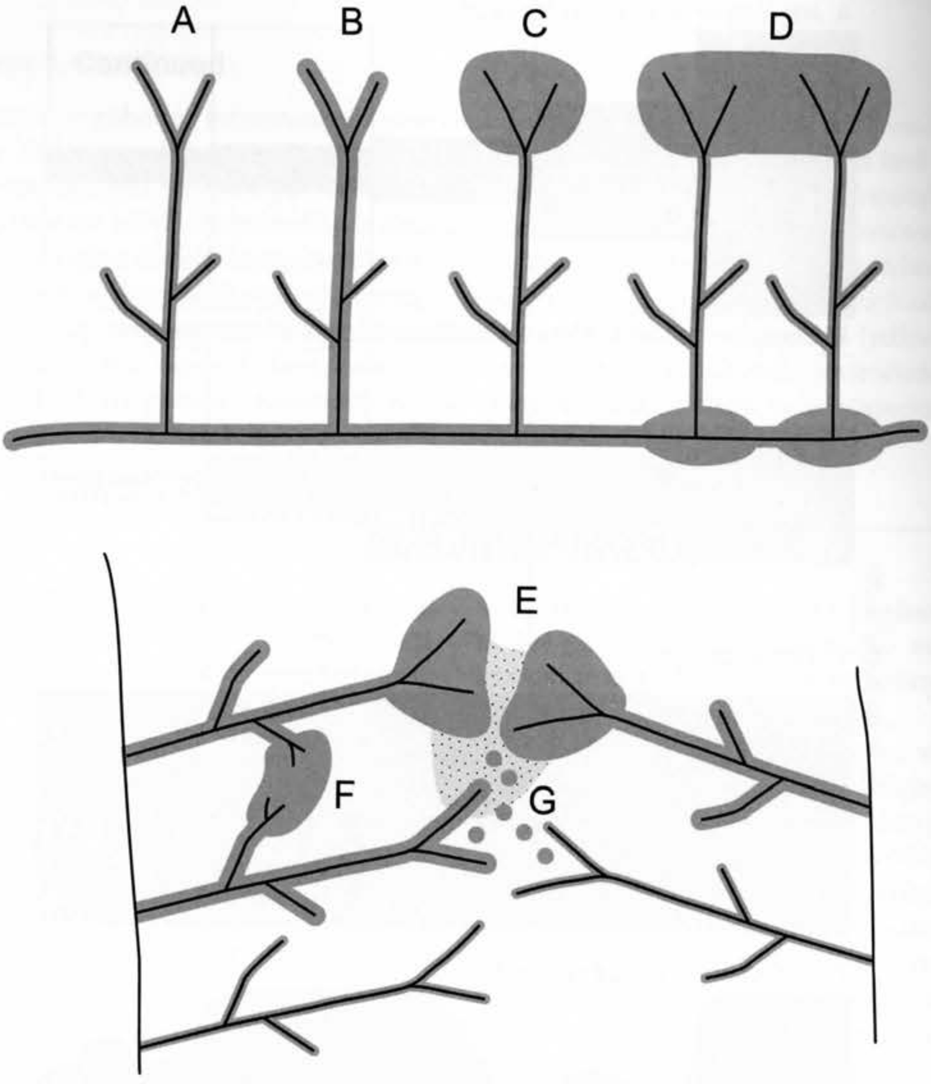

Figure 2. Beyond-BMP forested-stream management may address aquatic–riparian ecosystem integrity and mutually dependent geomorphological, hydrological, and biological components, structures, and functions. Box 1 describes **(A–G)**. Adapted from Olson et al. 2007.

temporary forested watershed management. Maintaining streamflow can integrate climate projections with local conditions (e.g., Jefferson et al. 2008; Tague and Grant 2009; Safeeq et al. 2013, 2014; Olson and Burton 2019) and forestry activities (Burt et al. 2015; Kelly et al. 2016). Hydrological extremes are important time periods that may have disproportionate effects on watershed exports of solutes (e.g., sediment, fertilizer, or herbicides) during high-flow events or on available habitat for aquatic biota during low-flow periods (i.e., Gronsdahl et al. 2019). Water delivery is a concern for ecosystem services, including native stream–riparian biota and their seasonal life history patterns reliant on certain conditions such as timing of peak flows, as well as downstream human

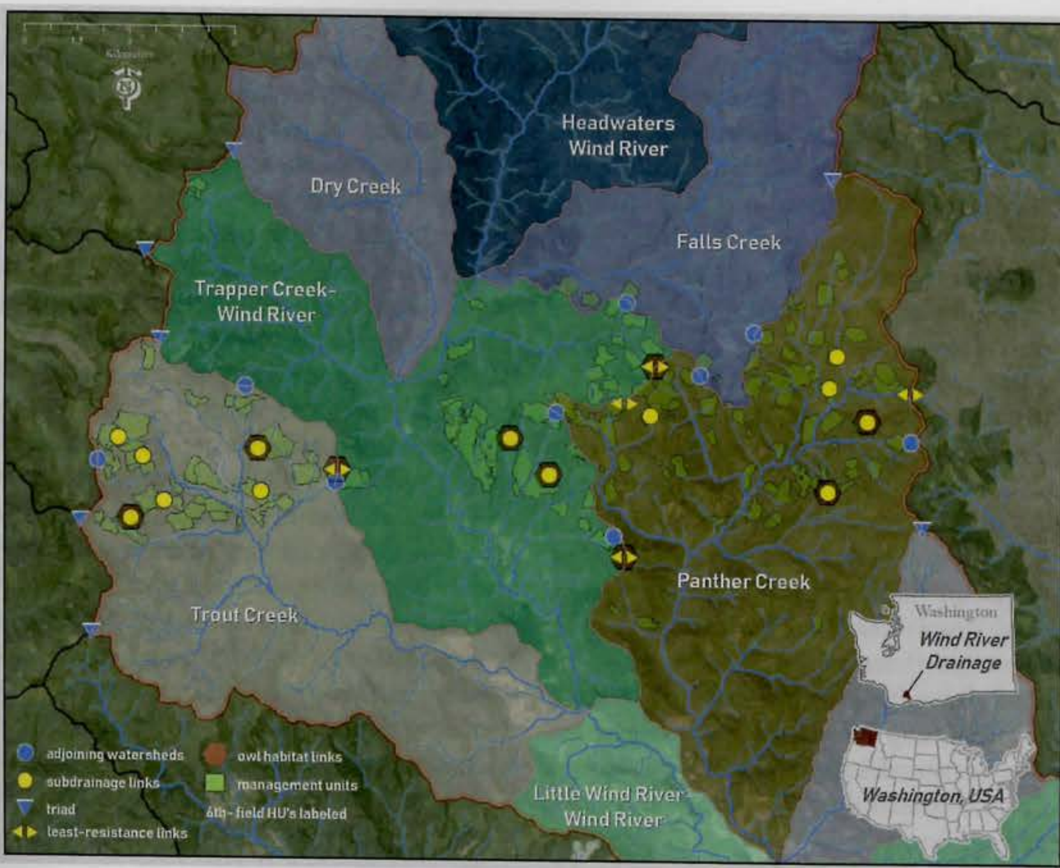

Figure 3. Connectivity considerations for the Gifford Pinchot National Forest management plan of the Middle Wind River watershed, Washington. Extensions of riparian buffers along streams (blue lines; >second order) provide over-ridge linkage opportunities. Box 1 further describes symbols.

communities for consumption, agriculture, and recreation. Precipitation extremes also have been shown to have adverse effects on aquatic-breeding amphibians with complex life histories (e.g., southeastern United States: Walls et al. 2013).

Timber harvest can affect streamflows, for example generally decreasing evapotranspiration and increasing runoff and streamflows for the first few years after harvest, yet patterns may vary with site conditions (Hibbert 1967; Rothacher 1971; Harr 1979; Bosch and Hewlett 1982; Troendle and King 1985; Campbell and Doeg 1989; Keppler and Ziemer 1990; Andréassian 2004). On longer timescales, seasonal low flow may decrease in some catchments (Keppeler and Ziemer 1990; Hicks et al. 1991; Jones and Post 2004; Perry and Jones 2017; Gronsdahl et al. 2019; Segura et al. 2020), including 16 of 25 catchments from the United States and Canada (Coble et al. 2020). In particular, Perry and Jones (2017) found up to 50% less seasonal low streamflow (late summer to early fall) in Pacific Northwest Douglas-fir *Pseudotsuga menziesii* plantations, ages 34–43 years, compared to old-growth forest stands, ages 150–500 years, with Douglas-fir, hemlock *Conium maculatum*, and other trees. They hypothesized that these declines were due to increased evapotranspiration of the younger trees during summer. They caution that the legacy of past forest management may confound the effects of climate change on streamflow, an emerging concern in the region. Similar observations of summer low-flow declines occurring earlier in the summer period (May and June) in British Columbia, Canada also may be related to alterations in the quantity of snowpack and timing of snowmelt following harvest (Gronsdahl et al. 2019). In small headwater basins in western Oregon, drainage area and climate factors showed a stronger relationship to surface streamflow patterns than upland forest harvest (Olson and Burton 2019).

With climate change projections, changes in the timing and type of precipitation (from snow to rain in regions that receive snow) are expected for much of the United States. Reductions in snow quantity and the timing of melt have important implications for the timing of peak flow, peak soil water availability, groundwater recharge, and base flow (Godsey et al. 2014; Creed et al. 2015; Harpold and Molotch 2015). For example, across watersheds in the Sierra Nevada range of California, a 10% decline in peak snow water equivalent corresponded with summer minimum flows that occurred 3–7 d earlier and had 9–22% less flow (Godsey et al. 2014). Streamflow responses are likely to interact with the drainage efficiency of watersheds, such that a dynamic response across geographies and time frames is expected as multiple factors interplay (Safeeq et al. 2013, 2014; Reeves et al. 2018). Kelly et al. (2016) suggested that forest management, including vegetation conversion, be considered as measures to compensate for water-flow responses to climate change, potentially mitigating extreme flow events in North Carolina. However, site-specific context is important in development of options (Kelly et al. 2016). Climate-smart forest management practices may not have a significant effect on precipitation-driven streamflow patterns in some geographies, yet overstory-canopy shade management in tandem with consideration of topographic hill-shading could affect local microclimates, including forest floor temperature and moisture regimes, which may keep water on the upland landscape longer by slowing snowmelt and runoff (Grant et al. 2013). Thus, changes in microclimate may be minimized for riparian-dependent species. With climate-future modeling, future climate niche space of today's native species could be projected, and forest-management planning to retain future species' climate refugia could be developed. For example, with peak flows projected to shift earlier to the winter season in some places of the U.S. Northwest, a downstream shift in optimal habitat for headwater stream associated species may be expected in locations where headwater channel drying occurs (Olson and Burton 2019).

Nutrients.—Eutrophic conditions, characterized by excessive nutrient loading, can lead to harmful algal blooms and hypoxic (low oxygen) environments that threaten aquatic biota and human drinking water supplies. Forestry activities can elevate stream nutrient concentrations by (1) direct application of fertilizer (as nitrogen and phosphorus), and (2) indirect increases in nitrate following removal of overstory biomass due to decreased plant uptake (Mupepele and Dormann 2017). An essential function of riparian buffers is to limit transport of both silviculturally applied and in situ chemicals to surface waters. Riparian buffers have been effective in reducing delivery of silvicultural chemicals (fertilizers, herbicides, or fire retardants) and in situ solutes (e.g., dissolved organic matter and sediment) to surface waters (Binkley et al. 1999; Dosskey et al. 2010; Tatum et al. 2017) by providing physical barriers (overstory vegetation, and organic soil layers) that slow or impede transport during precipitation events, and below-ground roots that promote soil stability, reduce erosion, and take up solutes. However, additional site contexts (i.e., geology, climate, topographic position, species composition, and legacy effects of prior management) are also important to consider relative to riparian forest management and nutrient loading.

In the U.S. Pacific Northwest, where ecosystems are nitrogen (N) limited, riparian overstory composition shifted from conifer-dominated to red alder *Alnus rubra* in many locations, following major forest disturbance that exposed mineral soil (e.g., harvest, burning; Newton and Cole 1994). These shifts in overstory vegetation have important implications for bottom-up food-web responses. Red alder, an N fixer and rapid colonizer after disturbance, contributes elevated N concentrations (as nitrate and dissolved organic N) to surface waters that have been associated with increased productivity of stream periphyton and may fuel stream food webs (Compton et al. 2003; Volk et al. 2003). The species composition of vegetation in the riparian zone also has important implications for the quality of allochthonous carbon (C) inputs, for example with more rapid breakdown of C from red alder leaf litter than Douglas-fir (McArthur and Richardson 2002). Furthermore, streams with more red alder along their riparian zones can export more invertebrate drift and detritus to downstream reaches, potentially contributing to greater fish biomass than in conifer-dominated streams (Wipfli and Musslewhite 2004). Over time, as riparian zones undergo natural succession, late-seral conifers will replace early colonizers in riparian zones and lower stream N concentrations, and less invertebrate drift and detritus are expected. Forest practice regulations in several western states encourage silvicultural conversion of riparian vegetation from red alder to conifer, but in practice, this is difficult. Alternatively, retaining diverse riparian vegetation can offer more diverse energy sources to aquatic biota. Experimental evaluations of alternative approaches to managing deciduous hardwoods such as alder in riparian buffers and corresponding effects on stream–riparian productivity is a current research need, especially for understanding the outcomes of alternative stream–forest restoration practices (e.g., project in development at the Olympic Experimental State Forest, Washington: University of Washington 2020).

Again, context is an important cofactor in extending these notions to other systems. In even-aged loblolly pine *Pinus taeda* landscapes in the Ouachita Mountains of Arkansas, Guzy et al. (2019) reported higher salamander species richness in riparian buffers where deciduous or mixed overstory forest conditions dominated buffers, in comparison to pine overstory. Additionally, interactions with other factors may be important. For example, allochthonous sources of C (leaf litter inputs) have lower concentrations of mercury than autochthonous sources of C (e.g., stream periphyton) and have important implications for bioaccumulation of mercury throughout the stream food web (Willacker et al. 2019). Our knowledge base of the complex interactions of aquatic–riparian site conditions, nutrient cycling, other chemical interactions, and biota is continuing to develop, especially as novel techniques are applied gaining new insights to system dynamics.

Sediment.—A greater understanding of sediment delivery to streams has been garnered by modern approaches to determine source areas, such as sediment fingerprinting and landscape-scale modeling, which can contribute to beyond-BMP guidance. More generally, Lisle et al. (2015) considered the efficacy of a two-tiered approach to identify sediment sources, combining a coarse-filter rapid assessment with a fine-filter in-depth analysis. The coarse-filter assessment focuses on primary contributors to sediment delivery at the location of interest while the fine-filter assessment evaluates sources, pathways of causal factors, and site history. They considered fine-filter analyses similar to cumulative effects analysis or watershed analysis, broadening the scale and scope to evaluate multiple potential contributors of sediment.

Numerous modeling tools have been developed to identify sources of sediment using fine- and/or coarse-filter approaches, for example from failing road-crossing culverts, gully development, and landslide-prone areas. A few examples of sediment models for beyond-BMP forestry applications include the Water Erosion Prediction Project (WEPP; Elliot et al. 1999; WEPP:Road, Elliot 2004), Geomorphic Roads Analysis and Inventory Package (GRAIP: Black et al. 2012; B. Staab, U.S. Forest Service, personal communication), and the erosion/sediment budgeting application developed by TerrainWorks. These tools are useful for evaluating the effectiveness of existing BMPs and identifying locations that may warrant strategic management approaches. For example, these tools have been useful to identify potential unstable slopes for inclusion within riparian reserve boundaries for the federal NWFP (USDA and USDI 1994). Unstable slopes are recognized as primary source areas for sediment and wood delivery to streams. An aim of the federal NWFP has been to improve aquatic ecosystem conditions, and after 20 years of NWFP implementation, 6.7% of the road network had been closed in the NWFP area, likely reducing sedimentation potential (Reeves et al. 2018; road network percent derived from data gathered by the NWFP's Aquatic-Riparian Effectiveness Monitoring Program [AREMP]). In preliminary analyses using the GRAIP-lite analysis (Black et al. 2012; Staab, personal communication) for the 25-year AREMP report, from 1993 to 2019 on federal lands in the NWFP area, estimates suggested a 7.1% reduction in the road network and a 4% reduction in sediment delivery to streams; however, not all road decommissioning projects were related to stream crossings (C. Hirsch, U.S. Forest Service, personal communication). Additionally, 10% of road-crossing culverts have been restored and now allow aquatic organism passage on federal lands of the NWFP (Reeves et al. 2018), a priority for the region articulated by the U.S. Government Accountability Office (USGAO 2001). Furthermore, concerted efforts across ownerships in the United States to disconnect road segments from streams by decommissioning roads (e.g., Sosa-Pérez and MacDonald 2017) and improving stream–road crossings (e.g., install culverts that could support a 50-year event rather than a 5–10-year event; Sugden 2018) has drastically reduced road-related sediment delivery (McBroom et al. 2008; Turton et al. 2009; NCASI 2012; Wear et al. 2013). These crossings also are much more resilient to flood damage (Gillespie et al. 2014). Upgrades to 28,000 km of road network in Idaho and Montana, including legacy roads on private ownership and jointly managed roads, led to a 46% reduction in sediment delivery to streams over a 10–15-year period and limited road-sediment delivery to within 5% of background erosion rates (Sugden 2018). Management for restoration is part of stream–riparian forest management priorities for this landscape and is often a beyond-BMP concept.

Down wood.—Large down-wood recruitment to forested streams has become a dominant priority over the past three decades due to an improved understanding of its importance for habitat structure, nutrient provision, and instream channel morphology (i.e., pool development and substrate distribution; Sedell and Swanson 1984; Bisson et al. 1987). Down-wood management is a beyond-BMP concept as it is not directly tied to water quality yet can be critical for aquatic ecosystem functions inclusive of at-risk species' habitats. In addition to providing physical habitat structure that can provide refuge for biota, down wood can alter stream morphology, hydraulics, sedimentation, and mineral and organic particles. Wood volume and distribution are related to pool frequency and size, water residence time, and flow paths via altered channel morphology and increased hyporheic flow (Naiman et al. 2002).

Scientific advances have led to a better understanding of the mechanisms and sources that contribute down-wood delivery to stream channels. In unconstrained stream reaches and floodplains of larger rivers, down wood has a key role in channel migration (Brummer et al. 2006; Hall et al. 2007; P. L. Olson et al. 2014). In a small stream–riparian system of the U.S. Intermountain West, Bragg (2000) modeled large down-wood recruitment from several disturbances (spruce beetle *Dendroctonus rufipennis* outbreak, fire, and clear-cut) and found that instream wood loads varied considerably in volume and with time. This variability was contingent on disturbance type, and in particular, a steady-state system of wood loading did not result from catastrophic disturbance events. They considered a new paradigm of natural disturbances as a necessary contributor to healthy ecosystems and suggested imitation of forest disturbance along streams depauperate in large down wood. Down-wood enhancement to depauperate streams recently has gained further recognition as a stream restoration measure (e.g., tree tipping: Benda et al. 2016; Reeves et al. 2016b), and riparian forest restoration to grow large trees for future down wood in streams has become a management consideration (e.g., Ruzicka et al. 2014).

Sources of instream down wood include streambank, riparian zone, and floodplain trees, as well as upland forest sources. Wood delivery to streams is related to tree mortality occurring with stand development, streambank erosion undercutting roots, windthrow and ice events, flood or fire, and stream-channel migration inundating trees (e.g., Naiman et al. 2002). Further, Pacific Northwest headwater basins are a key source of episodic pulses of down-wood delivery to downstream waters, facilitated by debris flows (May and Gresswell 2003, 2004; Reeves et al. 2003). Naiman et al. (2002) estimated that from 10% to 50% of wood in fish-bearing streams of the Oregon Coast Range were generated by landslides and debris torrents in low-order streams. This headwater wood could be managed under a more natural disturbance cycle with enhanced headwater riparian buffers that also address headwater landslide potential, as developed for the federal NWFP (FEMAT 1993). Additionally, in managed second-growth stands in northwest headwater basins, legacy large wood remaining from prior old-growth forests is generally of much larger diameter than newly recruited down wood from 60–80-year second-growth stands, which generally originates within 15 m of streams (Burton et al. 2016). Historically, riparian-zone tree falls are chronic sources of wood delivery to streams, with live-tree sources from one to two site-potential tree height distances upland from streambanks (FEMAT 1993), whereas wood from landslides are pulsed sources, and both may be important to manage.

As for other stream habitat components, models have helped shape our understanding of wood recruitment relative to forest management. Welty et al. (2002) and Meleason et al. (2003) assessed Pacific Northwest forests for down-wood delivery from riparian zones with forest management. The riparian aquatic interaction simulator (RAIS) development by Welty et al. (2002) forecasted wood-related aquatic functions, including down-wood abundance and stream shading over a range of forest and stream conditions for up to 300 years. They found that RAIS could identify long-term implications of past management on ecosystem function and could be useful in guiding future forest management decisions. Meleason et al. (2003) examined three management scenarios using the STREAMWOOD model. They found that forest age and riparian buffer width were the important factors in down-wood recruitment: minimal stream wood accumulated without a riparian buffer and forest clear-cutting. With riparian buffers ranging from 6 to 75 m wide, significant wood recruitment required 240–500 years of passive restoration; the 6-m buffer had 32% of the volume of the 75-m buffer. Minimal stream down-wood recruitment was found from stands upslope of buffers that were at least 10 m wide. Benda et al. (2016) modeled wood additions to the streams during harvest by intentional directional felling, with multiple entries to increase stream wood levels. Reeves et al. (2016b) synthesized the need for additional down wood for aquatic habitat complexity in streams in managed forests and applied the Benda et al. (2016) notion for managed tree tipping from riparian buffers as an approach that would also provide benefits for riparian forest restoration by decreasing live-tree densities in heavily stocked second-growth stands.

A consideration with down-wood models is the role of unanticipated disturbance such as windthrow to down-wood recruitment, especially as forest management can create edges prone to high-wind disturbances. In particular, green trees left in stands such as riparian buffers adjacent to clear-cuts could result in unanticipated blowdown, as was the case in the Riparian Ecosystem Management Study of western Washington (Bisson et al. 2013). For research on beyond-BMP riparian buffers at landscape scales, increasing the initial number of study sites and replicates could help with unanticipated disturbance factors, natural or anthropogenic, to enable analyses for initial aims despite surprises. Managing for future down wood in disturbance-prone landscapes includes retaining standing trees for later recruitment of larger-sized older trees, if needed, after windthrow, which may occur postharvest (Cissel et al. 2006). In British Columbia, Beese et al. (2019) described considerations for windthrow in a variable retention upland forest harvest regime. They found benefits of anchoring upland retention trees on required riparian buffers, hence reducing overall edge areas, which also may have helped confer life-boating functions for local species of interest, such as mature-forest-associated carabid beetles and gastropods. Additionally, the federal NWFP included unstable slopes as riparian reserves to recruit trees for future pulses of down wood associated with debris flow (USDA and USDI 1994).

Biotic Resources

Although biotic resources were not primary drivers of the initially implemented forestry BMPs, both regulatory BMPs and beyond-BMP considerations for abiotic factors have considerable effects on species' habitat conditions, benefiting biota (Warrington et al. 2017). With increasing concern for native, unique, and at-risk species, beyond-BMP concepts specific to biota are gaining U.S. national and international importance. Specifically, in the United States, concerns are elevated as some aquatic-associated species could trend towards listing as formal federal T&E species under the ESA, or their altered occurrences or abundances could affect associated ecological functions and processes (see below) if BMPs for abiotic factors were not sufficient protections. The identification of these species of concern and their habitat requirements and the forest management measures for the protection or restoration of their populations (or required habitat elements) are at the heart of many beyond-BMP approaches. Furthermore, these considerations can span species- to community-specific biological scales, as well as site- or project-specific to forest-ecosystem-based management spatial scales.

Sensitive species.—Sensitive species with obligate aquatic associations are often the primary concerns for expanded BMP measures, especially those with T&E status. In freshwater systems, these taxa include crayfish for which 32% of all species are threatened with extinction (Richman et al. 2015), freshwater mussels for which 65% of North American species are threatened (Haag and Williams 2014), and amphibians for which 40% are threatened overall (IUCN 2019), with 65% of all amphibians being forest-associated (Olson and Burton 2014), with a subset of those relying on forested aquatic habitats susceptible to adverse effects of streambed habitat alteration, such as sedimentation (e.g., eastern hellbenders *Cryptobranchus alleganiensis alleganiensis*; USFWS 2018).

Imperiled species that are also socioeconomically important species may rise to the top of beyond-BMP considerations. For example, maintenance of productive game fish populations is a priority in most U.S. states. In many states, such as Florida, Georgia, Kentucky, North Carolina, South Carolina, Texas, Virginia, and Minnesota, BMPs designate wider buffers for trout streams (NCASI 2009). In the Pacific states, native salmonids are a driver of streamside buffer widths in forests due to their combined concerns relative to their socioeconomic importance as food, being the foundation of both fisheries and recreation industries, and their cultural significance for native tribes and the general public, as well as due to declining populations. For example, in 1993, there was one T&E-listed salmonid in the greater northwest, the Sacramento winter Chinook Salmon *Oncorhynchus tshawytscha*, yet an additional 27 populations of Pacific salmon and Bull Trout have been listed under the ESA since (Reeves et al. 2018). A multipronged strategy of watershed protections has been designed across several states and land-ownership authorities, with reserved lands and other set-asides; a foundational element of these in forest landscapes managed for timber commodities are riparian-forest buffers. Riparian buffers are gauged to maintain key habitat requirements such as cool water temperatures by direct streamside riparian-tree shading, retention of streamside down-wood recruitment to provide instream structural heterogeneity (e.g., slow- and fast-water areas: pools, riffles), and reduced streamside erosion, which embeds substrates used for adult oviposition or as a refuge by juveniles. Despite the importance of common habitat elements across lands, streamside riparian buffer protections for salmonids can differ as other socioeconomic and ecological factors are weighed (e.g., Olson et al. 2007).

Spatial considerations of species habitat.—Other species ecology factors that come into play include an expanded view of their habitat requirements in both space and time. In Pacific salmonids, fish-bearing streams span entire stream networks from lower to upper portions of forested watersheds. Forest landscape characteristics along their occupied stream corridors have been tied to salmon-rearing habitat potential (Burnett et al. 2007). The high-intrinsic-potential stream reaches for salmon-rearing habitat is related to streamflow, valley constraint, and stream gradient of a watershed; hence simply, all streams or reaches in a watershed do not have comparable habitat conditions or the intrinsic potential to develop them. For example, stream reaches with high intrinsic potential to support Coho Salmon in coastal Oregon stream reaches are primarily found on private agricultural and forestland ownerships rather than federal land (Reeves et al. 2016b; Boisjolie et al. 2019). Furthermore, land-use legacies such as splash dams continue to influence Coho Salmon distributions across ownerships in this region (Miller 2010; Steel et al. 2017). Beyond-BMP application of riparian buffers could recognize the different jurisdictional contributions of stream reaches to salmon-rearing habitats throughout the river network and proactively protect and restore riparian-zones across forest ownerships in conjunction with other land uses (Boisjolie et al. 2019). In addition, the non-fish-bearing portions of watersheds in the upper headwaters provide important downstream subsidies for salmon. Headwaters deliver water, sediment, wood, and food to downstream salmonid-occupied areas, and headwaters are important for nutrient cycling, a key ecological process for downstream fish production (review in Reeves et al. 2016b). The recognition of the importance of smaller non-fish-bearing headwater streams for downstream fish has reinforced development of policies for headwater buffer guidance, often a beyond-BMP concept. In addition, Colvin et al. (2019) enumerated several additional ecological functions of headwaters in other geographic contexts, including provision of significant habitat for endemic and threatened fish.

Spatially explicit ecological functions and processes that are important for species are diverse and adds a new dimension for beyond-BMP considerations. As species concerns mount, it may become daunting to overlay multiple contexts for entire communities. To simplify, the web of interactions can be placed conceptually within an ecosystem services framework that categorizes final and intermediate goods and services as valued by people. Northwestern salmon might be considered final ecosystem services to denote them as dominant goods and services valued by people. Other species or processes could be considered intermediate ecosystem services if they are an integral part of the ecosystem that delivers the final services (Blahna et al. 2017); for example, a salmonid prey species would directly contribute energy to salmon, and hence, it would be an intermediate ecosystem service. Food webs are complex networks of direct and indirect interactions, often involving an assemblage of organisms across trophic levels and distinct ecosystems, which also can be dynamic processes affected by management activities (Naiman et al. 2012; Bellmore et al. 2017; see also Hartman and Kaller 2020, this volume). Thus, aquatic species may connect to terrestrial species via food webs, and vice versa, as there may be reciprocal subsidies (Bastow et al. 2002; Baxter et al. 2005) of energy via prey resources that disperse across terrestrial and aquatic boundaries, for example of headwater- or terrestrial-ecosystem prey fueling aquatic predators in larger, downstream perennial stream networks (Wipfli and Gregovich 2002; Wipfli and Musslewhite 2004; Danehy et al. 2011).

Similarly, species with complex life histories may transfer energy from aquatic to terrestrial ecosystems if they require aquatic habitats for breeding but emerge and disperse to terrestrial systems upon their development (e.g., Pacific Northwest: aquatic invertebrates, Progar and Moldenke 2002, 2009; aquatic-breeding amphibians, Regester et al. 2006). In some aquatic systems, extremely high productivity of aquatic-breeding organisms transfer remarkable energetic subsidies to forested uplands; for example, annual amphibian emergence from a single 10-ha wetland in South Carolina transferred more than 38,000 individuals per wetland hectare into uplands, corresponding to 159 $kg \cdot ha^{-1} \cdot year^{-1}$ (Gibbons et al. 2006). Also, trophic interactions between biphasic, aquatic-terrestrial organisms such as amphibians and many aquatic macroinvertebrates can increase detritivore abundances in either terrestrial or aquatic systems (Regester et al. 2006). Additionally, energy subsidies can be transferred across marine–freshwater–terrestrial ecosystem boundaries as anadromous Pacific salmon transport marine-derived nutrients to spawning streams, where terrestrial species use energy subsidies from carcasses and trophic networks transmit them across riparian forests. In Southeast Alaska, Ben-David et al. (1998) found support for marine-derived nutrients in some riparian plants to 1,000 m away from streams, with levels decreasing away from streams; they also reported this pattern for small mammals that rely on terrestrial vegetation or insects for food. They considered flooding to be an important mechanism for transfer of carcasses to riparian zones. Beyond predator–prey dynamics, there can be cascading effects of trophic networks on other ecosystem services, such as through C sequestration if predators rely upon invertebrate prey species that devour leaf litter, hence forestalling release of leaf-litter C; this is an ecological function that is supported for some amphibians (Best and Welsh 2014; Semlitsch et al. 2014). Hence, both direct and indirect energetic and ecosystem links integrate aquatic and upland forest domains, extending the ecological value of riparian buffers that bridge protection of forested streams and their neighboring riparian zones.

With this broader ecosystem-services conceptual framework in mind, as scientists and managers have focused their lens on nonfish-bearing streams in headwaters and delivery of subsidies to downstream fish-bearing streams, a host of additional biotic and abiotic concerns have arisen. Biologically, headwaters have different species assemblages, and in some regions, headwater vertebrates are dominated by amphibians (Sheridan and Olson 2003) and a different community of macroinvertebrates (e.g., emergence dominated by Diptera: Progar and Moldenke 2009). In the Pacific Northwest, the headwater amphibian community includes stream-breeding species, pond-breeding species, streambank associates, down-wood associates, and rock-substrate associates—all of which are unique to the region (e.g., coastal tailed frogs *Ascaphus truei*, giant salamanders *Dicamptodon* spp.) and some of which have state-sensitive status or are under consideration for T&E listing (e.g., torrent salamanders *Rhyacotriton* spp., Reeves et al. 2018). Due to the complex life history of many aquatic-breeding amphibians and macroinvertebrates that transform to terrestrial forms, their ecological functions include delivery of aquatic nutrient (energy) subsidies into the upslope forest and reciprocal delivery of terrestrial subsidies back to the water when adults return to streams during breeding seasons. As prey in aquatic and upland settings, both amphibians and aquatic-breeding arthropods stoke the engines of food webs and nutrient cycles (intermediate ecosystem services) across this trans-riparian gradient from water to upland forests. Riparian-buffer management to retain this species diversity and their associated ecosystem functions is a beyond-BMP concern for lands where maintenance of broad forest natural resources is a priority and is linked to downstream delivery of socioeconomically important fish.

For these headwater-associated communities, and especially for species with complex life cycles, habitat is more than aquatic breeding sites. Habitat includes riparian and upland forests for (1) foraging sites, (2) summer refugia from adverse conditions (e.g., amphibians require cool, moist conditions), (3) overwintering refugia from adverse conditions (e.g., from freezing temperatures), and (4) dispersal habitat enabling connectivity among headwater populations, such as over-ridge forest corridors to enable organisms with low mobility to trek to the headwaters of adjacent watersheds. A linear network of streamside riparian buffers and upland extensions of them, or extensions of upland forest structures such as down wood or leave-tree patches, are conceptually beneficial for a host of forest taxa for their entire set of life history functions, including dispersal for population connectivity (Olson and Burnett 2009, 2013; Olson and Kluber 2014). In particular, more than 100 northwestern species associated with late-successional forest conditions (bryophytes, fungi, lichens, vascular plants, mollusks, amphibians, fish, birds, and mammals) were estimated to benefit by the streamside riparian buffers of the federal NWFP (Olson and Burnett 2013), and many would likewise benefit by overland extensions from them. For example, the red tree vole *Arborimus longicaudus* is largely arboreal, with dispersal facilitated by intertwined tree branches of continuous forest canopies. It has populations with status concerns in western Oregon, and although it is not a riparian-obligate species, riparian forests in streamside buffer strips with upland extensions may provide incidental benefits for this terrestrial mammal (Huff 2016).

A wealth of studies is accruing support for the role of riparian buffer protections for forest resources and terrestrial or semiaquatic species (other than fish). For example, buffers ranging from ~30 to 70 m wide retained diverse fauna across studies in the southeastern and northwestern United States. Maximum herpetofaunal richness of 30 species was attained with 51-m buffers in the Ouachita Mountains, Arkansas (reptile richness increased in buffers to ~35 m wide, amphibian richness maximized with a 55-m buffer: Guzy et al. 2019). Ninety-five percent of the amphibian assemblage was retained with a 27-m buffer along Appalachian streams of North Carolina (one species needed 42.5 m: Crawford and Semlitsch 2007). In the northwestern United States, most birds utilizing riparian vegetation for foraging or nesting were retained by a 30-m buffer (>45 m was needed for the black-throated gray warbler *Septophaga nigrescens*: Pearson and Manuwal 2001). Similarly, invertebrates were retained in 30-m buffers in western Oregon (Rykken et al. 2007). In Australia, 30-m buffers protected frog populations (Lemckert and Brassil 2000). Integrating abiotic components, Young (2000) reported that buffers 70–90 m wide retained the full complement of riparian–stream linkages, including inputs of streamside down wood and litter, bank stability, slope stability, and microclimate.

In practice, forest managers sometimes voluntarily extend riparian buffers beyond prescriptions at a site level to ensure protection of water quality from disturbance or avoid inoperable areas during harvesting. These buffer extensions likely provide beyond-BMP benefits for species' habitats due to the greater areas they cover. For example, in the upper Gulf Coastal Plain states of Louisiana and Arkansas where BMPs are nonregulatory, >18% of the intensively managed landscapes were comprised of overstory trees retained for riparian buffers along perennial and ephemeral stream systems (Parrish et al. 2017). In western Oregon, variable-width buffers (Figure 1) with a 15-m minimum width, where wider buffers were applied along steeper inner gorges or to retain minority trees or other site conditions, retained sensitive fauna and stream habitats, including water temperatures after upland forest thinning (Anderson et al. 2007; D. H. Olson et al. 2014). A recent call for thinning of dense second growth in riparian forests to promote growth of larger trees for future large down-wood recruitment is also a consideration for managed buffer areas (Reeves et al. 2016b). Zones of management delineated by distance to the stream (Figure 1) may accommodate joint retention of key elements, restoration of degraded conditions, and wood production. Yet more comprehensive examinations of the contributions of operational riparian buffer approaches to maintaining biodiversity relative to other priorities are needed for refinement and adaptation of beyond-BMP approaches. In this volume, Richardson and Danehy (2022) discuss additional biotic components of freshwater streams relevant for beyond-BMP considerations.

Temporal considerations of species habitat.—In addition to expanding the spatial view of fish habitat needed to supply their various components (wood, sediment, and food), an expanded temporal perspective is needed. The processes that deliver wood, sediment, and food from headwaters to downstream fish-bearing reaches include seasonal-, annual-, and decadal- to century-scale periodicity. Seasonally to annually, fish prey availability pulses with upstream invertebrate and vertebrate life histories and the hydrologic conditions that may flush them from their sources and deliver them downstream (Wipfli and Gregovich 2002; Wipfli and Musslewhite 2004). Hydrology also regulates sediment transport at seasonal and annual scales; meanwhile, more episodic, mass-wasting events deliver significant quantities of wood and sediment to streams. The frequency of such events are contingent on topography, geography, and disturbance triggers (e.g., May and Gresswell 2003, 2004), and models can aid in predicting debris-flow prone areas in headwaters (Miller and Burnett 2007, 2008; see slope stability applications: TerrainWorks). Retention of overstory vegetation, as riparian buffers or additional green trees retained upslope (Figure 2), can protect landslide-prone areas (e.g., Burnett and Miller 2007), eventually providing larger-diameter down wood following natural disturbance events. Beyond-BMP riparian buffer management includes managing for natural disturbance processes, again with a biotic foundation as the structural elements in headwater-sourced debris flows provide fish habitat structures.

Relative to time, the paradigm that Pacific salmonid streams are dynamic ecosystems has gained support (e.g., Penaluna et al. 2017; Reeves et al. 2018,2020). Instream fish habitat conditions vary with the contexts of geographic setting and the natural disturbance regime, including time since disturbance. Incorporating habitat variation into management guidance is a contemporary challenge, especially as variability needs to be assessed among spatial scales and land ownerships, as well as estimated through time as different practices unfold. Nevertheless, managing for habitat variation can be limited by a one-size fits-all standard for riparian buffers. New science supports these spatial and temporal contexts, including protection of existing conditions and restoration to address degraded conditions. In response, a changing mix of riparian buffer strategies has been developed to address increasingly complex forested aquatic ecological systems. Our examples illustrate the basic concepts behind the proposed range of buffer configurations that seek to create a portfolio of dynamic abiotic and biotic conditions within forested aquatic-riparian ecosystems and to extend beyond BMPs (Box 1; Figure 1). Implementation examples for managing a complex portfolio of site-to-watershed-to-landscape aquatic–riparian abiotic and biotic conditions for both prevention of adverse effects during management and restoration of ecological integrity from past disturbances are discussed below.

Beyond-BMP Approaches

Beyond-BMP considerations include integrating across multiple natural resource concerns by implementing a range of stream–riparian management approaches, including different widths of no-entry and managed riparian buffers, as well as addressing natural resource issues across spatial scales, from local sites to watershed-and-landscape scales. As larger spatial-scale considerations are evaluated, multiple stakeholder collaborative groups are convening to address forest restoration approaches—fostering a new approach to beyond-BMP and watershed-to-landscape forest governance.

Context-Dependent Riparian Buffer Management

Use of multiple riparian buffer widths in different stream-to-watershed-to-landscape contexts is a useful focal point for integrating different stream–riparian management perspectives that may stem from a merging of regulatory compliance issues and forest-ecosystem and restoration concerns (Meli et al. 2019). As a result of numerous ways to assess forest management effects, including from the interplay of land ownerships and legal constraints, a myriad of riparian protection guidance can result in a range of buffer widths and management zones (Box 1; Figures 1 and 2). Riparian buffers for legal compliance of clean-water standards can be applied on a per-project basis and can result in riparian-forest retention with an inner zone near streams where no equipment or harvest is allowed and an outer zone with limited activities. Some state BMPs, such as in South Carolina, Florida, or Washington, already incorporate elements of these multi-zoned buffer approaches, although the degree of recommended management in each zone varies by jurisdiction.

Additional abiotic or biotic concerns for an area can be additive factors to help adjust buffer widths or riparian management intensities within buffers to fit ecological objectives and site contexts together with regulatory compliance. For example, knowledge synthesis conducted for the development of the U.S. federal NWFP estimated distances from a stream channel into upland forests that provided ecological benefits to aquatic ecosystems via numerous biotic and abiotic concerns: litter fall, rooting strength, shading, coarse wood inputs, soil moisture and temperature, air temperature and relative humidity, wind speed, and solar radiation (FEMAT 1993). These ecological process and function concerns informed policy development of the interim riparian reserves of the NWFP (USDA and USDI 1994). Naiman et al. (2000) conducted a more comprehensive synthesis of northwestern stream–riparian processes and functions, including hydrogeomorphic processes and dynamics, and management implications for heterogeneous riparian zones. For example, whereas riparian buffers and the streamside vegetation retained by them offer substantial benefits of rooting strength to reduce hydrologic scour leading to streambank erosion, hence retaining streambank stability (e.g., Simon and Collison 2002), Naiman et al. (2000) pointed out that there are natural processes of lateral channel movements in unconstrained stream reaches and floodplains that "foster essential interactions between streams and their valley floor and create a biologically rich and diverse environmental mosaic." More complex multivariate considerations can expand riparian buffer efficacy to address dynamic systems across spatial scales of sites to watersheds or landscapes, integrated geo-hydro-bio ecological sustainability, and additional ecosystem services desired by people.

For example, Pennsylvania's Stream Re-Leaf Forest Buffer Toolkit (Alliance for the Chesapeake Bay 1998) is an ongoing campaign to maintain and restore streamside forests because "Streamside areas are the link between land and water, and trees are a vital component of a healthy stream ecosystem." In particular, criteria such as buffer-width guidance per objective (e.g., ~23 m [75 ft] to moderate water temperature, >76 m [250 ft] to provide wildlife habitat), tree and shrub species planting directions where needed, or natural regeneration where possible is helping landowners design and establish riparian buffers. One-third of streamside forests in Pennsylvania were assessed to have been converted or degraded. Because an estimated 60% of streamside forests in the Chesapeake Bay drainage were impaired, a particular aim has been to restore 600 stream miles in that drainage alone (Alliance for the Chesapeake Bay 1998). Their guidance follows a three-zone system: Zone 1 is an undisturbed forest along stream banks where tree roots are maintained or restored to stabilize substrates and where leaf litter helps fuel food webs in the stream and the riparian zone, Zone 2 provides water quality functions and sediment control and can include forest management activities, and Zone 3 provides filtration functions for upland activities, helping to control runoff and accompanying sediments and chemicals.

With knowledge accrual over time, adaptive management of riparian management standards may be developed. Within the context of an alternative ecological forestry approach to forest-ecosystem management in the U.S. Pacific Northwest (Franklin and Johnson 2018) developed specifically for forested lands managed by the Bureau of Land Management in western Oregon, Reeves et al. (2016b) compared alternative stream–riparian management options to adaptively manage the one and two site-potential tree-height interim riparian reserve widths of the federal NWFP (USDA and USDI 1994). In the Reeves et al. (2016b) alternative schema, they developed tiered buffer decisions based on two categories of site ecological sensitivity and fish occurrence in a reach. For example, for the most sensitive areas, a one site-potential tree height buffer (one-tree buffer; e.g., ~70 m wide on each side of streams) was described and entirely managed for goals of the NWFP's aquatic conservation strategy (USDA and USDI 1994). Most-sensitive areas might include areas with high intrinsic potential for at-risk salmon habitat. For least-sensitive areas, the riparian buffer width was the same for fish-bearing and non-fish-bearing streams, a one-tree buffer, but inner buffer-zone widths differed, with twice the protection afforded fish-bearing reaches (30 m) than nonfish reaches (15 m). Inner zones were managed for goals of the NWFP's aquatic conservation strategy (USDA and USDI 1994), such as to maintain and restore the physical integrity, water quality, sediment regime, instream flows, and other habitat components to support aquatic–riparian species (USDA and USDI 1994). Outer-zone buffer widths could be managed for other goals such as wood production. Their rationale for dropping a two site-potential tree-height riparian buffer, initial interim guidance for fish-bearing streams (USDA and USDI 1994), was provided in their report (Reeves et al. 2016b) and included science support for benefits of a one site-potential tree-height buffer for down wood and microclimate provisions, which were previously thought to require wider areas. They also acknowledged that significant uncertainties remain and the ongoing need for adaptive management as new knowledge emerges.

In addition to use of multiple widths of riparian buffers based on site-specific conditions and site potential (especially relevant for restoration goals), other examples of feathered riparian buffer zones with gradations of impact may be conceived, with a near-stream no-impact zone, an adjacent band of limited entry and riparian-forest disturbance, and an outer band of increased activity such as overstory removal, but less than the upland harvest impact (Figure 1). These zones of impact may have the aim of restoring secondary forests to promote tree diversity and accelerate tree growth, and recruit down wood to streams. The edge of the buffer abutting a harvested upland produces an edge, and increased light or nutrients from that edge may accelerate buffer tree growth (Ruzicka et al. 2014, 2017). Thinning harvests or tree tipping within buffers may similarly have benefits for boosting live tree growth and could provide structure for stream habitat development (Benda et al. 2016; Reeves et al. 2016b), although this warrants further study at stream-reach to larger spatial scales. Alternatively, planning forest management activities along only one side of a stream (Figure 1) might ameliorate stream–riparian ecosystem effects of harvest. One-side harvest might be a consideration for stream temperature management, especially when topographic hill shading of the harvested side provides natural shade to uplands and streamside areas (dark-side harvest). Again, further study of this application is warranted as well as for novel partial harvest schemes within buffers such as patch cuts, patch thinning, selected tree removal, or the zipper design of alternating forest management areas within buffers on opposing stream sides (Figure 1).

Watershed-to-Landscape Considerations

Several specific natural resource contexts can extend aquatic–riparian BMPs to watershed and landscape spatial scales. First, extension of riparian buffers up and over forested watershed ridgelines can provide habitat connectivity for aquatic, riparian, and terrestrial species to adjacent watersheds (Olson et al. 2007; Olson and Burnett 2009, 2013; Olson and Kluber 2014; Olson and Burton 2019; Figures 2 and 3). For some species such as macroinvertebrates and amphibians, breeding occurs in water, but animals can disperse to riparian and upland forests upon metamorphosis. Streamside dispersal corridors are used by a host of other riparian and terrestrial species (Olson and Burnett 2013). Prioritization of over-ridge linkage areas for species dispersal and connectivity functions can include lower-elevation and lower-*resistance* pathways, as well as landscape locations where three watersheds meet (Figure 3). Greater recognition that habitat requirements may differ for species by breeding, foraging, and dispersal functions adds additional weight to development of integrated forest and stream management approaches that go beyond BMPs and beyond riparian buffers.

Second, beyond-buffer proposals include protection of special areas. These may include some entire larger watersheds (e.g., key watersheds: USDA and USDI 1994; Reeves et al. 2018) with key functions to provide clean water or fish habitat. Entire smaller headwater watersheds also have been proposed for protections (Figure 2; Cissel et al. 1998, 1999) for ecological protections of unique biota (e.g., in the Pacific Northwest: torrent salamanders [Sheridan and Olson 2003; Olson and Weaver 2007]), sources of sediment and down wood (e.g., Benda and Cundy 1990; Benda and Dunne 1997; Reeves et al. 2003, 2016b; May and Gresswell 2004; Miller and Burnett 2008), cold-water refugia for cold-adapted species (Isaak et al. 2015), and integrated functions due to the dominance of headwater subdrainages in forested montane landscapes, which can include 50–80% of the stream network (Sidle et al. 2000; Meyer and Wallace 2001; Gomi et al. 2002; Datry et al. 2014; Colvin et al. 2019). Within river basins, areas warranting additional consideration for beyond-buffer approaches include unconstrained reaches and floodplains where stream–riparian systems are particularly intertwined, producing a mosaic of conditions as stream channels meander, channel braiding occurs, in-channel islands or riparian terraces are created, and complex sediment, down-wood, and water-flow dynamics occur (Fetherston et al. 1995; Montgomery and Buffington 1998; Naiman et al. 2000, 2010). At smaller scales, local management of riparian buffers or areas adjacent to them has provided provisions for species (protection for sensitive-species sites, promotion of minority trees in riparian forest stands, protection of unique old wolf trees with multispecies functions, or other actions for invasive species and pathogens), as well as individual seeps or small wetlands and locally incised channels with steep side slopes (Olson et al. 2002). Patches of species-specific set-asides may augment riparian buffers for broader ecosystem service concerns (Figure 3). This design element has been used by timber companies and private forest landowners in development of habitat conservation plans and safe harbor agreements with government agencies to contribute to collaborative conservation and allow for forest management activities (e.g., USFWS 2015). In addition, tributary junctions have been identified as special locations within watershed networks that may have unique geological, hydrological, and biological conditions and significant ecological functions (Figure 2; Cissel et al. 1998, 1999; Reeves et al. 2018). Tributary junctions are locations that can accumulate and regulate instream materials such as substrates and wood (Gomi et al. 2002; Montgomery et al. 2003; Benda et al. 2004). They also can be a watershed node for coldwater influx (Ebersole et al. 2015). This physical habitat complexity can be associated with high biodiversity (Benda et al. 2004; Danehy et al. 2012).

Forest Ecosystem Management Paradigms

The emerging role of landscape ecology and joint aquatic–riparian and terrestrial ecosystem management addresses a complex composite of natural resource values that benefit by aquatic protection and restoration approaches. Various designs are being used to address multiple ecosystem values beyond regulatory guidance. For example, in intensively managed pine forests of the southeastern United States, land cover types were examined relative to clear-cuts and retained-cover types, including riparian buffers (Parrish et al. 2017, 2018). They found that an average of ~18% of forest management units were in green tree retention cover, including perennial and intermittent stream–riparian buffers (13.8%) and narrower stringers buffering ephemeral streams (4%). The importance of stringers as distinct habitat from riparian buffers for plant and animal communities was examined, with forest structural augmentation functions supported. In particular, such stringers appeared to enhance habitat conditions for some bird species, serving as likely dispersal, perching, and foraging habitat (Parrish et al. 2017, 2018). Their function as likely connectivity corridors across managed landscapes differentiated them from the downstream wider riparian buffers that may provide breeding habitat. Their counterpoint, however, was that the greater edge created by stringers may be associated with greater predation rates.

As BMPs intersect restoration priorities and the combined effects of the "ghost of land use past" and historic and novel natural disturbances, a host of additional considerations come to the foreground. These may include control of invasive species, down-wood provisioning by tree tipping or wood installation, sediment management, and tree species and diversity management (e.g., favoring hardwood and especially mast-producing species over pine in much of the United States east of the Rocky Mountains). In Michigan, the "Forests for Fish" campaign "celebrates the connections between woods and water" (www.forestsforfish.org), with participation from progressive forest landowners who are working to manage their woods to protect embedded streams and especially habitat for their world-class trout fishery (Forests for Fish: www.forestsforfish.org). Forest for Fish stewardship actions include water quality and fish habitat considerations and go beyond, with aims to minimize streambank erosion, remove invasive plants, replace dead streamside trees (e.g., ash trees that died from the emerald ash borer *Agrilus planipennis*) and promote riparian tree species and age diversity, and enhance wildlife habitat in streamside zones. In Washington, the Forests and Fish program focuses on native salmonid recovery using science-based management practices across 60,000 mi (96,561 km) of streams in 9.3 million acres (3.8 million ha) of state and private forestland (Forests and Fish: www.forestsandfish.com). They have a specific focus on maintaining cool, clean water with large down-wood inputs, steep-slope protection to limit landslides, road improvements for fish passage and reduced siltation, and road decommissioning. As these programs are implemented and efficacies evaluated relative to various resources and threats, further development and adaptive management can be anticipated.

At larger spatial scales of watersheds or riverscapes, abiotic and biotic characteristics can be summarized to assess broader conditions and aquatic ecosystem degradation. Results of watershed analyses and riverine assessments can identify conditions warranting focused attention and possibly more explicit BMP or beyond-BMP prescriptions for forest–aquatic system restoration. In the United States, three agencies lead national assessments of a variety of watershed-scale metrics, from water quality to water supply: the U.S. Geological Survey, U.S. Department of Agriculture, and U.S. Environmental Protection Agency (e.g., USGS 2019). More regionally, calls to conduct watershed analyses and methods to assess watershed condition frameworks have emerged over the past 30 years (e.g., Pacific Northwest: USDA and USDI 1994; Miller et al. 2017). Statistical analyses and modeling tools have also emerged to assist in this endeavor (e.g., specific metrics such as water temperature with scenarios such as climate change: Isaak et al. 2017; multiple metrics, see Benda et al. 2007). Watershed assessments are often multi-scalar in the data analyzed, hence providing clues to more localized areas where conditions fall below ideal criteria and where greater attention to on-the-ground BMPs may be needed (e.g., Miller et al. 2017). Adaptive management of approaches to watershed analyses and watershed condition assessment is recognized as a contemporary priority (Reeves et al. 2018). Riverscape analyses have followed similar trajectories, but novel approaches have included assessments of biotic conditions via food web analyses to inform river restoration priorities (Naiman et al. 2012; Bellmore et al. 2017).

Multistakeholder Partnerships and Larger-Scale Restoration

Beyond-BMP management ideals are intersecting broader forest landscape considerations through conceptual pathways to maintain and restore ecological integrity, as well as to promote societal pathways of stakeholder partnerships. Broader-scale forest–stream ecosystem approaches are supported by diverse landowners who work collaboratively with government agencies and nongovernmental organizations. Collaborative groups have been a dominant initiator of integrated restoration of multiple facets of dynamic forested-stream ecosystems and have transitioned governance of some land-management decisions to partnerships including watershed councils and multiforest stakeholder groups (Flitcroft et al. 2017). Collaboratives can ensure delivery of broad ecosystem services across the area of the entire collaborative group, rather than all services being produced by every landowner or parcel within its boundaries. In 2012, the U.S. Forest Service included multistakeholder collaboration as part of its 2012 national forest planning rule (U.S. Office of the Federal Register 2012). Two-dozen collaborative groups are active in Oregon (Flitcroft et al. 2017), and similar approaches are proving successful elsewhere. In Latin America, Meli et al. (2019) attributed bottom-up approaches among local stakeholders to better alignment of landscape-scale ecological-resource connectivity and effective restoration.

Intersecting the social dynamics of multistakeholder collaboration that are broadening the spatial extent of stream management, development of the stream evolution model (Cluer and Thorne 2014) and its characterization of various stages of stream development postdisturbance has helped to frame a resulting wave of stage-0 restoration projects (Box 2). Powers et al. (2019) described six of these in the Pacific Northwest, where focus on degraded streams from past anthropogenic activities have included management actions to promote development of multiple channels and habitats, and restoration of the water table and associated hydrological functions and processes, integrating geomorphic, hydrologic, and biological concerns (Castro and Thorne 2019; Box 2). This restoration program has been implemented at larger than traditional forest-management project scales and has a longer-term goal to make these stream systems more resilient to natural and anthropogenic disturbances. As project planning develops, reach-specific anthropogenic disturbances within the larger stream system can be addressed in more detail (Figure 4).

In U.S. geographies with a longer history of post-European settlement and growing impacts from rapidly increasing urbanization, effective conservation strategies for aquatic–riparian habitat types are developing at broader spatial scales and purposefully incorporating multistakeholder involvement. For example, in New England, ephemeral or vernal pools receive some regulatory protection, yet available information indicated that managing adjacent upland habitat types and landscape connectivity across multiple land ownerships was necessary for some vernal-pool species to minimize barriers to gene flow and movement or mortality from roads (Baldwin et al. 2006; Beaudry et al. 2008). Engaging a wide array of stakeholders for myriad tasks—from detecting and documenting cryptic ephemeral wetlands, conducting biological inventories, and implementing voluntary best development practices—has taken conservation of vernal pools in the northeastern United States beyond the intent of local and regional regulations. Likewise, stream salamanders in the Appalachian Mountains often make overland dispersal movements through dendritic networks (Grant et al. 2010) that may be embedded in upland landscapes with a mosaic of forested, urban, and agricultural land uses, which can complicate application of beyond-BMP principles. A multiple stakeholder-by-task approach could similarly serve landscape-scale conservation ob-

Box 2. Stage-0 Forested-Stream Restoration and the Stream Evolution Triangle

Past forestland uses have left profound signatures on today's stream ecosystems, prompting watershed-scale restoration approaches to be an integral component of contemporary forest-management programs. These signatures include stream habitat simplification and channelization, stream incision, altered hydrology such as base-flow changes, and siltation from the effects of practices such as historical timber harvest, road construction, and associated landslides (e.g., Sedell and Froggatt 1984; Walter and Merrits 2008; Merritts et al. 2011; Wohl 2019), as well as dams and dam removals (Bellmore et al. 2019) and large-wood removal from streams and riparian areas (e.g., Bisson et al. 1987). The stream evolution model recognizes various stages through which a stream may cycle in response to disturbances, which has specific utility for forested stream–riparian restoration approaches (Cluer and Thorne 2014); a single ideal condition does not recognize the natural dynamics of stream ecosystems in some settings (Penaluna et al. 2017). Cluer and Thorne's (2014) stage-0 (zero) systems mark the predisturbance (i.e., pre-Anthropocene) configuration of a stream where a multitude of wetland/flow paths adjust around forested islands. Process-based restoration approaches to restore stage-0 channel, floodplain, and hyporheic connectivity benefit myriad ecological functions (e.g., Cluer and Thorne 2014; Powers et al. 2019), including (1) the promotion of multichannel networks to store sediments, cycle nutrients, and produce clear water; (2) the restoration of dense near-channel vegetation to provide shade and affect temperature; (3) the development of high water tables and deep pools to provide drought refugia; and (4) the provision of higher biodiversity, including a proportion of native species and systems that are expected to be highly resistant to disturbances such as flood, drought, and wildfire (Powers et al. 2019). Furthermore, these actions incorporate concepts of the stream evolution triangle, a conceptual model that explicitly accounts for geological, hydrological, and biological recovery during stream restoration (Castro and Thorne 2019; see also Penaluna et al. 2017). Numerous stage-0 restoration actions are in development, with 20+ projects implemented in the U.S. Pacific Northwest (Powers et al. 2019), including projects in Douglas-fir-dominated forested-stream systems in the Oregon Coast Range, the western and southern Oregon Cascade Range, and the ponderosa pine and bitterbrush woodlands east of the Cascade Range.

Within broader stream restoration projects, site-specific goals can address local issues. Figure 4 shows a summer-ephemeral headwater stream section where an earthen-dam (Figure 4A) from an earlier mill and grazing allotment has altered the system hydrology by creating an extensive wetland (Figure 4B, high water in winter) with water retention to late summer (Figure 4C, 4D, 4F) and has channelized outflow from the dam (Figure 4E). Yet it developed into productive breeding

Box 2 continues

Box 2. Continued

habitat for a highly diverse amphibian community, inclusive of Oregon State sensitive species. Today, this wetland has high value for biota and is akin to the situation described by Gibbons et al. (2006), where a small isolated wetland can have a key ecological role, such as in disturbance recovery. Restoration along this stream reach within a larger stage-0 restoration project that is being planned addresses the stream evolution Triangle process domains (geological, hydrological, and biological: Powers et al. 2019), in addition to emerging recreational uses of the area.

jectives for forested stream salamanders in that region. Including the human and social aspects of conservation initiatives is integral to developing lasting adaptive changes to sustainability. These intersect development of beyond-BMP approaches in multiple landowner ecosystems.

In Conclusion

Beyond-BMP and beyond-buffer approaches are becoming more important as multiple stressors are addressed on forest landscapes, and as watershed-to-landscape models are developing to help project development of specific conditions and disturbance likelihoods with more accuracy. For example, there may be specific basins or stream reaches where down-wood recruitment is likely to be successful, sedimentation or landslide potential is higher, and greater water temperature differences are evident now and changes are projected. These larger-scale perspectives, the heterogeneity across sites and over time, and projected future changes are advancing acceptance of managing for a broader portfolio of ecosystem services across spatial and temporal scales and teasing apart which are practical or necessary for managing at specific smaller-scale projects (Penaluna et al. 2018). At broader scales, planning across ownerships and more extended time frames is adding clarity to how to manage constant change to retain a range of ecosystem services across the whole (Reeves et al. 2020). Managing for longer-term ecosystem resilience is a particular aim in climate-smart management planning for climate-change projections; such resilience-planning is likely to be a strong influencer of the beyond-BMP concept across forest–stream ecosystems. Watershed-scale refugia are being identified for microclimates due to topographic and vegetation shading, future projections of sustainable coldwater and clean-water sources, and sensitive species. Science-supported forest management plans to protect and restore those stream-to-upland forest habitats and optimize those futures now has become a front-burner task and is merging with historical BMP priorities.

Acknowledgments

This work was supported by the U.S. Forest Service Pacific Northwest Research Station, the National Council for Air and Stream Improvement, Inc., and Weyerhaeuser. We thank Bob Danehy and Gordie Reeves for their support with chapter development, and comments from Brian Staab and one anonymous reviewer, which improved the paper immensely. We also thank N. Chartier for his partnership in developing the conceptual

Figure 4. Stream-reach restoration planning at Prairie Farm Creek, Deschutes National Forest, Oregon, in ponderosa pine forest as part of a larger stage-0 restoration project. Box 2 describes panels **(A–F)**. Photographs by Deanna H. Olson: A (with Cari Press, U.S. Forest Service hydrologist and Kris Hennings, U.S. Forest Service wildlife biologist), D, and F. Photographs by Nate Dachtler, U.S. Forest Service fisheries biologist: B, C (with C. Press and D. H. Olson), and E.

connectivity design for Figure 3, K. Ronnenberg for editorial and graphics assistance, and K. Christiansen for developing the Figure 3 map.

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