Chapter 11.

Biological Responses to Stressors in Aquatic Ecosystems in Western North America: Cumulative Watershed Effects of Fuel Treatments, Wildfire, and Post-Fire Remediation

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Introduction

Aquatic communities in North America evolved with disturbance regimes (for example, glaciation, erosion, tectonics, volcanism, fire) that varied in frequency, intensity, and severity (Poff 1992; Power and others 1988; Resh and others 1988). Disturbance has been recognized for its importance in the organization and maintenance of aquatic ecosystems (Reeves and others 1995), in shaping species resilience and persistence (Reice and others 1990; Yount and Niemi 1990), and structuring the evolution of aquatic organisms (Lake 2000; Malanson 1984; Schlosser 1990; Sedell and others 1990). Disturbances are regarded as having a dominant role in determining the structure of stream communities (Palmer and others 1996; Resh and others 1988).

Natural and anthropogenic disturbance regimes are classified as pulse, press, or ramp types that vary in their temporal and spatial patterns of impact intensity and duration (Lake 2000). Pulse disturbances are short-term and often intense events, whereas press types may arise sharply but reach a constant level that is maintained. Ramp disturbances arise if the intensity increases over time. In most situations, discrete disturbance regimes are unlikely to occur and the system is more likely to be characterized by a mix of disturbance types. For example, the effects of a press disturbance, such as land use change, may interact with invasions by exotic species (ramp) and this regime may be affected by pulse disturbances in the form of floods that occur unpredictably and with varying intensity. However, the life history traits of the longest-lived affected population may determine the importance of disturbance in shaping aquatic ecosystem structure and function (Benda and others 2003; Bisson and others 1997; Reeves and others 1995; 1998; Rieman and others 2003).

Catastrophic shifts in ecosystems are often precipitated by stochastic (pulse) events such as fire, but the foundation for them lies in the gradual (press-ramp), underlying loss of resilience (fragmentation, habitat loss, etc). The real impact of a press disturbance on population persistence may only be evident after a pulse disturbance and over relatively long time scales. Land use changes constitute a press disturbance that may have a persistent effect on stream community structure and function over the long-term (Harding and others 1998). Press disturbances, such as timber harvesting, require longer recovery times than pulse disturbances such as floods or droughts (Detenbeck and others 1992). When forest management practices affect the stability of in-stream habitats, frequent pulse disturbance could result in the local extirpation of refugia-dependent species (Parkyn and Collier 2004). Short-term responses in abundance or survival of organisms or the physical attributes of streams to cumulative effects are not easily detected because suitable habitat features in disturbed landscapes may not provide stable refugia during pulse disturbances. These effects may only become evident over long time scales. Thus, it may also be important to consider the biological mechanisms (for example, survival, growth, dispersal) influencing the responses at different scales (Harvey and others 2006; May and Lee 2004). Maintaining a stability domain (sensu Scheffer and others 2001) that allows ecosystems to resist disturbance and recover will present significant challenges to resource managers and might be considered in terms of our ability to conserve resilient populations, evolutionary legacies, and ecological functions.

Disturbance responses depend on the ability of aquatic organisms to find refugia in space and time in heterogeneity of their physical habitat, diversity of life history strategies, behavioral adaptations, or connectivity to refugia at various spatial scales (Angermeier 1995; Poff and Allan 1995; Rieman and others 2000). In the southeastern United States, extinction prone aquatic species are typified by a limited geographic range, restricted range of habitat sizes, and highly specialized habits (Angermeier 1995; Jelks and others 2008; Taylor and others 1996; Warren and others 2000). These associations reflected the effects of reduced habitat area and increased isolation (insularization), which are also important determinants of extinction in terrestrial systems (Angermeier 1995).

Lotic systems, like most natural ecosystems, exhibit extreme heterogeneity in environmental conditions and biotic communities at multiple spatial scales, ranging from microhabitats to whole landscapes and ecoregions (Montgomery 1999; Pringle and others 1988; Townsend 1989; Townsend and others 2003; Vannote and others 1980). At each scale, variation in environmental conditions affects stream biota (Angermeier and Winston 1998; Lake 2000; Poff 1997; Walters and others 2003), leading to high variability in abundance and community structure at multiple spatial scales (Downes and others 1993; Li and others 2001; Vinson and Hawkins 1998). Vegetation, geology, hydrology, and land use generally account for differences in community structure among river systems (Richards and others 1997; Townsend and others 1997, 2003) but variation in species composition is related mainly to local and in-stream factors (Angermeier and Winston 1998; Gregory and others 1991; Li and others 2001; Walters and others 2003).

Fire is widely recognized as one of the most important disturbance processes in the western United States (Hessburg and Agee 2003). Fire regimes in western North America exert strong influences on patterns of forest composition, structure, and successional dynamics (Agee 1991; Halpern and Spies 1995) (Chapter 2). During the past century, fire suppression has altered fire regimes in some vegetation types, and consequently, the probability of large stand replacing fires has increased in those areas. Retrospective studies indicate that fire return intervals are longer than prior to European-American settlement as fire suppression, landscape conversion, and fragmentation altered fire regimes in much of the western United States (Agee 2003; Hessburg and Agee 2003). Fire regimes in riparian areas vary by region and forest type (Chapter 2). In wetter forests, riparian fire regimes were more moderate, fire return intervals were longer, and fire intensity and severity was lower than in adjacent upland forests (Dwire and Kauffman 2003). In drier forest types, fire regimes in riparian and upland forests were more similar. Local conditions, governed by microclimate, geomorphology, soils, and elevation in riparian areas, contribute to the variability of fire regimes and fire severity in riparian areas (Dwire and Kauffman 2003; Whitlock and others 2003). Land management practices, particularly in the western United States, usually conjure landscape degradation associated with decreases in vegetation density and cover. The indirect effects of selective and extensive timber harvest, fire suppression, and grazing practices have significantly altered forest structure and fuel loads. Forests that were once mosaics of species, ages, and patterns have been simplified; the area becoming dominated by higher density, middle aged stands, thereby reducing their resistance to the effects of severe wildfire (Hessburg and Agee 2003; Rieman and Clayton 1997; Rieman and others 1997).

The National Environmental Policy Act of 1969, Clean Water Act of 1972, and Endangered Species Act of 1973 required greater consideration of the relationships among ecosystem components and increased the focus on the effects of land use activities on fish and wildlife resources, especially threatened species (Rinne and Medina 1995). Fuel reduction and fire suppression are key elements of the National Fire Plan, which provides guidance for an interagency approach to fire and fire related management (USDA 2000). In implementing the management goals of the Healthy Forest Restoration Act of 2003 (H.R. 1904), it will be important for resource managers to understand the effects of fire related management on aquatic and terrestrial ecosystems and the tradeoffs between achieving fuel reduction and minimizing the effects of those efforts on aquatic and riparian ecosystems. In this paper, we attempt to summarize the effects of wildfire and fuel treatment practices on aquatic resources, identify areas of uncertainty about the impacts of fuel reduction strategies on the terrestrial-aquatic ecotone, and highlight research needs to better inform resource management.

Disturbance, Fire, and Land Management

The physical and biological effects of wildfire and forest harvest on aquatic ecosystems are not identical. Numerous studies comparing fire and logging disturbance regimes confirm the dominant role of the watershed in tempering the aquatic responses to terrestrial disturbance and reflect both important similarities and differences in the responses to disturbance within the catchment (Carignan and others 2000; Smith and others 2003). Both fire and logging exhibit similar stressor characteristics (temporary deforestation, sediment and nutrient influx, increased stream temperatures) but have important differences in spatial extent, frequency, intensity, and severity of disturbance with respect to water quality. Abiotic and biotic elements of a watershed interact to govern the direction and magnitude of change in response to disturbance. Habitat alteration probably has the greatest impact on individual organisms and local populations that are the least mobile, and reinvasion will be most rapid by aquatic organisms with high mobility. Perturbation associated with hydrological processes is probably the primary factor influencing post-disturbance persistence of fishes, benthic macroinvertebrates, and diatoms in fluvial systems. These effects may be immediate and direct or occur indirectly over long periods of time (Dunham and others 2003; Gresswell 1999; Minshall and others 1997). Many aquatic organisms (such as salmonids) have evolved strategies to survive perturbations occurring at the frequency of wildland fires (greater than 100 years), but this does not prevent extirpations of local populations (Gresswell 1999; Rinne 1996).

Physical Effects of Fire and Forest Management Practices

Upland and riparian vegetation interacts with soils, geology, and topology to influence channel form, habitat, flow characteristics, and nutrients (Bisson and others 1987; Gregory and others 1991; Montgomery 1999). Where vegetation cover has been disturbed by fire or human activity, terrestrial habitats may experience increased surface flows that cause rapid, concentrated surface runoff, accelerated erosion, and increased stream peak flows and sediment loads (DeBano and Schmidt 1989; DeBano and others 1996). Small streams are typically more affected by catchment disturbance than larger streams and, as adjacent slopes become steeper, the likelihood of disturbance from instream effects increases (Lee and others 1997; Megahan and Ketcheson 1996). The physical effects of fire on aquatic systems depend on the severity of the fire, post-fire climate, development of soil repellency, and alteration of the hydrologic regime (Benda and others 2003; Beschta and others 1987; DeBano and others 1996; Pierson and others 2001; Tiedemann and others 1979; Wondzell and King 2003). Short-term consequences of fire include mobilization of nutrients, soil modification, increased water temperature (including direct heating), and changes in hydrology, water chemistry, and geomorphology (Bisson and others 2003; Bozek and Young 1994; Gresswell 1999; Minshall and others 1989). Timber harvest activities may accelerate surface erosion and increase sedimentation (Chamberlin and others 1991; FEMAT 1993; MacDonald and others 1991; Meehan 1991; Reid 1993; Rhodes and others 1994).

Erosion can be initiated or accelerated by timber harvest and fire management activities including the construction of fire lines, roads, and post-fire rehabilitation efforts (Landsberg and Tiedemann 2000; Robichaud and others 2000). Tractors and skidders promote soil compaction and may temporarily increase the potential for overland flow but reduce interstitial flow through the soil, which may require decades to recover (Backer and others 2004; Hartman and others 1996) (Whitson and others 2003; Williamson and Neilsen 2000) (Chapter 9). The use of heavy equipment in timber management or restoration may disturb soil integrity, increasing erosion (McIver and Starr 2000; Robichaud and others 2000). Burned Area Emergency Restoration (BAER) treatments, including felling trees and snags for erosion control, may not reduce storm runoff, erosion, or sedimentation and may cause additional disturbance (McIver and Starr 2000; Robichaud and others 2000). The cumulative effects of timber harvest and associated road building on aquatic life is exacerbated in forest catchments on steeper, more environmentally sensitive terrain (Gucinski and others 2001; Megahan and Hornbeck 2000; Platts and Megahan 1975).

Increased fine sediment delivery to streams is usually associated with timber harvesting and road construction (Platts and Megahan 1975; Eaglin and Hubert 1993). The majority of sediment from timber harvest activities is related to roads and road construction (Chamberlin and others 1991; Furniss and others 1991; Megahan and Hornbeck 2000) and associated increased erosion rates (Beschta 1978; Meehan 1991; Reid 1993; Rhodes and others 1994; Swanson and Dyrness 1975; Swanston and Swanson 1976). Serious degradation of aquatic habitat can result from poorly designed, constructed, or maintained roads (Furniss and others 1991; MacDonald and others 1991; Rhodes and others 1994). Road networks interact with stream networks and lake basins at the landscape scale and affect biological and ecological processes in stream and riparian systems. Peak flows and debris flows are influenced by the arrangement of the road network relative to the stream network (Swanson and others 1988; Thompson and Lee 2000, 2002) and they can alter the balance between the intensity of flood peaks and the stream network's resistance to change (Jones and others 2000). Timber harvest activities caused increases in lake sedimentation rate and lake productivity in three of four lakes studied in western Washington, accelerating the rate of change in the trophic status of each lake (Birch and others 1980).

Water Quality

The modification of terrestrial habitats is often accompanied by changes in water quality and quantity (Bjornn and Reiser 1991; Chamberlin and others 1991; Rhodes and others 1994; Chapter 8) and perturbation of nutrient cycles within aquatic ecosystems (Megahan and Hornbeck 2000; Spencer and others 2003). Timber harvest often temporarily increases water yield and alters the timing of the flow, usually seen as an increase in low flows. The magnitude and timing of storm and peak flows depend on the degree of soil loss, soil compaction or hydrophobicity, and the pattern and schedule of harvest. The effects, which vary depending on the prevailing climate, rate of vegetation recovery, and type of vegetation, can decrease after initial disturbance but may remain above natural levels for many years (Bolstadt and Swank 1997; Hartman and others 1996; Platts and Megahan 1975; Swanson 1981; Chapter 7). As vegetation recovers, dry season minimum flows may be reduced because of enhanced evapotranspiration (Hicks and others 1991).

Water quality can be altered by timber harvest activities (Bolstad and Swank 1997; Chamberlin and others 1991; Chapter 8). Stream temperature may rise following loss of streamside shading, disrupted subsurface flows, reduced stream flows, elevated sediments, and morphological shifts toward wider and shallower channels with fewer deep pools (Beschta and others 1987; Chamberlin and others 1991; MacDonald and others 1991; Reid 1993; Rhodes and others 1994; Swank and others 1989). Logging may alter temperature as riparian shading is reduced (Hartman and others 1996; Johnson 2004; Johnson and Jones 2000; Swank and others 1989). Increased solar input into streams may also change the seasonal thermal regimes causing shifts toward earlier and longer summers when solar input is at its highest (Hartman and others 1996; Johnson and Jones 2000; Poole and Berman 2001). Increased stream temperatures can exceed thermal preferences of many species in the PNW and may remain elevated for up to 15 years after timber harvest (Johnson and Jones 2000). Dissolved oxygen can be reduced by low stream flows, elevated temperatures, and increased fine inorganic and organic materials that have infiltrated into stream gravels (Chamberlin and others 1991; Wondzell and King 2003).

Nutrients

Stream concentrations of particulate organic matter, phosphorus, nitrogen, and ions can increase following forest fires (Bayley and others 1992; Earl and Blinn 2003; Spencer and Hauer 1991) and clearcutting (Feller and Kimmins 1984; Hartman and others 1996; Likens and others 1970; Webster and others 1990). Nutrient concentrations may increase following logging but generally return quickly to normal levels (Chamberlin and others 1991). Increases in total phosphorus and nitrogen concentrations, dissolved organic carbon (DOC), and other trace nutrients appear to be driven by higher discharge, which enhances nutrient loading from the watershed and (or) from the stream channel (Carignan and others 2000; Prepas and others 2003; Spencer and others 2003). During subsequent years, nutrient concentrations may periodically increase in fire impacted sites during spring run-off. Post-fire changes propagated through the aquatic food web suggest shifts from reliance on terrestrial and other allochthonous sources to a periphyton-based food web following canopy removal and nutrient enrichment. Chlorophyll *a* concentrations increase, presumably in response to nutrient run-off and increased light levels (Allen and others 2003). Some chemical effects on water quality diminish with time, but nutrient levels may remain unchanged or continue to increase, suggesting that longer time frames may be necessary for increased nutrient input to aquatic ecosystems to return to normal levels (Carignan and others 2000). As a result, biotic responses to alterations of water quality may take longer to manifest themselves (Brass and others 1996). Paleoecological studies of lake sediments revealed fundamental changes in lake mixing regimes following logging with associated alterations of hypolimnetic trophic structure persisting for over 100 years (Scully and others 2000). Experimental clearcut logging in some lake catchments produced no significant changes in water quality (dissolved organic carbon, chlorophyll *a*, total nitrogen increased; Ca^{2+} and Mg^{2+} decreased), though water clarity decreased (Steedman 2000; Steedman and Kushneriuk 2000). The responses, however, varied regionally. In some cases, forest harvesting was associated with increases in nutrient and chlorophyll *a* concentrations, cyanobacteria, and net primary production (Prepas and others 2001; Rask and others 1998). In other cases, differences in nutrient dynamics between logged watershed lakes and reference lakes were undetectable (Steedman 2000).

The benefits of the type of fuel management applied (logging, thinning, prescribed fire) depend on the frequency and intensity of their application. Presently, the influence of disturbance type (logging or fire), time elapsed since the disturbance, and extent of natural variation limits our ability to detect the direct effects of fire management activities. Shorter rotations associated with frequent treatments may reduce soil fertility (Chapter 9). Low intensity prescribed fires post-harvest may increase short-term productivity but soil nitrogen may be volatilized and lost to the catchment when fire is used as a fuel reduction tool. Roads contribute more sediment to streams than any other land management activity (Gucinski and others 2001; Meehan 1991), but land management activities designed to combat wildfires or restore forest conditions depend on roads. Natural and anthropogenic disturbances that reduce terrestrial litter inputs to streams alter aquatic ecosystem function, highlighting the importance of riparian ecotones in sustaining diverse aquatic food webs (England and Rosemond 2004; Wallace and others 1997). Reduced stream shading, accompanied by increased nutrient input, may contribute to algal blooms.

Habitat

The supply of large woody debris to stream channels is typically a function of the size and number of trees in riparian areas, and thus can be profoundly altered by timber harvest (Bisson and others 1987; Naiman and others 2000; Robison and Beschta 1990; Wood-Smith and Buffington 1996). Shifts in the composition and size of trees within the riparian area affect the recruitment potential and longevity of large woody debris within the stream channel. Large woody debris influences channel morphology, especially in forming pools, slow water refuges, and instream cover, and provides shade, retention of nutrients, and storage and buffering of sediment (Robison and Beschta 1990; Rhodes and others 1994). In intensively logged watersheds, the size of instream woody debris was smaller and pool depths significantly shallower than those found in a relatively undisturbed watershed (Overton and others 1993; Ralph and others 1994). All of these changes can eventually culminate in the loss of biodiversity within a watershed (Hauer and others 1999; Hawkins and others 1997).

Biotic Responses to Watershed Disturbance

Macroinvertebrates

Changes in aquatic invertebrate assemblages have been used for many decades to monitor impacts on land and in water. Land and water uses and impacts are reflected in species assemblages in streams and lakes. However, the level of detail of most monitoring is not sufficient to track species losses in aquatic invertebrates. Following watershed disturbance, the biomass of stream macroinvertebrate communities has been shown to increase in some cases (Burton and Ulrich 1994; Haggerty and others 2004; Stone and Wallace 1998) but not in others (Minshall and others 1997). Minshall (2003) described general patterns of responses of stream macroinvertebrate assemblages to fire, finding only minor or no direct effects except in extreme cases of intense heating of the stream from severe wildfire. Short-term, post-fire alterations of assemblage structure and decreases in biomass may be associated with changes in riparian vegetation. Most impacts were indirect effects on species composition and food web processes that stemmed from altered runoff and channel morphology (Minshall and others 2001). Following severe wildfire, macroinvertebrate assemblages showed low resistance to spate-induced debris flows, and high resilience but low assemblage similarity to pre-fire assemblage structure with the post-fire assemblage dominated by generalist taxa (Mihuc and Minshall 1995; Vieira and others 2004). In comparative studies of the consequences of timber harvest and fire on lake aquatic communities, responses of macroinvertebrate densities varied. Generally, invertebrate biomass was greater in lakes from burned catchments than from harvested and reference catchments. Scrimgeour and others (2001) found post-wildfire nutrient enrichment prompted significant increases in total benthic macroinvertebrate biomass in recently burned lake catchments. These analyses suggest that benthic biomasses continue to be elevated for about 15 to 20 years following fire before declining to pre-disturbance levels. Under the influence of phosphorus, nitrogen, and chlorophyll *a*, biomass response depended on percent of catchment disturbed (Scrimgeour and others 2000). In some cases, forest harvesting was associated with increases in chlorophyll *a* concentrations and primary production causing moderate increases in zooplankton density (Rask and others 1998). Biomass increased in burned watershed lakes but declined in logged catchments (Patoine and others 2000; Prepas and others 2001). Changes in a food source of such importance as aquatic invertebrates can have repercussions in many parts of the food web (Hernandez and others 2005; Spencer and others 2003).

Fish

As with other aquatic organisms, the short-term direct effects of high severity fires on fish populations may be minimal (Spina and Tormey 2000) or intense (Bozek and Young 1994). Intense fires and their subsequent effects on hydrologic regimes, erosion, debris flows, woody debris recruitment, and riparian cover can strongly influence the structure and function of aquatic systems (Rieman and others 2003; Swanson 1981). Post-fire effects may result in fish mortality (Bozek and Young 1994; Minshall and others 1997; Rieman and Clayton 1997; Rinne 1996; Spencer and others 2003), but local extirpation of fishes is patchy, and recolonization is often rapid (Bisson and others 2003; Gresswell 1999; Rieman and others 1997, 2003). Subsequent effects associated with the loss of vegetation and infiltration capacity of soils may include increased erosion, changes in the timing and amount of runoff, elevated stream temperatures, and changes in the structure of stream channels (Benda and others 2003; Rinne and Neary 1996, Swanson 1981; Wondzell and King 2003). The nature of these changes depends on the extent, continuity and severity of the fire, and on lithology, landform, and local climate (Rieman and Clayton 1997; Swanson and others 1987). Where native fish populations are naturally depauperate or have declined and become increasingly isolated because of anthropogenic activities, the effects on fish populations are more pervasive and long lasting (Propst and others 1992; Rieman and others 2000; Rinne 1996; Rinne and Minckley 1991). Ecological specialists—species with narrow habitat requirements—in highly degraded and fragmented systems are likely to be most vulnerable to disturbance (Angermeier 1995; Angermeier and Winston 1998; Dunham and others 2003; Trebitz and others 2003). The role of fire in facilitating invasions by non-indigenous aquatic organisms is unknown, but must be considered among the indirect effects. Disturbance associated with fire may make already vulnerable native populations susceptible to colonization by invasive species (Dunham and others 2003). Aquatic systems may not experience shifts in assemblage structure, but may exhibit effects at the population level that translate into long-term effects (St.-Onge and Magnan 2000; Tonn and others 2003, 2004). This illustrates the importance of post-fire monitoring and research at more relevant spatial and temporal scales to better understand the natural response regime (Gresswell 1999).

The impacts of timber harvest on fish assemblages are extensions of their effects on aquatic ecosystems (Rinne and Neary 2000; Rinne and Stefferud 1999). The extent to which hillslope and riparian soils are disturbed and mobilized to the stream channel will reduce pool habitats (McIntosh and others 1994, 2000), decrease the survival of incubating salmonid eggs (Reiser and White 1990), and/or increase turbidity (Bolstadt and Swank 1997; Lisle and Napolitano 1998). A change in timing or peak flow magnitudes may scour redds or embed them. Removal of timber from riparian areas decreases the amount of large woody debris available for recruitment into the channel, affecting pool formation, sediment storage, and cover availability (Beechie and Sibley 1997; Bilby and Ward 1991; Bisson and others 1992; Solazzi and others 2000; Reeves and others 2002), though the extent of management activity in the catchment may determine the severity of the impacts (Reeves and others 1993). Short-term increases in recruitment of large woody debris in the channel may benefit fish and amphibian populations but the benefits may be transient as the long-term supply of large trees in the riparian zone is depleted. Thinning of the riparian canopy increases solar input, stream temperatures, and aquatic productivity. Fish populations may exhibit lower abundance or productivity resulting from reduced coldwater habitats or increased stream temperatures over time spans of decades (Hornbeck and Kochenderfer 2000; VanDusen and others 2005).

Vegetation removal, whether by fire, logging, or other human activity, acts at multiple scales to affect the natural processes that control catchments and stream processes, destabilizing flow and thermal regimes, simplifying habitats through siltation, reducing water quality, and impacting biotic communities (Osborne and Wiley 1988; Rabeni and Smale 1995; Snyder and others 2003; Wang and others 1997). Patterns in fish assemblage structure are often attributed to longitudinal changes in stream attributes (Jackson and others 2001; Jones and others 1999; Lyons 1996; Rahel and Hubert 1991; Schlosser 1982) and hydrologic variability (Poff and Allan 1995). Changes in richness, density, and species composition are associated with decreased hydrologic disturbance (in other words, more stable flows), increases in pool depth and habitat diversity, and local geomorphic conditions and processes that contribute to spatial heterogeneity within the stream continuum (Poff and Allan 1995; Schlosser 1990) and may serve to mask responses to anthropogenic disturbance (McCormick and others 2000).

Changing fire regimes and the potential for larger, more destructive fires may threaten the loss of aquatic habitat diversity and lead to accelerated extinction of some vulnerable populations (Dunham and others 2003; Gresswell 1999; Minshall 2003; Rieman and Clayton 1997; Rieman and others 2003). A simple focus on managing fuel, however, may not address the role of fire or the primary threats to the persistence of many species. An approach that aims to restore resiliency to fire related disturbances in both terrestrial and aquatic ecosystems is needed. Development of predictive models relating physical attributes of streams and fish population abundance have shown promise in identifying the high priority reaches for restoration (Barnett and others 2003; Latterell and others 2003; Wu and others 2000). This suggests that similar models might be developed that would identify stream reaches that would be high priority areas for exclusion of treatments.

Amphibians and Reptiles

Amphibians are the most abundant vertebrates in many forests and have the potential to play a significant role in ecosystem dynamics (Wahbe and Bunnell 2003). Riparian and upland habitats provide important habitat for amphibians and semi-aquatic reptiles that depend on mesic ecotones to forage, aestivate, and reproduce (Burke and Gibbons 1995; Castelle and others 1994; Semlitsch 1998). Terrestrial amphibian species richness, abundance, and community composition are highly dependent on catchment forest cover (Houlahan and Findlay 2003; Wahbe and Bunnell 2003). Intensive harvest completely eliminated terrestrial salamanders or reduced them to very low numbers when mature forests were clearcut (Knapp and others 2003; Naughton and others 2000; Perison and others 1997; Petranka and others 1994) though species may persist where large amounts of woody debris are left on the forest floor (Biek and others 2002). At larger catchment scales (400 to 4,000 ha), responses of amphibian and reptile species to management practices (including clearcutting) varied considerably depending on the taxon (Loehle and others 2005; Renken and others 2004). Post-harvest declines in local amphibian populations persist for years post-harvest but abundance and species composition may remain relatively stable at larger spatial scales (Babbitt and Tanner 2000; Herbeck and Larsen 1999). Selective harvests that create small gaps may have little or no effect on amphibians (MacCracken 2005; Messere and Ducey 1998). Reductions in litter depth and coarse woody debris contribute to declines in some amphibian populations because of structural changes to forest floor habitats (DeGraaf and Rudis 1990; Houlahan and Findlay 2003; Loehle and others 2005; Mitchell and others 1997), but studies of forest structure in the Pacific Northwest found no evidence that variation in amphibian abundances was strongly influenced by the amount of coarse woody debris on the forest floor (Aubry 2000; Bunnell and others 1999). Abundance of stream dwelling amphibians is also reduced following timber harvest (Adams and Bury 2002; Bury and others 2002; Corn and Bury 1989).

The vulnerability of amphibian populations to wildfire varies by region, species' life histories, and fire regimes. The coincidence of fire and migration, reproduction, and larval periods may determine the vulnerability of amphibian populations to wildfire. Studies suggest that direct fire related mortality of adult amphibians is rare, either because of the timing of the fire or because amphibian species were able to exploit refugia from fire (for example, burrows, moist ground, ponds, streams; see papers summarized in Pilliod and others 2003). Increases in stream temperature, because of canopy loss, will affect species that exhibit strong thermal preferences (Pilliod and others 2003; Welsh and others 2001; Welsh and Lind 2002). Sedimentation in streams results in reductions in interstitial spaces that can affect reproductive success in amphibian populations, depress growth rates from lost foraging space, and expose individuals to increased predation. Fire may alter conditions along migratory corridors, from terrestrial habitats to the aquatic systems where amphibians breed. Preliminary surveys of post-fire amphibian populations in the Klamath-Siskiyou Region suggest no negative effects of wildfire on terrestrial amphibians, but stream amphibians decreased following wildfire.

The timing of fuel treatments and prescribed burns may be of critical importance to the maintenance of overwintering habitats, post-emergence dispersal, and reproduction of amphibian populations (Thompson and others 2003). In fire driven ecosystems, Russell and others (1999) suggested that in the long-term, prescribed burning could help maintain amphibians in managed forests by sustaining some of the natural processes of ground cover development. Two studies of salamanders in eastern United States plantation forests supported those predictions, although the plantation forests studied were young (25 years) and were compared with much older natural origin forest (Bennett and others 1980; Pough and others 1987). Prescribed fire and thinning to reduce fuel loads will remove large amounts of coarse woody material from forests, which reduces cover for amphibians and alters nutrient inputs to streams. Prescribed fire may increase the mortality of terrestrial amphibians by fire because prescribed burning usually occurs from fall to spring when amphibians in the Northwest are active (Bury 2004). Most reptiles are adapted to open terrain, so fire usually improves their habitat. Reptiles, which often exploit open areas for feeding, basking, and display behaviors, tend to increase in harvested areas (Moseley and others 2003; Perison and others 1997; Renken and others 2004; Shipman and others 2004).

While working to restore "healthy" forests and reduce the risk of catastrophic fires, forest managers must confront the challenge of maintaining biodiversity in western forests and incorporating the understanding of how fire affects semi-aquatic biota with the effects of fuel reduction management on wildlife in western forests (Bury 2004; Olson and others 2002). Management implications for forest lands adjacent to aquatic systems include effects on terrestrial and semi-aquatic species whose habitat requirements extend beyond the margins of wetlands, streams, and rivers (Houlahan and Findlay 2003; Semlitsch and Bodie 2003; Thompson and others 2003). Implementation of an ecosystem management strategy that reverses the current trend of having landscapes dominated by early and mid-successional forests would help restore depleted populations to levels where salamanders better fulfill their ecological roles as forest floor insectivores. Other management techniques that would benefit salamanders include leaving buffers along headwater streams (Sheridan and Olson 2003; Stoddard and Hayes 2005) and using harvesting techniques that ensure that the basic structure and function of forests remain intact following timbering operations.

For purposes of conservation and management, it is important to define core habitats used by local breeding populations surrounding aquatic habitats (Houlahan and Findlay 2003; Semlitsch and Bodie 2003). Semlitsch and Bodie (2003) reviewed studies of riparian habitat use by herpetofauna and found that the mean distances of riparian habitat use ranged from 117 m by salamanders to 368 m by frogs with no significant differences between mean minimum or mean maximum distances exploited by amphibians and reptiles. The survival of semi-aquatic vertebrate populations may rely on intact terrestrial habitats (up to 2 km from aquatic systems) during reproductive seasons, for overwintering, and for maintaining connections among populations (Findlay and Houlahan 1997; Houlahan and Findlay 2003; Roe and others 2003).

Houlahan and Findlay (2003) were unable to resolve the interaction between forest cover and road density in explaining amphibian species richness, but roads have been implicated in reducing amphibian dispersal (Gibbs 1998), increased mortality (Fahrig and others 1995), and reduced genetic diversity (Reh and Seitz 1990). Responses to habitat alterations associated with management activities suggest that these basins may be useful as reserves, especially in catchments where timber harvest may not be commercially viable (Sheridan and Olson 2003).

Fire Suppression Chemicals, Toxicity, and Mortality in Aquatic Organisms

Toxicity effects of fire suppression chemicals on aquatic organisms have been poorly studied (see reviews by Kalabokidis 2000; Gimenez and others 2004). Most fire suppression compounds are based on ammonium salts and toxicity is inferred to result from ammonium ion concentrations (Hamilton and others 1996). Fish, particularly salmonids, and some invertebrates appeared to be vulnerable to the application of these compounds. Boulton and others (2003) observed no short-term effects of fire suppressant chemicals on water chemistry and macroinvertebrates in streams following wildfire, but Buhl and Hamilton (1998, 2000) reported both laboratory toxicity and fish kills associated with fire control compounds.

Fuel Management Activities, Best Management Practices, and Cumulative Watershed Effects

Post-Fire Remediation and Logging

In response to the increased risk of runoff and erosion, land managers and technical specialists sometimes apply erosion control efforts (Burned Area Emergency Rehabilitation or BAER treatments) to mitigate the effects of fire (Neary and others 2000). A recent review of BAER practices indicated inadequate scientific evaluation of the effectiveness of the treatments (Robichaud and others 2000). Some practices contribute to loss of soil integrity, impede the persistence or recovery of native species, disrupt riparian functions, and impair water quality (Karr and others 2004; McIver and Starr 2000). Postfire logging and road building, undertaken on steep slopes with sensitive soils, exacerbate erosion associated with changes in soil and vegetation structure that decrease infiltration and increase overland flow (DeBano and others 1996; McIver and Starr 2000). Too little is known about the cumulative effects of site specific responses at the watershed scale, knowledge that is essential if forest management is to be linked to aquatic ecosystem integrity (Chapter 14). Research at the watershed level that integrates terrestrial and aquatic components is needed to inform management about the risks and opportunities available in the post-fire landscape. Research and resource management agencies should cooperate to develop the basic tools of experimental design that can rapidly evaluate post-fire treatments and reduce the uncertainty of its long-term effects. Salvage harvesting policies could be prepared before major disturbances occur that would guide the timing and intensity of salvage harvesting.

Natural disturbances are key ecosystem processes that help maintain biodiversity, and productivity and support ecosystem restoration by recreating some of the structural complexity and heterogeneity lost through intense management of natural resources (Beschta and others 2004; Bisson and others 2003; DellaSala and others 2004). Salvage harvesting activities undermine many of the ecosystem benefits of major disturbances by removing large quantities of "biological legacies" (for example, snags and downed trees) that are critical habitat for species and important for the recovery of terrestrial and aquatic systems (Benda and others 2003; Lindenmayer and others 2004; May and Gresswell 2003; Swanson 1981; Van Nieuwstadt and others 2001). Effects from postfire logging in riparian areas can persist for many decades because of the loss of dead trees that would normally become incorporated into stream channels and forest floors over several decades or more (Beschta and others 2004; May & Gresswell 2003). Similarly, logging large trees from upslope areas prone to landslides would also reduce, over time, the recruitment of large wood to riparian and aquatic ecosystems. Fire and subsequent hydrologic events can contribute wood and coarse sediment necessary to create and maintain productive in-stream habitats (Bisson and others 2003; Reeves and others 1995) and produce important heterogeneity in channel structure (Benda and others 2003). Natural disturbances interacting with complex terrain has been linked to a changing mosaic of habitat conditions in both terrestrial and aquatic systems (Bisson and others 2003; Miller and others 2003; Naiman and others 2000; Reeves and others 1995). Even with mitigation of fuel, large disturbances are inevitable. Only frequency and magnitude of individual events can be changed (Istanbulluoglu and others 2004). This variation of conditions in space and time may be the key to evolution and maintenance of biological diversity, and ultimately, the resilience and productivity of many aquatic populations and communities (Bisson and others 2003; Dunham and Rieman 1999; Dunham and others 2003; Poff and Ward 1990).

In forested watersheds, valued riparian functions such as stream shading, bank stabilization, and large wood recruitment are largely protected by best management practices, particularly the establishment of riparian buffers since the influence of most riparian features decreases with distance from the stream channel (Beechie and others, 2000; Van Sickle and Gregory 1990). However, the indirect effects of upland fuel treatments on riparian habitats are poorly understood (Chapter 10). Forest harvest strongly affected the riparian microclimate and the riparian environment became more similar to upland conditions (Brosofske and others 1997), but the effects do not necessarily contribute to increases in stream temperature (Poole and Bermann 2001). The effect of fuel reduction activities on drivers of stream temperature needs to be incorporated into management and restoration planning.

Hydrological, geomorphological, and ecological processes in streams and rivers are affected by the recruitment of large wood from riparian and upland portions of watersheds (Bilby and Bisson 1998; Gregory and others 2003; Lienkaemper and Swanson 1987; Montgomery and others 2003). Management plans for fuel reduction that could affect the recruitment of large wood to stream systems need to consider the importance of wood delivery, retention, and transport processes in stream habitats.

Discussion

The widespread decline in forest health has been linked to timber harvest and fire suppression (Bisson and others 2003; Brown and others 2004; Hessburg and Agee 2003). Restoration and management of healthy forest ecosystems must start from the realization that they cannot be fireproofed (Agee 1997). Given the goals of ecosystem restoration and reduction of the risk of severe wildfire, a comprehensive program of pre-fire management, post-treatment monitoring, and adaptive management will be necessary to restore western forests. Effective fuel management will recognize differences among fire regimes, forest and landscape types, and departures from natural regimes, and incorporate the differences among systems (Hessberg and others 1999a, b). Plans must address the importance of spatial pattern of treatments in changing fire behavior at the landscape scale and the strategic placement of treatment areas within constraints imposed by land ownership, the occurrence of endangered species, and the protection of riparian buffers. Resource management strategies that operate under the assumption that forest health can be improved simply by managing vegetation through silvicultural treatments risk damage to key components of aquatic ecosystems. Repeated fire and fuel management programs require knowledge of the cumulative effects of those treatments on aquatic ecosystems.

Restoration efforts based on reestablishing conditions within the range that existed in some former sustainable state with an appropriate fire and forest management program requires knowledge of historic and current conditions and conditions in reference areas (Angermeier 1997; Bisson and others 2003; DellaSala and others 2004; Quigley and others 2001; Winston and Angermeier 1995). We lack information about key characteristics of indicators of forest condition that supports management for conservation of biodiversity (Lindenmayer and others 2000; McRae and others 2001). Potential indicators that move beyond single species management focus on the composition, complexity, connectivity, and heterogeneity of forest structure, the same features that characterize the resistance and resilience of the aquatic network (Rieman and others 2003). Past conditions, including understanding the effects of the frequency, magnitude, and extent of disturbance regimes and the conditions they create over time, can be used to provide a context for managing ecosystems (Benda and others 2003; Cissel and others 1999; Swetnam and others 1999). Among the limitations of applying the "natural disturbance regime" to ecosystem management is that the extent of anthropogenic change in a region may have diminished the ability of species to respond to the disturbance (Swanson and others 1987, 1994). Silvicultural and prescribed fire management tools can lead to the goal of restoring stand structure and composition, but such restoration may have mixed implications for restoring other aspects of failing ecosystems such as fishes and their habitats. The interrelationships of terrestrial and aquatic disturbance regimes and succession processes must be understood if effective land management strategies that do not degrade aquatic resources are to be employed (Hessburg and Agee 2003; Lee and others 1997; MacDonald 2000; Macdonald and others 2004; Rieman and others 2003).

Natural variability of land use, natural vegetation, species diversity, and interactions with inherent disturbance processes needs to be defined at relevant spatial and temporal scales that are climatically, topographically, and biogeographically consistent to provide an appropriate geographic scale (Hann and others 1997). Quantifying variability requires knowledge of both the statistical properties of the condition indicator and an appreciation of the specific attributes of the indicator being described. Describing the "range" of natural variability may be inadequate as the sole descriptor because the occurrence of extreme events (pulse disturbances) may be critical in shaping ecosystem characteristics. Incorporating natural variability into management plans as testable hypotheses about the mechanisms of ecosystem change will facilitate development of future fuel treatment plans. By understanding the variability of natural regimes, using the "natural" state as a template, and modeling the departure of physical systems from that distribution of conditions, we will improve our ability to quantify cumulative effects of treatments on aquatic systems. Successful adoption of such strategies will require explicit statements about the uncertainties involved. Because restoring forest health will require repeated applications of treatments, we require better understanding of the cumulative effects of repeated disturbances.

Reducing Uncertainty: Knowledge Gaps and Research Opportunities

Effective management of riparian areas would minimize cumulative watershed effects on riparian functions by preserving their dynamic connections to upland areas and stream corridors (Reid 1998). Understanding the effects of timber harvest, fuel reduction, and fire requires integration of information about the spatial extent of management activities, temporal aspects of natural disturbance regimes (for example, fire return or landslide frequencies), and historical human disturbance (Franklin and Agee 2003). Anticipating the cumulative watershed effects of fuel treatments on riparian and aquatic ecosystems will be more difficult because of the limited knowledge of the impacts of spatially dispersed, temporally intensive, and repeated treatments in the watershed. As such, effective experimental design of fuel treatment prescriptions and post-impact monitoring will be necessary to increase the available information about the cumulative effects of management activities in sensitive areas.

Uncertainty exists over the approaches for incorporating fire and other disturbance processes into the management of systems from which it has been excluded. Treatments need to be applied as experiments that provide new sources of knowledge that will inform future management decisions (Robichaud and others 2000). Restoration of forest landscapes that protect aquatic resources requires strategies that identify and protect areas with high ecological integrity and connect them at the catchment level to increase the resistance and resilience of ecosystems (Gresswell 1999; Lee and others 1997; Reiman and others 2000). Status (condition) and trends (changes in condition over time) may be tracked at multiple levels of biological organization (from the individual level through population and metapopulation dynamics, assemblage structure, or ecosystem processes). Responses across spatial scales demonstrate the importance of designing sampling strategies and analyses capable of discerning differences from local to regional scales (Angermeier and Winston 1998; Frissell and Bayles 1996; Gregory and others 1991; Li and others 2001; Poff and Allan 1995). Study designs that measure abiotic and biotic factors at multiple spatial scales provide important information for the monitoring and assessment of stream ecosystems (Kershner and others 2004; Larsen and others 2004). Replicating habitats sampled within a stream (as is commonly done in an upstream-downstream paired design comparing reference versus impacted sites) may not reveal the impact, but only portray the natural background variability of stream communities. Both spatially extensive designs with little sampling over time and temporally extensive designs with little or no spatial sampling may be biased in terms of their view of the relative importance of local and landscape factors (Wiley and others 1997). Therefore, study designs with temporal and spatial replication that account for assemblage variability at a range of spatial scales may improve the likelihood of detecting responses of stream ecosystems to wildland fire, fuel treatments, and restoration efforts. Studies designed to follow recovery from disturbance over long time scales (decades or more) would be necessary if we are to overcome limitations imposed by data collected at time scales consistent with more frequent (seasonal or annual) disturbance events. Detailed and temporally and spatially intensive monitoring may be necessary to resolve the variance components of data collected in lotic systems (McCormick and Peck 2000; Minshall and others 2001). Alternatively, paired watershed studies intended to monitor post-fire or post-treatment effects could be designed using the comparative approaches inherent in treatment versus control and before versus after disturbance studies (Before-After, Control-Impact or BACI designs; Barbour and others 1996; Smith and others 2003; Underwood 1992; Wiens and Parker 1995).

To be an effective alternative to cumulative effects studies, adaptive management requires a commitment to regular monitoring and analysis for subsequent management decisions (MacDonald 2000). Forest management and restoration planning require data from regional assessments of forest condition that incorporate spatial and temporal patterns of vegetation, habitats, fuel, and potential fire behavior. Further planning should consider the relations between these conditions and a host of issues surrounding terrestrial habitats and associated aquatic ecosystem conditions. Before management alternatives can be selected and implemented, they must be adequately evaluated for their effects on many terrestrial and aquatic ecosystem components. However, because post-harvest effects often require decades to dissipate, the long-term experimental study of cumulative effects is very costly. In addition, high variance confounds attempt to provide integrated assessments of the effects of timber harvest on aquatic habitats and biota. There is a need for development of a modeling capability for these processes that addresses the large variations in habitat conditions (Benda and others 2004; Davies and others 2000; Keane and others 2002; Poole 2002;).

The spatially discontinuous nature of river networks can inform restoration efforts by providing a better understanding of variability at different spatial scales (Poole 2002). Prioritization of sites for treatment may be based on physical models of fire behavior and response regimes as they relate to key habitats for aquatic populations at risk (Rieman and others 2000; Brown and others 2004). Once identified, such high priority stream reaches could be reconnected via restored corridors at the landscape level. Large scale catchment features successfully predict local scale habitat (Burnett and others 2003; Davies and others 2000) or process controls (Istanbulluoglu and others 2002, 2004; Miller and others 2003; Wondzell and Howell 2004). Independent constraints on climate and geology strongly influence lower level processes in catchment hierarchies and the assemblage responses to the abiotic regime (Burnett and others 2003; Davies and others 2000). The refinement of these models to address spatial and temporal variation in landscape processes supports the emerging capability for modeling catchment scale habitat influences on animal populations and characterizes the species specific potential of streams to provide habitat for fish (Burnett and others 2003). The development of risk assessment models for population and assemblage responses to changes in catchment land use will require detailed information (Keane and others 2002). Further research will contribute to modeling capabilities that assimilate historical conditions and predict future conditions under different management scenarios by reducing the uncertainty associated with the need to estimate model parameters (Keane and others 2002; Roloff and others 2005).

Conclusions

Forest resource managers are confronted with two related management challenges. Aquatic resources, particularly imperiled salmonid populations, require protection and restoration. At the same time, the imperative to reduce the risk of catastrophic wildfires requires ecosystem based management that accounts for the inherent linkage between aquatic and terrestrial systems and involves processes that are fraught with uncertainties (Bisson and others 2003). To ensure the resilience of terrestrial and aquatic ecosystems, it is necessary to consider the restoration of terrestrial and aquatic ecosystems simultaneously. A challenge for research will be to integrate the emerging understanding of changing vegetation and fire with that of watershed and aquatic ecological processes to understand the full implications of the changes made. A challenge for management will be to restore ecological processes that support both resilient terrestrial and resilient aquatic communities. Research and management need to coordinate their efforts to arrive at a common conceptual model that expresses the uncertainties associated with particular courses of management actions and perceived risk to aquatic resources.

The Healthy Forests Restoration Act of 2003 (HFRA; H.R. 1904) increases the emphasis on fuel reduction in forest planning. However, the main impact of HFRA is largely procedural. It is not a strategy for wildland fire risk management. The prevailing conditions in today's forests developed over a century of fire suppression and cannot be dealt with effectively except by long-term adaptive management (Agee and Skinner 2005; Hessburg and Agee 2003). While restoration may be an appropriate course of action, particularly to protect valued aquatic resources, fire disturbance of forests is inevitable and even desirable. Restoration efforts must incorporate natural variability, which precludes a one size fits all approach to fuel management and post-fire activities (Landres and others 1999). The procedural mandates of HFRA will necessitate action before such research can inform the decision making process. Adaptive management, undertaken with controls (including both unlogged and unburned catchments) and replication, can provide extremely valuable information to resource managers.

Successful fuel management will depend on a strategy that incorporates natural variability in patterns of disturbance and its effects on aquatic resources. Fire management is adaptive and requires a long-term commitment to monitoring. Data will be necessary to inform the decision making process, either to reduce uncertainty in decision support tools or evaluate the results of a management option through effectiveness monitoring. Efforts to restore forest condition and maintain the connectivity of terrestrial habitats with their aquatic ecosystems will require that we inventory what we know, analyze variability in our existing data, express the uncertainty associated with analyses and associated predictions, articulate clear goals, design treatments as experiments to test specific hypotheses, monitor treatment outcomes, and apply the results in future planning processes.

We can study the natural vegetation and fire patterns of areas designated for treatment and other areas like it and apply knowledge of those patterns to their management. Recent bioregional assessment projects (for example, Interior Columbia River Basin Ecosystem Management Project and Sierra Nevada Ecosystem Project) provided more information about existing forest and rangeland conditions and the state of ecosystems and their inhabitants than ever before. Incorporation and integration of this information to address interactions between landscape spatial and temporal patterns of vegetation, habitats, fuel, and potential fire behavior will provide a basis for adaptive management that recognizes the functional attributes of the terrestrial-riparian-aquatic interface. Data analyses that characterize variability at different spatial scales will support adaptive management and planning. Modeling and simulation tools capable of incorporating multidimensional data and examining the effects of management activities on key facets of ecosystems are needed. Ideally, they would also serve as tools for planning and evaluating the effects of alternative courses of action on aquatic ecosystems. Modeling and predicting potential impacts of forest harvest operations and wildfire on water quantity and quality are critical tools for forest managers. To make these predictions, the impacts of harvest operations and wildfire on model input parameters must first be quantified with measurements. No one knows exactly how to restore healthy forests that sustain viable populations of native species in functional habitat networks across space and through time. Acknowledging that the inherent complexity and dynamism of ecosystems contributes to uncertainties about outcomes of management practices will be necessary if we are to learn from the effects of those practices and incorporate them into future management planning. Recognition that risks to aquatic ecosystems may be additive, multiplicative, or synergistic across space and time will not preclude mitigation of high fuel loads in forests. Experimental, adaptive approaches to fuel management would unite researchers and resource managers in planning, implementing, and monitoring treatments.

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