The Ecology and Management of Wood in World Rivers

Edited by

Stan V. Gregory

Department of Fisheries and Wildlife, Oregon State University
Corvallis, Oregon 97331, USA

Kathryn L. Boyer

USDA Natural Resources Conservation Service
Wildlife Habitat Management Institute, Department of Fisheries and Wildlife
Oregon State University, Corvallis, Oregon 97331, USA

Angela M. Gurnell

Department of Geography, King's College London
Strand, London WC2R 2LS, UK

American Fisheries Society Symposium 37

International Conference on Wood in World Rivers
held at Oregon State University, Corvallis, Oregon
23–27 October 2000

American Fisheries Society
Bethesda, Maryland
2003

The American Fisheries Society Symposium series is a registered serial. Suggested citation formats follow.

Entire book

Gregory, S. V., K. L. Boyer, and A. M. Gurnell, editors. 2003. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Chapter within the book

Abbe, T. B., A. P. Brooks, and D. R. Montgomery. 2003. Wood in river rehabilitation and management. Pages 367–389 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Printed in the United States of America on acid-free paper.

Library of Congress Control Number 2003112769
ISBN 1-888569-56-5
ISSN 0892-2284

American Fisheries Society website address: www.fisheries.org

American Fisheries Society
5410 Grosvenor Lane, Suite 110
Bethesda, Maryland 20814-2199
USA

American Fisheries Society Symposium 37:407–420, 2003

Riparian Management for Wood in Rivers

Kathryn L. Boyer

USDA Natural Resources Conservation Service, Wildlife Habitat Management Institute
Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon 97331, USA

Dean Rae Berg

Sivicultural Engineering, 15806 60th Avenue W., Edmonds, Washington 98026, USA

Stan V. Gregory

Department of Fisheries and Wildlife, Oregon State University, Corvallis, Oregon 97331, USA

Abstract.—Riparian and floodplain forests are vital components of landscapes. They are transitional zones (ecotones) between river and upland ecosystems where ecological processes occurring in riparian areas and floodplains connect and interact with those of rivers and streams. These forests are the major source of large wood for streams and rivers. Extensive loss of riparian and floodplain forests around the globe is evident from the dramatically reduced supply of large wood in rivers. Clearly, it is necessary to conserve and restore riparian forests to sustain a supply of wood for rivers. This chapter discusses river and land management practices that are designed to provide a continuous source of large wood for rivers and retain wood once it has entered the channel or floodplain. These management practices include conservation of intact riparian and floodplain forests, restoration of ecological processes necessary to sustain riparian forests in the long term, and management of riparian forests specifically to accelerate recruitment of large wood to rivers and streams.

Ecological Functions of Riparian Forests

Large wood is a critical component of rivers and streams of forested ecosystems throughout the world. It provides structure and organic matter that create and enhance habitat diversity and food sources for many riparian and aquatic organisms (Benke and Wallace 2003; Bilby 2003; Dolloff and Warren 2003; Pollock et al. 2003; Steel et al. 2003; Wondzell and Bisson 2003; Zalewski et al. 2003; all this volume). Large wood in rivers and streams originates from both riparian and upland forests (Gurnell 2003; Swanson 2003; both this volume). Upland contributions of wood to streams are highly variable and generally a result of landslides from adjacent hillslopes in headwaters and steeper portions of watersheds (Keller and Swanson 1979; Benda et al. 2003; Nakamura and Swanson 2003; both this volume). The proportion of wood in streams and rivers from landslides historically is relatively small in relation to that recruited cumulatively along the longitudinal miles of intact riparian forests from headwaters to the mainstems of large river systems (Keller and Swanson 1979; Sedell and Froggatt 1984; Townsend 1996; Piégay et al. 1999; Piégay 2003, this volume).

Native riparian forests develop and function in complex and cyclical ways, primarily through disturbances such as floods, fires, pest and disease outbreaks, and hurricanes. These natural disturbances result in regeneration and succession of floodplain and riparian forests (Junk et al. 1989; Stromberg et al. 1993; Piégay and Bravard 1997; Scott et al. 1997; Middleton 2002), channel avulsion and lateral migration, "pulses" of wood transport and relocation, and floodplain development (Agee 1988). Riparian and floodplain forest composition, structure, and successional attributes are affected both by local conditions (such as land management of individual parcels of land and small-scale disturbance regimes) and large-scale changes in climate and human alterations of hydrologic regimes, channel morphology, and land use. Over the past 150–300 years in North America, the past 1,000+ years in Europe, and perhaps even longer in Africa and Asia, riparian forests and their important ecological functions have been chronically and cyclically compromised by human actions at multiple scales (Décamps et al. 1988; Tabacchi et al. 1996; Elosegi and Johnson 2003; Montgomery et al. 2003; both this volume). Throughout the world, riparian forests have high ecological, economic, and intrinsic values (such as natural beauty). These values subject riparian forests to controversy and conflict in an increasingly populous human landscape of multiple jurisdictions and conflicting points of view.

Ecological and physical linkages among riparian forests, rivers and their floodplains are critical to the processes that maintain their many functions (Gregory et al. 1991; Nilsson 1991). Riparian processes occur in three spatial dimensions (longitudinal, lateral, and vertical) and over time within a basin. The conservation, enhancement and restoration of linkages among these processes—necessarily at multiple spatial and temporal scales—is likely one of the most complex land management challenges of the 21st century. Watershed management strategies that recognize relationships among processes acting on riparian forests in space and time are now being incorporated into land management actions and long-term planning (Gregory et al. 1998; Wissmar and Beschta 1998). Land managers and planners are beginning to identify mechanisms that can restore ecological processes of watersheds and should sustain a more continuous, albeit patchy, supply of large wood to rivers (Oliver et al. 1992; Beechie and Bolton 1999; Zalewski et al. 2003). Conservation or management of uplands, rivers, streams, and their floodplains for the purposes of maintaining or restoring riparian function demands technical acuity and interdisciplinary cooperation in forest and riparian ecology, fisheries biology, fluvial geomorphology, hydrology, soil science, silviculture and forest stand dynamics, forest and civil engineering, resource economics, sociology, and other disciplines (Mitsch and Jorgensen 1989; Berg 1995; Montgomery 1997; Zalewski et al. 2003).

Riparian forests affect, and are affected by, their streams and rivers (Junk et al. 1989; Gregory et al. 1991; Bren 1993; Brookes et al. 1996; Hupp and Osterkamp 1996; Huggenberger et al. 1998). Interactions between intact riparian and floodplain forests and their rivers are reciprocal for numerous riparian and riverine processes and functions, especially the exchange of organic matter, including large wood. Land management practices that maintain these functional linkages should be considered when formulating long-term land/river management goals.

Geomorphological linkages of riparian forests: considerations for riparian management

The dynamic nature of riparian forest composition and structure reflect the complex linkages among geomorphic processes acting on rivers and adjacent floodplains (Malanson 1993; Hupp and Osterkamp 1996; Hughes 1997). The geomorphology of the channel and its floodplain will affect rates, amounts, and spatial distribution of wood recruitment resulting from bank erosion and lateral channel migration. Recent studies in the Pacific Northwest of North America indicate that recruitment of wood from forest stands of mountainous streams is greater along unconstrained stream reaches compared to constrained reaches (Acker et al. 2003). Valley form, as well as soil type and quality, also influences the fall direction of a tree potentially available as river wood (Sobota 2003). Studies in montane streams of Oregon draining forests of different management regimes demonstrated that, during a flood, floating large wood and the amount mobilized (congested versus uncongested wood transport) influenced the degree to which floods affect riparian tree toppling. In addition, this water-borne wood significantly influenced the consequent amount of large wood that was recruited to the system during a flood event, with longer-term affects likely influenced by forest management practices that occurred over the previous decades (Johnson et al. 2000). In essence, congested wood transport was a function of recent and historical land-use practices and toppled more riparian trees and deposited more jams in the channel after a flood.

The interaction of in-channel wood, flood-borne deposits, and riparian forest development is essentially a positive feedback loop for wood recruitment. Instream wood accumulations are roughness elements that strongly influence fine sediment and gravel deposition in rivers and floodplains. In turn, these deposits provide substrate suitable for riparian tree seedlings (Swanson and Lienkaemper 1982; Fetherston et al. 1995; Gerhard and Reich 2000). Floodplain and island trees that are able to withstand floods and grow to large size are future sources of large wood for the channel. For example, in a recent study on the Tagliamento River in northeastern Italy, van der Nat et al. (2003) demonstrated that large wood mass in vegetated island-braided reaches was higher (100–150 t/ha) than in a bar-braided reaches (15–70 t/ha).

Seral stage of the riparian forest stand influences amount, type, and size of wood that is recruited through processes of bank failure, windthrow, and mortality from disease (Lienkaemper and Swanson 1987; Hedman et al. 1996; Benda et al. 2003). In large rivers of France, the successional stage of riparian forests coupled with bank erosion rates differ between meandering channels of the Ain River and braided channels of the Drôme River, with consequent differences in wood input volumes (Citterio 1996; Piégay 2003): wood inputs in the Ain River study reach were twice that of the Drôme over the same 8-year period.

Hydrological linkages with riparian forests: considerations for riparian management

Annual hydrological patterns, including flood frequency and magnitude, affect active recruitment of riparian trees to the channel and regeneration success of newly established seedlings on the floodplain, especially for flood-dependent species like cottonwood (*Populus* spp; Howe and Knopf 1991; Décamps 1996; Scott et al. 1997; Shafroth et al. 1998; Stromberg 2001). Natural and altered hydrologic regimes also affect regeneration rates as well as species composition of riparian forests (Johnson 1992; Tabacchi et al. 1996). For example, in arid watersheds of the western United States, exotic species such as saltcedar *Tamarix chinensis* thrive under altered flow regimes that inhibit success of native cottonwood *Populus fremontii* recruitment (Busch and Smith 1995). Hydrological regimes thus influence the susceptibility of a particular river system to invasion by exotic plant species, which, in turn, determines plant community dynamics for long time periods (decades and centuries). This is very evident in the riparian forests along the Garrone River of France, which has a high diversity of tree species (about 200), but greater than 50% of these are exotic species (E. Tabacchi, University of Toulouse, personal communication).

Riparian forest composition and nutrient dynamics: considerations for riparian management

Riparian forest composition affects both spatial and temporal dynamics of wood in streams and rivers, including arrangement and stability of individual pieces and accumulations of wood and decomposition rates. Decomposition rates of large wood in streams and rivers vary widely and depend on tree species, piece size, wood quality and condition, and location within the riparian/aquatic system (Harmon et al. 1986; Beechie and Bolton 1999; Bilby 2003). In forested regions of North America, conifers provide the most desirable structural elements in streams and rivers because they are resistant to movement and decompose slowly (Bisson et al. 2003; Dolloff and Warren 2003). Though deciduous trees generally decompose more quickly than conifers, submerged hardwood species in beaver ponds decompose very slowly, in several reported cases as low as 1.1% per year (Hodkinson 1975).

The contiguity of the riparian forest in a watershed and connectivity of the river with its floodplain affect flow discharge rates, channel migration rates, exchange of nutrients between surface and subsurface flows, all of which in turn affect dynamics of riparian plant communities. Intricacies of these linkages are well illustrated in nutrient cycling processes of temperate forests of the northwest Pacific rim. In this region, returning anadromous salmon and steelhead *Oncorhynchus* spp. are significant nutrient sources to rivers, streams, and adjacent riparian forests. Adult fish, both through excretion and releasing gametes in the month or so following return to freshwater and prior to death, contribute substantial amounts of marine-derived nitrogen (approximately 30% of the total) to a stream (Cederholm et al. 1999). Spawned-out carcasses are the other main source of returning nutrients and, under natural conditions, are distributed extensively throughout the aquatic system where salmon are able to spawn (Cederholm and Peterson 1985; Michael 1995; Bilby et al. 1996; Larkin and Slaney 1997). Recent studies in Alaska compared growth rates of trees in riparian forests adjacent to salmon spawning sites to growth rates of trees in riparian areas adjacent to streams where no spawning historically occurred (Helfield and Naiman 2003). Total annual growth per unit forest area was more than three times higher along spawning reaches. In the same study, tree ring data indicated that trees reached large enough size to fall into and persist in the spawning streams 200 years earlier than in nonspawning reaches. Thus marine-derived nitrogen from spawning salmon appears to fertilize riparian trees that eventually enter the stream and, in turn, may enhance habitat for future generations of salmon.

In the Pacific Northwest of the United States, coastal riparian forests in early seral stages following logging have a large red alder *Alnus rubra* component. Recent studies in Washington State demonstrated that red alder is also a significant source of nitrogen to streams and, thus, may be an important component of riparian forest nutrient cycles, particularly since its nitrogen fixation is directly involved in riparian hardwood production (Volk et al. 2003). Alder-derived nitrogen may offset the lower marine-nitrogen contributions that have occurred with drastic declines in returning adult salmon.

Management Applications for Maintaining a Source of Large Wood for Rivers

The complexity of interactions among the forest and river, its physical setting, its ecological role, and disturbance history poses an intellectual challenge to natural resource scientists and land managers trying to design strategies to restore ecological functions, including those provided by wood in rivers. Add to this inherent complexity the mix of jurisdictional boundaries and socioeconomic concerns of multiple landowners within a watershed, and the land management challenge becomes even more daunting. Wood budgets and models are effective tools in light of this complexity (Benda et al. 2003; Gregory 2003; this volume). Several wood models have been linked to forest models and used to explore the long-term consequences of various riparian management regimes on wood dynamics in streams (Prognosis, Rainville et al. 1985; ORGANON, Berg 1995; FVS, Bragg et al. 2000; RAIS, Welty et al. 2002; Meleason et al., in press) and the fate of carbon from riparian forests (Malanson and Kupfer 1993). Other wood models have been linked to forest stand data to explore wood recruitment characteristics, such as source distance (McDade et al. 1990), frequency distributions of piece volume, length and orientation (Van Sickle and Gregory 1990), and influence of valley wall slope on tree fall angle (Minor 1997; Sobota 2003). A wood budget approach has also been used to explore wood standing stock at the reach- (Murphy and Koski 1989) and network-scale (Benda et al. 2003). Collectively, a range of insights into forest–stream interactions has resulted from wood simulation studies that would otherwise be difficult to obtain through field research alone (Gregory 2003).

Interim- or smaller-scale approaches to improve river and stream fish habitats and to alter fluvial dynamics have focused on the intentional placement of wood in channels (Abbe et al. 2003; Bisson et al. 2003; Reich et al. 2003; all this volume). These short-term approaches can expedite improvement of degraded rivers and streams. However, these approaches are likely to prove even more effective when designed to complement long-term riparian forest management objectives that focus on recovery of a sustainable source of wood for rivers as a central goal. Long-term riparian forest management strategies that highlight wood recruitment as an objective include (1) conservation of intact riparian and floodplain forests, (2) restoration of degraded riparian forests and their ecological processes and functions, and (3) active forestry management that prescribes silvicultural treatments specifically for wood recruitment.

Conservation of intact functional riparian and floodplain forests

Numerous estimates of the dramatic loss of riparian and floodplain forests around the world are alarming in their implications for water quality and aquatic habitats (Welcomme 1979; Tabacchi et al. 1990; NRC 1992, 2002a, 2002b; Malanson 1993). Because of the rapid loss of functional wetlands and riparian areas around the world, the scientific community is calling for aggressive protection of these limited resources. Conservation of intact riparian areas may prove to be the most cost-effective management approach for initial restoration of ecological functions to watersheds, including delivery of wood to channels (Frissell and Nawa 1992; Naiman et al. 1992; Gregory 1997). For example, conservation of soil and soil quality on managed riparian areas can be accomplished indirectly with sound land use practices that protect riparian soils and woody vegetation, such as fencing to exclude livestock from sensitive riparian areas. On private lands, incentive programs that compensate landowners for the purchase of conservation easements or provide tax incentives for riparian conservation are promising approaches to protect intact riparian and floodplain forests as a source for large wood in streams and rivers. However, determining the appropriate value of these lands is not without controversy in market-based economies where ecological goods and services are not customarily considered in real estate appraisals (Daily et al. 1997).

Restoration of degraded riparian and floodplain forests

Management actions that restore long-term dynamics of riparian forests should eventually provide a renewable source of wood for rivers. Restoration of ecological functions may take decades, and in some cases centuries, of concerted management focus to achieve recovery of riparian forests and complex river and stream habitats. This requires patience and perseverance by the people and governments that pay for and implement restoration of impaired ecosystems. In the United States, federal programs such as those of the Farm Bill provide funding for landowners interested in improving fish and wildlife habitat, water quality, and soil erosion, all of which can influence riparian conditions on private lands. However, inadequately trained program managers responsible for developing incentive program objectives may not address the ecological complexity of river-riparian systems and underestimate the time required to restore desired ecological functions. For example, the United State Department of Agriculture's (USDA) Conservation Reserve Enhancement Program provides incentive payments to agricultural landowners in more than 27 states to limit agricultural production in converted riparian areas and replant them with native riparian species. However, out of the 1.4 million acres available for riparian improvement as of 2002, less than 14% have as their primary objective improving riparian areas as a source of large wood for aquatic habitat (USDA, unpublished data). In addition, many of the agreements made between USDA and the landowner require only a 15-year contract period. Longer-term (30–50 years) leases are needed to restore ecological functions to riparian areas, such as wood recruitment to adjacent waters.

Riparian forest restoration goals need not be old-growth forests per se. In most scenarios around the world, restoring riparian forest to late-successional seral stages may not be feasible because managers must work within shorter time frames, infrastructure constraints, and political and economic mandates. In some cases, mimicking or restoring natural flow regimes are promising approaches for riparian restoration (Hughes 1997; Molles et al. 1998; NRC 2002b). Reconnecting floodplains and rivers with connected riparian forest patches of various structure and widths also deserves consideration (Gore and Bryant 1988; Wissmar and Beschta 1998; Ward et al. 1999; Mutz 2000). This approach has potential for restoring large-scale ecological functions to river systems as a whole. Planning and implementing restoration actions as controlled experiments, collecting baseline data, and comparing results to relevant reference sites encourages evaluation and learning about the effectiveness of these innovative approaches and their efficacy for long-term adaptive watershed management (Berg et al. 1998; Zalewski et al. 2003).

Riparian forest management: silvicultural treatments

Stochastic natural disturbances, such as floods, windstorms, fires, landslides, and flood-induced bank erosion, can be expected to deliver most of the potential large wood to rivers and streams, but may be ineffective in reaching supplementation goals for today's wood-deprived rivers. Therefore, a key component of any ambitious watershed restoration strategy should be riparian silviculture. Silvicultural designs that consider principles of stream ecology and forest stand dynamics when developing management prescriptions can accelerate riparian forest succession and wood recruitment. In the Pacific Northwest, goals for stand structure are based on reference conditions of the few remaining old-growth stands, as well as habitat needs of aquatic species (such as complex structure and water quality), especially fish and amphibians. Appropriate riparian forest silvicultural approaches must consider the interactions of aquatic and terrestrial ecosystem processes (Gregory et al. 1991) coupled with life history requirements for a variety of salmon and other aquatic species that live in adjacent streams and rivers. The declines of economically and culturally important salmon have led to numerous studies to determine important freshwater habitat elements, including the size and amounts of instream large wood (Bryant 1983; Bilby and Bisson 1991; Bjornn and Reiser 1991; Bisson et al. 1992; Fausch and Northcote 1992). Scientists and land managers have applied these studies to determine appropriate wood loading standards for maintaining complex salmon and trout habitats, especially on federal lands. As described in previous sections, wood dynamics are complex, and thus, prescribing uniform standards makes less sense than establishing a range of desired conditions tailored to the local area. It is possible to determine the size and amount of wood a riparian forest is expected to provide for specific reaches of stream and river habitat and then determine if this amount lies within a range considered acceptable by aquatic habitat specialists. Tree growth models (for example, Wykoff et al. 1982) have been developed that link site-specific stream wood objectives to the size and density of potential large wood in the riparian forest. Silvicultural systems can be designed to focus on wood recruitment to streams and rivers and incorporate forest growth models for stand projection, site preparation and maintenance regimes, planting density and stand development plans, thinning prescriptions, and monitoring protocols. Each of these aspects is described below:

Stand projections of riparian forests.—The USDA Forest Service Forest Vegetation Simulator (FVS, Wykoff et al. 1982) is an example of a public-domain growth and yield model that can be used to compare growth of various stands once they are established under a silvicultural system. In addition to modeling growth of multispecies stands, FVS can also predict yields in stands of mixed composition (for example, 50% hardwood and 50% conifer species). While there are numerous other public-domain models (for example, DF-SIM, Curtis et al. 1981; TASS, Mitchell and Cameron 1985; ORGANON, Hester et al. 1989), FVS has many versions adaptable to most regions of North America.

While most simulation models are easily accessible, several other methods can estimate riparian forest stand structure through time. Empirical yield tables (McArdle et al. 1949; Minore 1983; Nystrom et al. 1984) predict the growth of a particular species at specific sites. Density management diagrams (DMD) show the relationship between stocking and various growth parameters of a species (for example, Hibbs 1987; Smith 1987; Long et al. 1988). Length of time to desired conditions under different stocking levels can be estimated using these methods.

Site preparation and early stand maintenance.—Riparian forests may be difficult to re-establish in areas where trees have not existed for long periods of time, as in lowland agricultural areas. Often, disturbed sites are prone to invasion by exotic weeds and shrubs, especially immediately following discontinued use of herbicides and pesticides for crop production. Early, intensive site preparation is one key to suppressing weed competition. Nonnative plants (weeds) will likely sprout and grow among planted stock regardless of soil condition. Generally, this is a temporary nuisance because these species are often shade intolerant and do not survive once sapling canopies begin to close (usually within 2–5 years). Some more aggressive exotic species, such as Himalayan blackberry, will competitively exclude desired riparian shrub species for decades and should be controlled early on.

Native riparian understory species also provide important ecological functions of riparian communities, including structural diversity, food sources, microclimate, nutrient cycling, and habitat for riparian species that may influence reciprocal habitat subsidies between riparian areas and streams (Hilderbrand et al. 1999; Steel et al. 2003). These understory plant species should also be considered when designing silvicultural systems for the re-supply of large wood to streams and rivers.

Planting density and stand development.—Initial planting density significantly affects forest stand development. High-density plantations have smaller trees compared to low-density plantations over similar periods of growth. Under high-density scenarios, larger numbers of stems become available for use in stream habitat improvement projects. Actively selecting trees to be thinned, based on the current size or species, can optimize growth. Mixed stock plantations have advantages. Diseases associated with mono-cultures are minimized because pathogen migration is interrupted by plants of different genera, which are resistant to each other's diseases.

Planting pattern.—Once the stand is established and undesirable species are controlled, silvicultural systems can be modified to create desired ecological structure and function (Berg et al. 1998). Numerous species and spatial patterns are possible (Franklin et al. 1996). Two important functions should be considered when establishing riparian forests: (1) adequate trees of the proper size and species should be grown to supply streams or rivers with sufficient volumes of wood, and (2) stands should be managed to maintain adequate shade to moderate stream temperatures.

Competition between planted trees and invasive, exotic vegetation can be reduced by mechanically controlling weeds as frequently as possible. Conventional herbicides are an alternative to mechanical removal, but their use near streams may contaminate surface waters or harm organisms.

Thinning impacts on stand development.—Thinning riparian forest trees can accelerate the time required to reach desired stand conditions by concentrating growth on fewer stems (Daniel et al. 1979; Curtis et al. 1997; Beach and Halpern 2001; Zeide 2001). Competition for nutrients and sunlight among plants is well understood and has been applied to forest stands (Beach and Halpern 2001). As forest stands mature, competition for limited light and nutrients increases. Thinning less desirable species is intended to establish or accelerate development of species of greater economic and/or ecological value, such as providing large, slowly decomposing wood for rivers. Rainville and others (1985) suggest that thinning, if not done properly, will reduce the amount of large wood available for recruitment. While thinning has potential benefits, these methods are largely untested in riparian ecological applications (Berg 1995, 1997; Beechie et al. 2000). Forest managers who invest time and resources must recognize some level of risk, such as tree loss, because of the physically active and dynamic nature of floodplains and riparian areas. Simulations from FVS models predict that thinning produces larger numbers of trees that meet the desired size criteria within the given time for both Douglas-fir *Pseudotsuga menzesii* and western redcedar *Thuja plicata* (Table 1). Though average diameters of two stands may be comparable, small trees are far more numerous in an un-thinned stand (Berg, author's unpublished data). Thinning concentrates growth in fewer individuals so that the sizes of trees are larger though density is lower. This equates to a potentially higher value from both financial and ecological standpoints. If the objective is to maximize the number of trees of a desired size, stands could be planted at high densities along all streams up to 20 m wide, since by year 100 (earlier on the smaller streams), enough wood could be recruited to the stream to meet the desired outcomes. Other stocking levels produce larger diameter trees but at lower overall density, limiting the available large wood for recruitment to streams and rivers. The former might be necessary where streams are devoid of large wood, while the latter may be useful on streams with desired amounts of large wood, and regenerating standing stock in the riparian forest would be available as a long-term source of wood for the channel.

Thinning can be done in patches or applied uniformly across a forest stand (Franklin et al. 1996). Various patterns of thinning can affect the type and amount of natural regeneration of riparian forest. For example, openings of one-quarter to one-half acre have been found to provide sufficient growing space for Douglas-fir regeneration (Isaac 1943; Curtis et al. 1997). Because of the proximity to edges in many riparian stands (streamside and fieldside), light availability may be greater than in forest interiors, resulting in greater natural regeneration.

Monitoring.—Monitoring managed riparian forests provides a framework for systematic and quantitative measurements of change over time. Monitoring silvicultural systems that are designed and implemented specifically as a source for wood in rivers can generate timely information about the progress of riparian forest development and the effectiveness of silvicultural treatments to meet wood recruitment goals. Through monitoring, problems can be identified and silvicultural practices can be modified to better achieve goals and objectives of the landowner (Berg 1997).

Vegetation monitoring generally includes estimating seedling survival and density, measuring annual growth rates, estimating cover and/or biomass production, and quantifying species diversity. Performance standards for vegetation are based on the initial planting density, which is site-specific, and a function of the managed stem density. High survival is desired because high density will block invasive exotic plants and provide the broadest possible selection for thinning. Data collected when monitoring a stand can be used to develop contingency plans for corrective measures to take in the event that performance standards are not met.

Monitoring channel conditions to assess wood loading and habitat changes provides a way to evaluate effectiveness of forest management

TABLE 1. FVS modeled stands for Douglas-fir and western redcedar, demonstrating the effect of thinning on tree diameter (DBH) and height. Stand initiation conditions for these silvicultural systems were 4,064 total stems per hectare (SPH); thinning was from below (removing the smallest stems first) and removed 50% of the stems at each entry.

	Douglas-fir			Western redcedar			
Stand treatment	Mean DBH (cm)	Mean tree height (m)	SPH	Mean DBH (cm)	Mean tree height (m)	SPH	Total SPH
50 years							
No thin	29.4	26	540	29.4	26	529	1069
Thin twice at age 20 and 40	35.6	28	716	35.4	28	54	303
Thin once at age 25	33.9	28	635	33.8	28	214	849
100 years							
No thin	51.6	39	179	51.6	39	175	354
Thin twice at age 20 and 40	56.0	41	287	56.0	41	20	307
Thin once at age 25	55.7	41	235	55.7	41	76	312

and the rate at which aquatic habitat is improving as a result of riparian silvicultural practices. Where target numbers of large wood pieces have been achieved by placing logs from the adjacent stand after a thinning or from off-site sources, periodic monitoring (annually for 5–10 years) is necessary to evaluate the long-term effectiveness of the project. This includes surveys to determine if large wood remains within the project reach or if replacement from upstream or the riparian forest has kept the reach in desired condition. Amounts of wood can change if the export of wood exceeds the import or if the wood traps other pieces that have moved from upstream. If large wood is exported faster than it is delivered from the adjacent riparian area or from upstream, wood supplements may need to be added. This additional wood should only come from the adjacent riparian forest if monitoring data suggest that trees of sufficient size exist in adequate numbers to sustain a long-term source of wood into the future.

In addition, characteristics of the riparian forest (density of trees, average and maximum sizes, crown structure, rate of growth and regeneration, understory vegetation, and overall community structure) should be monitored to guide ongoing riparian management. These attributes of riparian forests are related to the effectiveness and validation of the proposed or implemented silvicultural system.

A multifunctional silvicultural plan designed to improve riparian forest conditions for long-term recruitment of wood to rivers should be designed to evaluate the effectiveness of different riparian management strategies in meeting ecological objectives. A network of well-documented and monitored riparian silvicultural systems then becomes a robust set of treatments to test various prescriptions and ecological responses in the watershed. Riparian forest management does come at some price. The costs of tending the stand may not be recovered from harvest revenue and are thus an unrewarded investment in ecological services for the benefit of fish, water quality, and riparian forests. If designed, implemented, and monitored carefully, these systems can also serve as demonstration sites of successful forestry applications for agencies or landowners seeking to justify the costs of providing ecological services to society.

Conclusion

Riparian forest management applications presented here integrate what we know about riparian processes with specific techniques to restore or improve riparian functions. They are based on current knowledge of natural ecosystem functions and practical considerations (Berg 1995; Gregory 1997; Bilby and Bisson 1998; Naiman et al. 1999). Hypotheses about riparian forest improvement and subsequent wood recruitment to rivers can be tested using an experimental, science-based approach with cooperation from stakeholders who are applying innovative techniques on their land (Franklin 1997; Hulse et al. 2002). Concurrently, managers and stakeholders must acknowledge the dynamic nature of riparian and floodplain forests and the amount of time required to restore ecological functions in a constantly changing landscape. The spatial significance of the effects of riparian forests on river landscapes and the globally significant conditions that are likely to impact their conservation must also be recognized. Climate and land-use changes coupled with their impacts on hydrological regimes have clear consequences on the quality, quantity, and dynamics of wood in rivers. Restoring function to altered landscapes may be daunting, and a return to what we think of as historical presettlement conditions is not feasible. Restoring even a fraction of a managed riparian landscape is warranted if, in doing so, key processes important for clean water, fish and wildlife habitat, and intrinsic values are sustained for future generations.

Acknowledgments

We are grateful to the following colleagues for technical assistance with this chapter: Mark Meleason assisted with wood modeling text and content. Art Mckee, Mike Maki, and Dan Sobota provided timely and thorough editorial review and suggestions for improvement.

References

Abbe, T. A., A. P. Brooks, and D. R. Montgomery. 2003. Wood in river rehabilitation and management. Pages 367–389 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Acker, S. A., S. V. Gregory, G. Lienkaemper, W. A. McKee, F. J. Swanson, and S. D. Miller. 2003. Composition, complexity, and tree mortality in riparian forests in the central Western Cascades of Oregon. Forest Ecology and Management 173:293–308.

Agee, J. K. 1988. Successional dynamics in forest riparian zones. Pages 31–43 *in* K. J. Raedeke, editor. Streamside management: forestry and fishery interactions. Institute of Forest Resources, University of Washington, Seattle.

Beach, E. W., and C. B. Halpern. 2001. Controls on conifer regeneration in managed riparian forests: effects of seed source, substrate, and vegetation. Canadian Journal of Forest Research 31:471–482.

Beechie, T., and S. Bolton. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries 24(4):6–15.

Beechie, T., G. Pess, P. Kennard, R. E. Bilby, and S. Bolton. 2000. Modeling recovery rates and pathways for woody debris recruitment in Northwestern Washington streams. North American Journal Fisheries Management 20:436–452.

Benda, L., D. Miller, J. Sias, D. Martin, R. Bilby, C. Veldhuisen, and T. Dunne. 2003. Pages 49–73 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Benke, A. C., and J. B. Wallace. 2003. Influence of wood on invertebrate communities in streams and rivers. Pages 149–177 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Berg, D. R. 1995. Riparian silvicultural system design and assessment in the Pacific Northwest Cascade Mountains. Ecological Applications 5:87–96.

Berg, D. R. 1997. Active management of riparian habitats. Pages 50–61 *in* K. B. McDonald and F. Weinmann, editors. Wetland and riparian restoration: taking a broader view. US EPA, Region 10, Publication EPA 910-R-97–007, Seattle.

Berg, D. R., P. Stevenson, and S. Hashisaki. 1998. Riparian silvicultural trials in Washington State. Pages 23–25 *in* Ecosystem restoration: turning the tide; proceedings 1998 Society of Ecological Restoration Northwest Chapter Symposium. Society of Ecological Restoration and University of Washington Center for Streamside Studies.

Bilby, R E., and P. A. Bisson. 1991. Enhancing fisheries resources through active management of riparian areas. Pages 201–209 *in* B. White and I. Guthrie, editors. Proceedings of the 15th Northeast Pacific Pink and Chum Salmon Workshop. Pacific Salmon Commission, Vancouver.

Bilby, R. E., B. R. Fransen, and P. A. Bisson. 1996. Incorporation of nitrogen and carbon from spawning coho salmon into the trophic system of small streams: evidence from stable isotopes. Canadian Journal of Fisheries and Aquatic Sciences 53:164–173.

Bilby, R. E., and P. A. Bisson. 1998. Function and distribution of large woody debris. Pages 324–346 *in* R. J. Naiman and R. E. Bilby, editors. River ecology and management lessons from the Pacific coastal ecoregion. Springer-Verlag, New York.

Bilby, R. E. 2003. Decomposition and nutrient dynamics of wood in streams and rivers. Pages 135–147 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Bisson, P. A., T. P. Quinn, G. H. Reeves, and S. V. Gregory. 1992. Best management practices, cumulative effects, long-term trends in fish abundance in Pacific Northwest river systems. Pages 189–232 *in* R. J. Naiman, editor. Watershed management: balancing sustainability and environmental change. Springer-Verlag, New York.

Bisson, P. A., G. H. Reeves, and S. V. Gregory. 2003. Trends in using wood to restore aquatic habitats and fish communities in western North American rivers. Pages 391–406 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Bjornn, T. C., and D. W. Reiser. 1991. Habitat requirements of salmonids in streams. Pages 83–138 *in* W. R. Meehan, editor. Influences of forest and rangeland management on salmonid fishes and their habitats. American Fisheries Society, Special Publication 19, Bethesda, Maryland.

Bragg, D. C., J. L. Kershner, and D. W. Roberts. 2000. Modeling large woody debris recruitment for small streams of the Central Rocky Mountains. United States Department of Agriculture Forest Service, Rocky Mountain Research Station General Technical Report RMRS-GTR-55, Fort Collins, Colorado.

Bren, L. J. 1993. Riparian zone, stream, and floodplain issues: a review. Journal of Hydrology 150:277–299.

Brookes, A., J. Baker, and C. Redmond. 1996. Floodplain restoration and riparian zone management. Pages 201–228 *in* A. Brookes and J. F. Shields, editors. River channel restoration: guiding principles for sustainable projects. Wiley, Chicester, UK.

Bryant, M. D. 1983. The role and management of woody debris in West Coast salmonid nursery streams. North American Journal of Fisheries Management 3:322–330.

Busch, D. E., and S. D. Smith. 1995. Mechanisms associated with decline of woody species in riparian ecosystems of the southwestern U.S. Ecological Monographs 65:347–370.

Cederholm, C. J., and N. P. Peterson. 1985. The retention of coho salmon (*Oncorhynchus kisutch*) carcasses by organic debris in small streams. Canadian Journal of Fisheries and Aquatic Sciences 42:1222–1225.

Cederholm, C. J., M. D. Kunze, T. Murota, and A. Sibatani. 1999. Pacific salmon carcasses: essential contributions of nutrients and energy for aquatic and terrestrial ecosystems. Fisheries 24(10):6–15.

Citterio, A. 1996. Dynamique de dépôts et de prise en charge du bois mort sur deux hydrosystèmes l'Ain et la Drôme (The dynamics of deposition and mobilisation of dead wood in two hydrosystems: the River Ain and the River Drôme). Master's Thesis. Université Lyon, Lyon, France.

Curtis, R. O., G. W. Clendenen, and D. J. DeMars. 1981. A new stand simulator for coastal Douglas-fir: DFSIM users guide. USFS Pacific Northwest Forest and Range Experiment Station, General Technical Report PNW-128, Portland, Oregon.

Curtis, R. O., D. D. Marshall, and J. F. Bell. 1997. LOGS: A pioneering example of silvicultural research in coast Douglas-fir. Journal of Forestry 95:19–25.

Daily, G. C., S. Alexander, P. R. Ehrlich, L. Goulder, J. Lubchenco, P. A. Matson, H. A. Mooney, S. Postel, S. H. Schneider, D. Tilman, and G. M. Woodwell. 1997. Ecosystem services: benefits supplied to human societies by natural ecosystems. Issues in Ecology 2:1–16.

Daniel, T. W., J. A. Helms, and F. S. Baker. 1979. Principles of silviculture. 2nd edition. McGraw-Hill, New York.

Décamps, H., M. Fortune, F. Gazelle, and G. Pautou. 1988. Historic influence of man on the riparian dynamics of a fluvial landscape. Landscape Ecology 1:163–173.

Décamps, H. 1996. The renewal of floodplain forests along rivers: a landscape perspective. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 26:35–59.

Dolloff, C. A., and M. L. Warren, Jr. 2003. Fish relationships with large wood in small streams. Pages 179–193 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Elosegi, A., and L. B. Johnson. 2003. Wood in streams and rivers in developed landscapes. Pages 337–353 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Fausch, K. D., and T. G. Northcote. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Canadian Journal of Fisheries and Aquatic Sciences 49:682–693.

Fetherston, K. L., R. J. Naiman, and R. E. Bilby. 1995.

Large woody debris, physical process, and riparian forest succession in montane river networks of the Pacific Northwest. Geomorphology 13:133–144.

Franklin, J. F., D. R. Berg, D. A. Thornburgh, and J. C. Tappener. 1996. Alternative silvicultural approaches to timber harvesting: variable retention harvest systems. Pages 111–130 *in* K. A. Kohm and J. F. Franklin., editors. Creating a forestry for the 21st century: the science of ecosystem management. Island Press, Washington, D.C.

Franklin, J. F. 1997. Ecosystem management: an overview. Pages 21–53 *in* A. W. Haney and Mark S. Boyce, editors. Ecosystem management: applications for sustainable forest and wildlife resources. Yale University Press, New Haven, Connecticut.

Frissell, C. A., and R. K. Nawa. 1992. Incidence and causes of physical failure of artificial habitat structures in streams of western Oregon and Washington. North American Journal of Fisheries Management 12:182–197.

Gerhard, M., and M. Reich. 2000. Restoration of streams with large wood: effects of accumulated and built-in wood on channel morphology, habitat diversity and aquatic fauna. International Review of Hydrobiology 85:123–137.

Gore, J. A., and F. L. Bryant. 1988. River and stream restoration. Pages 23–38 *in* Rehabilitating damaged ecosystems. CRC Press Inc., Boca Raton, Florida.

Gregory, S. V., F. J. Swanson, W. A. McKee, and K. W. Cummins. 1991. An ecosystem perspective of riparian zones: focus on links between land and water. Bioscience 41:540–551.

Gregory, S. V. 1997. Riparian management in the 21st century. Pages 69–85 *in* K. A. Kohm and J. F. Franklin, editors. Creating a forestry for the 21st century. Island Press, Washington, D.C.

Gregory, S. V., D. W. Hulse, D. H. Landers, and E. Whitelaw. 1998. Integration of biophysical and socioeconomic patterns in riparian restoration of large rivers. Pages 231–247 *in* H. Wheater and C. Kirby, editors. Hydrology in a changing environment. Wiley, Exeter, UK.

Gregory, S. V. 2003. Modeling the dynamics of wood in streams and rivers. Pages 315–335 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Gurnell, A. M. 2003. Wood storage and mobility. Pages 75–91 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Harmon M. E., J. F. Franklin, F. J. Swanson, P. Sollins, S. P. Cline, N. G. Aumen, J. R. Sedell, G. W. Lienkaemper, K. Cromack, Jr., and K. W. Cummins. 1986. The ecology of coarse woody debris in temperate ecosystems. Pages 133–302 *in* A. MacFadyen and E. D. Ford, editors. Advances in ecological research. Volume 15. Academic Press, New York.

Hedman, C. W., D. H. Van Lear, and W. T. Swank. 1996. In-stream large woody debris loading and riparian forest seral stage associations in southern Appalachian Mountains. Canadian Journal of Forestry Research 26:1218–1227.

Helfield, J. M., and R. J. Naiman. 2003. Effects of salmon-derived nitrogen on riparian forest growth and implications for stream productivity. Ecology 82:2403–2409.

Hester, A. S., D. W. Hann, and D. R. Larson. 1989. Organon: southwest Oregon growth and yield model user manual, version 2.0. Forest Research Lab, College of Forestry, Oregon State University, Corvallis.

Hibbs, D. E. 1987. The self-thinning rule and red alder management. Forest Ecology and Management 18:273–281.

Hilderbrand, G. V., T. A. Hanley, C. T. Robbins, and C. C. Schwartz. 1999. Role of brown bears (*Ursus arctos*) in the flow of marine nitrogen into a terrestrial ecosystem. Oecologia 121:546–550.

Hodkinson, I. D. 1975. Dry weight loss and chemical changes in vascular plant litter of terrestrial origin, occurring in a beaver pond ecosystem. Journal of Ecology 63:131–142.

Howe, W. H., and F. L. Knopf. 1991. On the imminent decline of the Rio Grande cottonwoods in central New Mexico. Southwestern Naturalist 36:218–224.

Huggenberger, P., E. Hoehn, R. Beschta, and W. Woessner. 1998. Abiotic aspects of channels and floodplains in riparian ecology. Freshwater Biology 40:407–425.

Hughes, F. M. R. 1997. Floodplain biogeomorphology. Progress in Physical Geography 21:501–529.

Hulse, D., S. Gregory, and J. Baker. 2002. Willamette River basin planning atlas: trajectories of environmental and ecological change. Oregon State University Press, Corvallis.

Hupp, C. R., and W. R. Osterkamp. 1996. Riparian vegetation and fluvial geomorphic processes. Geomorphology 14:277–295.

Isaac, L. A. 1943. Reproductive habits of Douglas-fir. C. L. Pack Forestry Foundation, Washington D.C.

Johnson, W. C. 1992. Dams and riparian forests: case study from the upper Missouri River. Rivers 3:229–242.

Johnson, S. L., F. J. Swanson, G. E. Grant, and S. M. Wondzell. 2000. Riparian forest disturbances by a mountain flood—the influence of floated wood. Hydrological Processes 14:3031–3050.

Junk, W. J., P. B. Bayley, and R. E. Sparks. 1989. The flood pulse concept in river-floodplain systems.

Canadian Special Publications in Fisheries and Aquatic Sciences 106:110–127.

Keller, E. A., and F. J. Swanson. 1979. Effects of large organic material on channel form and fluvial processes. Earth Surface Processes 4:361–380.

Larkin, G. A., and P. A. Slaney. 1997. Implications of trends in marine-derived nutrient influx to south coastal British Columbia salmonid production. Fisheries 22(11):16–24.

Lienkaemper, G. W., and F. J. Swanson. 1987. Dynamics of large woody debris in streams in old-growth Douglas-fir forests. Canadian Journal of Forest Research 17:150–156.

Long, J. N., J. B. McCarter, and S. B. Jack. 1988. A modified density management diagram for coastal Douglas-fir. Western Journal Applied Forestry 3(3):88–89.

Malanson, G. P. 1993. Riparian landscapes. Cambridge University Press, Cambridge, UK.

Malanson, G. P., and J. A. Kupfer. 1993. Simulated fate of leaf litter and woody debris at a riparian cutbank. Canadian Journal of Forest Research 23:582–590.

Meleason, M. A., S. V. Gregory, and J. P. Bolte. In press. Implications of riparian management strategies on wood in streams of the Pacific Northwest. Ecological Applications.

McArdle, R. E., W. H. Meyer, and D. Bruce. 1949. Yield of Douglas-fir in the Pacific Northwest, Revised. USDA Technical Bulletin 201, Washington, D.C.

McDade, M. H., F. J. Swanson, W. A. McKee, J. F. Franklin, and J. V. Sickle. 1990. Source distances for coarse woody debris entering small streams in western Oregon and Washington. Canadian Journal of Forest Research 20:326–330.

Michael, J. H. 1995. Enhancement effects of spawning pink salmon on stream rearing juvenile coho salmon: managing one resource to benefit another. Northwest Science 69(3):228–233.

Middleton, B. 2002. Flood pulsing in wetlands: restoring the natural hydrological balance. Wiley, New York.

Minor, K. P. 1997. Estimating large woody debris recruitment from adjacent riparian areas. Master's thesis. Oregon State University, Corvallis.

Minore, D. 1983. Western redcedar: a literature review. USDA USFS General Technical Report PNW-150, Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Mitchell, K. J., and I. R. Cameron. 1985. Managed stand yield table for coastal Douglas-fir: initial density and precommercial thinning. Ministry of Forests, Victoria, BC.

Mitsch, W. J., and S. E. Jorgensen. 1989. Ecological engineering. Wiley and Sons, Inc., New York.

Molles, M. C. Jr., C. S. Crawford, L. M. Ellis, H. M. Vallett, and C. N. Dahm. 1998. Managed flooding for riparian ecosystem restoration. BioScience 48:749–756.

Montgomery, D. R. 1997. What's best on the banks? Nature 388:328–329.

Montgomery, D. R., B. D. Collins, J. M. Buffington, and T. B. Abbe. 2003. Pages 21–47 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Murphy, M. L., and K. V. Koski. 1989. Input and depletion of woody debris in Alaska streams and implications for streamside management. North American Journal of Fisheries Management 9:427–436.

Mutz, M. 2000. Influences of woody debris on flow patterns and channel morphology in a low-energy, sand-bed stream reach. International Review of Hydrobiology 85:107–121.

Naiman, R. J., T. J. Beechie, L. E. Benda, D. R. Berg, P. A. Bisson, L. H. MacDonald, M. D. O'Conner, P. L. Olsen, and E. A. Steele. 1992. Fundamentals of ecologically healthy watersheds in the Pacific Northwest coastal ecoregion. Pages 127–188 *in* R. J. Naiman, editor. Watershed management: balancing sustainability and environmental change. Springer-Verlag. New York.

Naiman, R. J., S. R. Elliott, J. M. Helfield, and T. C. O'Keefe. 1999. Biophysical interactions and the structure and dynamics of riverine ecosystems: the importance of biotic feedbacks. Hydrobiologia 410:79–86.

Nakamura, F., and F. J. Swanson. 2003. Dynamics of wood in rivers in the context of ecological disturbance. Pages 279–297 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Nilsson, C. 1991. Conservation management of riparian communities. Pages 352–372 *in* L. Hansson, editor. Ecological principles of nature conservation. Elsevier Press, Amsterdam.

NRC (National Research Council). 1992. Restoration of aquatic ecosystems: science, technology, and public policy. National Academy Press, Washington, D.C.

NRC (National Research Council). 2002a. The Missouri River ecosystem: exploring the prospects for recovery. National Academy Press, Washington, D.C.

NRC (National Research Council). 2002b. Riparian areas: functions and strategies for management. National Academy Press, Washington, D.C.

Nystrom, M. N., D. S. DeBell, and C. D. Oliver. 1984. Development of young growth Western redcedar stands. USFS Research paper. PNW 324. Pacific Northwest Forest and Range Experiment Station, Portland, Oregon.

Oliver, C. D., D. R. Berg, D. R. Larsen, and K. L. O'Hara. 1992. Integrating management tools, ecological knowledge, and silviculture. Pages 361–382 *in* R. J. Naiman, editor. Watershed management: balancing sustainability and environmental change. Springer-Verlag, New York.

Piégay, H., and J.-P. Bravard. 1997. Response of a Mediterranean riparian forest to a 1 in 400 year flood. Ouveze River, Drome-Vaucluse, France. Earth Surface Processes and Landforms 22:31–43.

Piégay, H., A. Thevenet, and A. Citterio. 1999. Input, storage and distribution of large woody debris along a mountain river continuum, the Drôme River, France. Catena 35:19–39.

Piégay, H. 2003. Dynamics of wood in large rivers. Pages 109–133 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland

Pollock, M. M., M. Heim, and D. Werner. 2003. Hydrologic and geomorphic effects of beaver dams and their influence on fishes. Pages 213–233 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Rainville, R. P., S. C. Rainville, and E. L. Lider. 1985. Riparian silvicultural strategies for fish habitat emphasis. Pages 186–196 *in* Proceedings of 1985 Society of American Foresters National Convention. Fort Collins, Colorado.

Reich, M., R. Wildman, and J. L. Kershner. 2003. Restoring streams with large wood: a synthesis. Pages 355–366 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Sedell, J. R., and J. L. Froggatt. 1984. Importance of streamside forests to large rivers: The isolation of the Willamette River, Oregon, U.S.A., from its floodplain by snagging and streamside forest removal. Verhandlungen Internationale Vereinigung für Theoretische und Angewandte Limnologie 22:1828–1834.

Scott, M. L., G. T. Auble, and J. M. Friedman. 1997. Flood dependency of cottonwood establishment along the Missouri River, Montana, USA. Ecological Applications 7:677–690.

Shafroth, P. B., G. T. Auble, J. C. Stromberg, and D. T. Patten. 1998. Establishment of woody riparian vegetation in relation to annual patterns of streamflow, Bill Williams River, Arizona. Wetlands 18:577–590.

Smith, N. J. 1987. Stand density control diagram for Western Redcedar, *Thuja plicata*. Forest Ecology and Management 27:235–244.

Sobota, D. J. 2003. Fall directions and breakage of riparian trees along streams of the Pacific Northwest. M. S. Thesis. Oregon State University. Corvallis.

Steel, E. A., W. H. Richards, and K. A. Kelsey. 2003. Wood and wildlife: benefits of river wood to terrestrial and aquatic vertebrates. Pages 235–247 in S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Stromberg, J. C., S. D. Wilkens, and J. A. Tress. 1993. Vegetation-hydrology models as management tools for velvet mesquite (*Prosopis velutina*) riparian ecosystems. Ecological Applications 3:307–314.

Stromberg, J. 2001. Restoration of riparian vegetation in the south-western United States: importance of flow regimes and fluvial dynamism. Journal of Arid Environments 49:17–34.

Swanson, F. J. 2003. Wood in rivers: a landscape perspective. Pages 299–313 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Swanson, F. J., and G. W. Lienkaemper. 1982. Interactions among fluvial processes, forest vegetation, and aquatic ecosystems, South Fork Hoh River, Olympic National Park. Pages 30–34 *in* E. E. Starkey, J. F. Franklin and J. W. Matthews, editors. Ecological research in national parks of the Pacific Northwest. Oregon State University Press, Corvallis.

Tabacchi, E., A. M. Planty-Tabacchi, and H. Décamps. 1990. Continuity and discontinuity of the riparian vegetation along a fluvial corridor. Landscape Ecology 5:9–20.

Tabacchi, E., A. Planty-Tabacchi, M. J. Salinas, and H. Décamps. 1996. Landscape structure and diversity in riparian plant communities: a longitudinal comparative study. Regulated Rivers: Research and Management 12:367–390.

Townsend, C. R. 1996. Concepts in river ecology: pattern and process in the catchment hierarchy. Archiv Fur Hydrobiologie Supplement 113:4–21.

van der Nat, D., K. Tockner, P. J. Edwards, and J. V. Ward. 2003. Large wood dynamics of complex Alpine river floodplains. Journal of the North American Benthological Society 22:35–50.

Van Sickle, J., and S. V. Gregory. 1990. Modeling inputs of large woody debris to streams from falling trees. Journal of Forest Research 20:1593–1601.

Volk, C. J., P. M. Kiffney, and R. L. Edmonds. 2003. Role of riparian red alder in the nutrient dynamics of coastal streams of the Olympic Peninsula, Washington, USA. Pages 213–225 *in* J. Stockner, editor. Nutrients in salmonid ecosystems: sustaining production and biodiversity. American Fisheries Society, Symposium 34, Bethesda, Maryland.

Ward, J. V., K. Tockner, and F. Schiemer. 1999. Biodiversity of floodplain river ecosystems: ecotones and connectivity. Regulated Rivers: Research and Management 15:125–139.

Welcomme, R. 1979. Fisheries ecology of floodplain rivers. Longman, New York.

Welty, J. J., T. Beechie, K. Sullivan, D. M. Hyink, R. E. Bilby, C. Andrus, and G. Pess. 2002. Riparian Aquatic Interaction Simulator (RAIS): a model of riparian forest dynamics for the generation of large woody debris and shade. Forest Ecology and Management 162:299–318.

Wissmar, R. C., and R. L. Beschta. 1998. Restoration and management of riparian ecosystems: a catchment perspective. Freshwater Biology 40:571–585.

Wondzell, S. M., and P. A. Bisson. 2003. Influence of wood on aquatic biodiversity. Pages 249–263 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Wykoff, W. R., N. L. Crookston, and A. R. Stage. 1982. User's guide to the Stand Prognosis Model {FVS}. USDA, Forest Service, Intermountain Research Station, General Technical Report INT-133, Ogden, Utah.

Zalewski, M., M. Lapinska, and P. B. Bayley. 2003. Fish relationships with wood in large rivers. Pages 195–211 *in* S. V. Gregory, K. L. Boyer, and A. M. Gurnell, editors. The ecology and management of wood in world rivers. American Fisheries Society, Symposium 37, Bethesda, Maryland.

Zeide, B. 2001. Thinning and growth. Journal of Forestry 99:20–25.