How did fixed-width buffers become standard practice for protecting freshwaters and their riparian areas from forest harvest practices?

Author: Richardson, John S.

Source: Freshwater Science, 31(1) : 232-238

Published By: Society for Freshwater Science

URL: https://doi.org/10.1899/11-031.1

Freshwater Science, 2012, 31(1):232–238
© 2012 by The Society for Freshwater Science
DOI: 10.1899/11-031.1
Published online: 24 January 2012

BRIDGES

How did fixed-width buffers become standard practice for protecting freshwaters and their riparian areas from forest harvest practices?

John S. Richardson[1]
Department of Forest Sciences, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z4

Robert J. Naiman[2]
School of Aquatic and Fishery Sciences, Box 355020, University of Washington, Seattle, Washington 98195 USA

Peter A. Bisson[3]
US Department of Agriculture Forest Service, Pacific Northwest Research Station, Olympia Forestry Sciences Laboratory, Olympia, Washington 98512-9193 USA

Abstract. Riparian buffers provide improved protection for water quality and biota, and narrow, fixed-width buffers of native vegetation along streams have been used to mitigate the effects of forest harvest at least since the 1960s. The practice of leaving unmanaged strips of vegetation along water courses in agricultural lands had been used before the 1960s in southern Europe and in eastern North America, but the scientific basis for leaving riparian buffers on forested lands came from observations in the coastal temperate rainforests of western North America. Those observations often were applied to other forested landscapes without further considerations. Fixed-width buffers are administratively simple to implement and assess, and have come to be the norm for streamside protection from forestry. Most guidelines for streamside protection allow some local modification for site and watershed-scale considerations, but frequently, the option to deviate from fixed-width buffers is not exercised because of uncertainty about outcomes. Few experiments have been done to test the efficacy of buffers of a particular width or of site- or landscape-specific modifications.

Key words: forestry, riparian buffers, historical context, natural disturbance emulation.

Not long ago, forests in many parts of the world seemed inexhaustible, and streams and lakes were convenient conveyors of wood to mills. Common practice was to harvest trees down to the edge of the water and to drag them through the water to splash dams or haul roads. In many places, this practice continued to the 1950s (Bilby and Ward 1991, Maser and Sedell 1994), after which splash dams were prohibited in western North America and other regions. Streams were often used to float logs downstream, so large wood was removed and streams were cleared to enhance the efficacy of these conduits for timber. As late as the 1970s, logging to the stream bank (Fig. 1) and removing wood from streams to improve fish passage were still common practices (Bisson et al. 1987, Mellina and Hinch 2009). As industrial forestry expanded dramatically in the mid-20th century, it became evident that fish, water, and other resources were being negatively affected by forestry practices in and alongside freshwaters (streams, lakes, and wetlands, but we will refer primarily to streams) (Beschta et al. 1987, Bisson et al. 1987, Hicks et al. 1991). The primary tool for protection of freshwater systems soon became the use of fixed-width buffers of native vegetation along stream banks. During recent decades, a profusion of

[1] E-mail addresses: john.richardson@ubc.ca
[2] naiman@uw.edu
[3] pbisson@fs.fed.us

FIG. 1. Examples of forest harvesting to stream sides in 1974 and the obvious need for streamside protection. Photographs courtesy of Professor Hamish Kimmins, University of British Columbia, Canada.

objectives for protecting freshwaters from forestry arose, including protecting fish and fish habitat, intercepting sediment, shading, moderating temperature, maintaining organic matter inputs and bank stability, providing wildlife habitats and dispersal corridors, and enhancing nutrient uptake. The type of protection varied with landscape context but remained site-specific. Fixed-width buffers were administratively and operationally simple, but they were not the only strategy available for protecting freshwater ecosystems.

Contemporary guidelines for streamside protection vary tremendously among jurisdictions, categories of land ownership, and stream sizes to allow local modifications (Blinn and Kilgore 2001, Lee et al. 2004), but most are based on the model of a fixed-width, vegetated buffer. Moreover, most guidelines are applied at the reach scale and managers do not take a process-based view of landscape scales or positions within watersheds (e.g., headwaters vs large alluvial reaches). Alternative models for stream protection have been proposed, often without adoption by managers, perhaps because of the uncertainty of outcomes. We provide a brief history of the science and practice of streamside management to mitigate the negative effects of forest harvest on freshwaters.

Development of Guidelines for Forestry

Concerns in the 1950s and 1960s about damage to fish habitat and water quality led policy makers in many jurisdictions to consider protecting streams and lakes from forestry practices. This shift in attitude was especially common in the Pacific Northwest of North America where culturally and commercially valuable salmon were being negatively affected by forest harvesting. By the late 1960s, use of buffer strips of riparian forest was encouraged in parts of western

North America, with the chief objectives being provision of shade, minimization of streambank erosion, and administrative simplicity (Brosofske et al. 1997, Naiman et al. 2005). Vegetated buffers maintained along streams during forestry have been used in parts of Europe and South America for centuries (McClain and Cossio 2003, Lee et al. 2004). In North America, many of the guidelines and practices for forested buffer strips and other streamside management in the 1970s and 1980s were voluntary and, therefore, often not applied (Moore and Bull 2004), leading eventually to a more rules-based approach.

Decisions on providing streamside protection of some sort were contentious. However, agreements between agencies and industry about the actual buffer widths and proportion of tree retention were even more difficult. Such decisions rested on defining specific management objectives based on stream size and presence of fish, adjacent land use, and other site-specific conditions (e.g., Castelle et al. 1994). By the 1980s, the importance of large wood for fish habitat was acknowledged in riparian management rules and tree size began to enter into buffer requirements.

Specific buffer widths and tree-retention levels varied dramatically across jurisdictions (Blinn and Kilgore 2001, Lee et al. 2004). Widths were based, in part, on observations of the distance from which large wood entered streams (Murphy and Koski 1989), shading was provided (Brown and Krygier 1970, Beschta et al. 1987), or buffers could be made wind firm. Some studies provided evidence that widths had to be ~30 m on each side of a stream to protect most of the aquatic community (Erman et al. 1977, Newbold et al. 1980), and this distance seems to have been used widely as a basis for buffer widths. In the Pacific Northwest of North America, the Forest Ecosystem Management Assessment Team (FEMAT 1993) proposed a strategy for federal lands that used the potential tree height at a site (the average height of dominant trees in their mature state) as the basis for buffer widths. However, these decisions were intended to apply primarily to moist, coastal forests of western North America in the range of the northern spotted owl (*Strix occidentalis caurina*) and managed by the federal government.

Protection of riparian-associated terrestrial organisms has become an explicit conservation objective associated with protection of streams. The FEMAT approach used buffer widths equivalent to up to 2 tree heights for the sake of protecting riparian obligate and riparian associated species because forest harvesting of the upslope affects microclimate of the remnant riparian area (e.g., Darveau et al. 1995, Brosofske et al. 1997). Many studies have been done to evaluate how various terrestrial organisms respond to the creation of narrow, fixed-width buffers (Darveau et al. 1995, Pearson and Manuwal 2001, Cockle and Richardson 2003, Semlitsch et al. 2009). Many species do not find sufficient habitat within currently specified riparian buffers (Marczak et al. 2010). Guidelines from various jurisdictions clearly indicated that the target of streamside management was the creation and maintenance of late-successional vegetation (Naiman et al. 2000). However, maintaining late-successional vegetation in all forested riparian areas may not account for the potential diversity across the landscape resulting from variation in extent and magnitude of disturbances, especially where natural disturbance regimes create patterns different from bands of mature trees along streams (Kardynal et al. 2009, Moore and Richardson 2012). In contrast, many species require disturbance to persist in the landscape over time (Machtans et al. 1996). FEMAT and other plans accommodated this need for landscape and site-scale variation by allowing thinning and salvage logging of riparian buffers under some conditions.

How Did Fixed-Width Buffers Come to be the Standard Adopted in Most Places?

Federal environmental legislation, such as the US Clean Water Act (USA) and the Fisheries Act (Canada), provides a site-level regulatory framework without serious consideration of landscape-scale processes. Even 40 y ago, concern was expressed that fixed-width buffer strips would come to be applied everywhere, even though they might be appropriate only under particular circumstances (Streeby 1970). Forest harvest was so widespread and aggressive in the 1950s to 1970s that environmental regulators felt that any protection was better than none at all (Hicks et al. 1991), and many studies demonstrated that leaving vegetated buffers serves most environmental objectives (Mellina and Hinch 2009, Semlitsch et al. 2009). In many parts of the world, the use of riparian buffers followed similar trends, and the ~30-m width (or one similar) became commonly adopted before evidence was available to indicate that it was sufficient to achieve environmental objectives. This width was adopted even in areas of plantation forestry with nonnative tree species (Quinn et al. 2004). However, an effective buffer width depends on objectives and on local landscapes.

Guidelines developed in one location or ecoregion were quickly adopted for other landscapes. For instance, in British Columbia, Canada, most of the guidelines produced in 1995 were based on the recommendations of FEMAT (1993) for coastal (wet) ecosystems, and then were applied throughout the physiographically diverse province without modification, except to note that "temperature sensitive streams" should be treated specially (British Columbia Ministry of Forests 1995). In Washington, USA, different guidelines were applied to moist coastal regions on nonfederally managed lands than on the drier, continental side of the Coast and Cascade mountains, but still without finer geographic considerations (Washington Department of Natural Resources 2010).

Most US states and Canadian provinces have had riparian protection guidelines since the late 1970s, particularly for the protection of water quality (Blinn and Kilgore 2001, Lee et al. 2004). Buffer-strip guidelines generally are modified within jurisdictions on the basis of water body type and size, presence of fish, use as a drinking-water source, and shoreline and channel slopes (Lee et al. 2004). About 80% of jurisdictions in the USA and Canada allow some level of selective harvest from riparian buffers, primarily to allow higher rates of timber extraction and faster growth of remaining trees (Blinn and Kilgore 2001, Lee et al. 2004). However, the effectiveness of most of these guidelines has had little empirical evaluation.

How Have Buffers Been Evaluated?

Several tests of the effectiveness of riparian buffers alongside water bodies have been made in the last 2 decades. A challenge in all field trials is identifying the appropriate response variables and temporal and spatial scales on which they should be quantified. In other words, investigators must decide whether the expectation is no change (total protection) or how much change is tolerable if the ecosystem recovers in a specified time frame (Richardson and Thompson 2009). In some cases, any amount of forest harvest, even when $\geq$30 m from a stream, can lead to reach- and watershed-scale changes in the aquatic and riparian ecosystems (Darveau et al. 1995, Kiffney et al. 2003, Kreutzweiser et al. 2008, Lecerf and Richardson 2010). Fortunately, many investigators are trying to determine ecologically effective widths for riparian buffers.

The results of most assessments of effectiveness of riparian buffers suggest that typically mandated widths are insufficient to prevent some alterations of stream and riparian function, but effectiveness depends on the objectives, which are often vaguely stated (Castelle et al. 1994, Naiman et al. 2000, Richardson and Thompson 2009). Some buffer widths are insufficient for conservation of riparian organisms (Darveau et al. 1995, Marczak et al. 2010), and if the objective is to maintain populations of some riparian-dependent amphibians and reptiles, forested buffers $>$100 m may be necessary (Semlitsch et al. 2009). If the buffer width is intended to maintain natural patterns of long-term channel dynamics and contributions of large wood, some rivers, such as the Queets River, Washington, will need buffers of $\geq$900 m (Latterell and Naiman 2007) in areas with broad floodplains. For example, fires and floods constitute large-scale disturbances that help structure aquatic and riparian ecosystems (Pettit and Naiman 2007a, b). Both types of disturbances result in short-term habitat degradation by raising water temperatures and adding fine sediment to streams, but they confer long-term habitat benefits in terms of channel complexity by recruiting large wood and boulders. The width of a naturally disturbed riparian zone and adjacent hill slope needed to provide these key habitat elements varies according to the geomorphic setting of the watershed and may (or may not) exceed the width of the prescribed buffer.

Many government policies indicate the need to protect or mitigate against adverse effects, but few specify the magnitude or scale of change deemed tolerable or loss of resilience deemed acceptable (Richardson and Thompson 2009, Naylor et al. 2012). The consequences of not considering the variation in disturbance intensity and extent are that guidelines are set for average conditions, which could provide significantly less (or perhaps more) protection than needed during extreme conditions with potentially long-lasting impacts (Bisson et al. 2009). Site-specific assessments may be insufficient because of the idiosyncrasies of particular sites, especially if made without regard for the landscape-level spatial scale and temporal scales appropriate to the particular forest ecosystem.

Site-Specific and Landscape-Specific Approaches

In most jurisdictions, Best Management Practices (BMPs) for streamside protection from forestry have included options for site-specific management plans for riparian areas, including hands off (e.g., Welsch et al. 2000). Lee et al. (2004) pointed out that many jurisdictions in North America have moved progressively toward more site-specific guidelines for riparian protection from forestry, often by using a complex set of modifiers of widths or degree of selective harvest allowed. For instance, in British Columbia the Forest and Range Practices Act (2002) allows managers to use discretion when setting harvesting plans to achieve appropriate results, but most practitioners have adhered to fixed-width buffers because of their simplicity and uncertainty of potential outcomes of deviation from the fixed width. Basically, landscape- and watershed-scale processes often are not well incorporated into environmental regulations. Nevertheless, sets of rules derived from local watershed analyses and incorporated into long-term habitat conservation plans and restoration efforts are often a federal requirement where at-risk species occur.

Buffer widths vary dramatically by stream size. Small streams usually have no buffers, whereas larger streams typically have larger buffers (Richardson and Danehy 2007). These rules occur because of the potential loss of harvestable land base, but also via lack of integration of activities at larger spatial and temporal scales. The lack of landscape-level planning in many jurisdictions means that sources of large wood, cool water, and supplies of organic materials to downstream reaches may be compromised.

Proposals have been made for incorporation of landscape-level planning into forest management, especially in fire-affected forest types. The idea of emulation of natural disturbance (END) as a template has gained traction as a planning tool for nonriparian areas in recent years (Perera et al. 2004, Naylor et al. 2012). However, these planning approaches may have inconsistent objectives for protection of riparian areas (e.g., Cissel et al. 1999, Perera et al. 2004, Kreutzweiser et al. 2012, Naylor et al. 2012). Active management of riparian areas, such as selective harvesting (or thinning), differs from natural disturbance largely in that the wood supply is removed and cannot contribute to in-stream or riparian functions (Moore and Richardson 2012).

The Blue River, Oregon, Management Plan (Cissel et al. 1999) is one of the first integrated management plans based on natural disturbance regimes. This plan also is a significant departure from the site-based default management prescriptions in the Northwest Forest Plan resulting from the FEMAT effort. The natural disturbance regime in the Blue River watershed is dominated by wildfire, but the approach is worthy of consideration in any forested setting as an alternative to fixed-width riparian buffers that do not provide for active management. Under the default Northwest Forest Plan buffers, the network of riparian reserves forms a complex landscape pattern that poses a challenge to implementation of forest management activities, including timber harvest and road building. In the Blue River Plan, unmanaged riparian reserves are generally confined to the larger streams in the watershed, and riparian zones on smaller tributaries are managed as part of upland treatments, including large and small openings. The upland treatments are meant to emulate forest structure that resulted from historical fires, i.e., the location, size, and silvicultural treatments are tailored to interpretations of wildfire maps. The riparian management guidelines are meant to maintain the natural conditions that would result from the fire and erosion patterns near streams in this area. The design of riparian buffer areas in Cissel et al. (1999) included 70- to 200-m slope distance on each side of all fish-bearing streams, which covered the entire valley bottom and part of the adjacent hillslopes, and thereby, potentially provided corridors linking reserve areas in small watersheds.

In an increasingly complicated management arena, the challenge will be to find alternatives to fixed-width buffers that meet the multiple objectives of providing clean water (minimizing nutrient and sediment inputs), aquatic habitat, habitat for riparian species, connectivity across landscapes, and related responses. Administratively, fixed-width buffers may be simple to implement and to monitor for compliance. Lee et al. (2004) noted a move toward more site-specific guidelines in riparian management practices around North America, but did not mention such a trend for watershed approaches. Consideration of the scales of management will be a key to ensuring the maintenance of ecosystem resilience for stream–riparian systems (Bisson et al. 2009). Applying BMPs will depend upon defining outcomes, testing methods to achieve those outcomes with margins for safety, and committing to long-term monitoring to verify that targets are being met.

Guidelines for riparian-area management often change before appropriate tests of their effectiveness or efficiency have been done (Richardson and Thompson 2009). The field trials to test some of these provisions are just beginning to show that riparian buffer widths may be sufficient or insufficient depending on site-specific characteristics (e.g., Washington Department of Natural Resources 2010). Given the landscape scale of the alterations that forest practices create, trials need to be conducted across landscapes and on longer time scales to address ecosystem changes explicitly and to compare these to natural disturbance regimes. Forest managers are already moving towards END approaches for riparian areas in some jurisdictions, and these actions should be considered as hypotheses in need of testing.

Conclusions

Many changes have occurred in the practice of forestry in the last 50 y, particularly adjacent to streams, lakes, and wetlands. Riparian buffers were created in recognition of the need to protect surface waters from harm by forest harvest and have become the norm for protecting freshwater ecosystems. However, requirements for narrow, fixed-width buffers usually originated for administratively simple but scientifically untested reasons. Reliance on fixed-width buffers suffers from a scarcity of actual tests and evaluations of the effectiveness of current guidelines. Landscape-level considerations usually have been absent from the site-specific guidelines (reach scale) used in many places. Strategies to maintain ecologically functional aquatic and riparian ecosystems in the face of forest practices will require carefully designed, large-scale field experiments, coupled with long-term monitoring and explicit incorporation of spatial (catchment vs reach) and temporal scales.

Acknowledgements

We appreciate the comments of Fred Swanson, Bob Danehy, Ashley Moerke, Dave Kreutzweiser, and Brian Naylor on the manuscript.

Literature Cited

BESCHTA, R. L., R. E. BILBY, G. W. BROWN, L. B. HOLTBY, AND T. D. HOFSTRA. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. Pages 191–232 *in* E. O. Salo and T. W. Cundy (editors). Streamside management: forestry and fishery interactions. Institute of Forest Resources Contribution Number 57. University of Washington, Seattle, Washington.

BILBY, R. E., AND J. W. WARD. 1991. Characteristics and function of large woody debris in streams draining old-growth, clear-cut, and second-growth forests in southwestern Washington. Canadian Journal of Fisheries and Aquatic Sciences 48:2499–2508.

BISSON, P. A., R. E. BILBY, M. D. BRYANT, C. A. DOLLOFF, G. B. GRETTE, R. A. HOUSE, M. L. MURPHY, K. V. KOSKI, AND J. R. SEDELL. 1987. Large woody debris in forested streams in the Pacific Northwest: past, present, and future. Pages 143–190 *in* E. O. Salo and T. W. Cundy (editors). Streamside management: forestry and fishery interactions. Contribution Number 57. Institute of Forest Resources, University of Washington, Seattle, Washington.

BISSON, P. A., J. B. DUNHAM, AND G. H. REEVES. 2009. Freshwater ecosystems and resilience of Pacific salmon: habitat management based on natural variability. Ecology and Society 14(1):45 (online). (Available from: http://www.ecologyandsociety.org/vol14/iss1/art45/)

BLINN, C. R., AND M. A. KILGORE. 2001. Riparian management practices: a summary of state guidelines. Journal of Forestry 99(8):11–17.

BRITISH COLUMBIA MINISTRY OF FORESTS. 1995. Riparian management area guidebook. British Columbia Ministry of Forests, Victoria, British Columbia. (Available from: http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/riparian/rip-toc.htm)

BROSOFSKE, K. D., J. CHEN, R. J. NAIMAN, AND J. FRANKLIN. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. Ecological Applications 7:1188–1200.

BROWN, G. W., AND J. T. KRYGIER. 1970. Effects of clear-cutting on stream temperature. Water Resources Research 6: 1133–1139.

CASTELLE, A. J., A. W. JOHNSON, AND C. CONOLLY. 1994. Wetland and stream buffer size requirements – a review. Journal of Environmental Quality 23:878–882.

CISSEL, J. H., F. J. SWANSON, AND P. J. WEISBERG. 1999. Landscape management using historical fire regimes: Blue River, Oregon. Ecological Applications 9:1217–1231.

COCKLE, K. L., AND J. S. RICHARDSON. 2003. Do riparian buffer strips mitigate the impacts of clearcutting on small mammals? Biological Conservation 113:133–140.

DARVEAU, M., P. BEAUCHESNE, L. BÉLANGER, J. HUOT, AND P. LARUE. 1995. Riparian forest strips as habitat for breeding birds in boreal forest. Journal of Wildlife Management 59:67–78.

ERMAN, D. C., J. D. NEWBOLD, AND K. B. ROBY. 1977. Evaluation of streamside bufferstrips for protecting aquatic organisms. California Water Resources Center, Contribution Number 165. University of California, Davis, California.

FEMAT (FOREST ECOSYSTEM MANAGEMENT ASSESSMENT TEAM). 1993. Forest ecosystem management: an ecological, economic, and social assessment. US Forest Service, US Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, United States Bureau of Land Management, Fish and Wildlife Service, Portland, Oregon. (Available from: http://www.blm.gov/or/plans/nwfpnepa/FEMAT-1993/1993_%20FEMAT-ExecSum.pdf)

HICKS, B. J., J. D. HALL, P. A. BISSON, AND J. R. SEDELL. 1991. Responses of salmonids to habitat changes. American Fisheries Society Special Publication 19:483–518.

KARDYNAL, K. J., K. A. HOBSON, S. L. VAN WILGENBURG, AND J. L. MORISSETTE. 2009. Moving riparian management guidelines towards a natural disturbance model: an example using boreal riparian and shoreline forest bird communities. Forest Ecology and Management 257:54–65.

KIFFNEY, P. M., J. S. RICHARDSON, AND J. P. BULL. 2003. Responses of periphyton and insects to experimental manipulation of riparian buffer width along forest streams. Journal of Applied Ecology 40:1060–1076.

KREUTZWEISER, D. P., K. P. GOOD, S. S. CAPELL, AND S. B. HOLMES. 2008. Leaf-litter decomposition and macroinvertebrate communities in boreal forest streams linked to upland logging disturbance. Journal of the North American Benthological Society 27:1–15.

KREUTZWEISER, D. P., P. K. SIBLEY, J. S. RICHARDSON, AND A. M. GORDON. 2012. Introduction and a theoretical basis for using disturbance by forest management activities to sustain aquatic ecosystems. Freshwater Science 31:224–231.

LATTERELL, J. J., AND R. J. NAIMAN. 2007. Sources and dynamics of large logs in a temperate floodplain river. Ecological Applications 17:1127–1141.

LECERF, A., AND J. S. RICHARDSON. 2010. Litter decomposition can detect effects of high and moderate levels of forest disturbance on stream condition. Forest Ecology and Management 259:2433–2443.

LEE, P., C. SMYTH, AND S. BOUTIN. 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. Journal of Environmental Management 70:165–180.

MACHTANS, C. S., M. A. VILLARD, AND S. J. HANNON. 1996. Use of riparian buffer strips as movement corridors by forest birds. Conservation Biology 10:1366–1379.

MARCZAK, L. B., T. SAKAMAKI, S. L. TURVEY, I. DEGUISE, S. L. R. WOOD, AND J. S. RICHARDSON. 2010. Are forested buffers an effective conservation strategy for riparian fauna? An assessment using meta-analysis. Ecological Applications 20:126–134.

MASER, C., AND J. R. SEDELL. 1994. From the forest to the sea: the ecology of wood in streams, rivers, estuaries and oceans. St Lucie Press, Delray Beach, Florida.

MCCLAIN, M. E., AND R. E. COSSIO. 2003. The use of riparian environments in the rural Peruvian Amazon. Environmental Conservation 30:242–248.

MELLINA, E., AND S. G. HINCH. 2009. Influences of riparian logging and in-stream large wood removal on pool habitat and salmonid density and biomass: a meta-analysis. Canadian Journal of Forest Research 39:1280–1301.

MOORE, K., AND G. BULL. 2004. Guidelines, codes and legislation. Pages 707–728 *in* T. G. Northcote and G. F. Hartman (editors). Fishes and forestry: worldwide watershed interactions and management. Blackwell Science, Oxford, UK.

MOORE, R. D., AND J. S. RICHARDSON. 2012. Natural disturbance and forest management in riparian zones: Comparison of effects at reach, catchment and landscape scales. Freshwater Science 31:239–247.

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.

NAIMAN, R. J., R. E. BILBY, AND P. A. BISSON. 2000. Riparian ecology and management in the Pacific Coastal rain forest. BioScience 50:996–1011.

NAIMAN, R. J., H. DÉCAMPS, AND M. E. MCCLAIN. 2005. Riparia: ecology, conservation, and management of streamside communities. Elsevier Academic Press, San Diego, California.

NAYLOR, B. J., R. W. MACKERETH, D. P. KREUTZWEISER, AND P. K. SIBLEY. 2012. Merging END concepts with protection of fish habitat and water quality in new direction for riparian forests in Ontario: a case study of science guiding policy and practice. Freshwater Science 31:248–257.

NEWBOLD, J. D., D. C. ERMAN, AND K. B. ROBY. 1980. Effects of logging on macroinvertebrates in streams with and without buffer strips. Canadian Journal of Fisheries and Aquatic Sciences 37:1076–1085.

PEARSON, S. F., AND D. A. MANUWAL. 2001. Breeding bird response to riparian buffer width in managed Pacific Northwest Douglas-fir forests. Ecological Applications 11:840–853.

PERERA, A. H., L. J. BUSE, AND M. G. WEBER (EDITORS). 2004. Emulating natural forest landscape disturbances. Columbia University Press, New York.

PETTIT, N. E., AND R. J. NAIMAN. 2007a. Fire in the riparian zone: characteristics and ecological consequences. Ecosystems 10:673–687.

PETTIT, N. E., AND R. J. NAIMAN. 2007b. Post-fire response of riparian vegetation and soils and the effect of flood-deposited wood in a semi-arid landscape. Ecology 88: 2094–2104.

PETTIT, N. E., AND R. J. NAIMAN. 2007b. Fire in the riparian zone: characteristics and ecological consequences. Ecosystems 10:673–687.

QUINN, J. M., I. K. G. BOOTHROYD, AND B. J. SMITH. 2004. Riparian buffers mitigate effects of pine plantation logging on New Zealand streams 2. Invertebrate communities. Forest Ecology and Management 191:129–146.

RICHARDSON, J. S., AND R. J. DANEHY. 2007. A synthesis of the ecology of headwater streams and their riparian zones in temperate forests. Forest Science 53:131–147.

RICHARDSON, J. S., AND R. M. THOMPSON. 2009. Setting conservation targets for freshwater ecosystems in forested catchments. Pages 244–263 *in* M. A. Villard and B. G. Jonsson (editors). Setting conservation targets for managed forest landscapes. Cambridge University Press, Cambridge, UK.

SEMLITSCH, R. D., B. D. TODD, S. M. BLOMQUIST, A. J. K. CALHOUN, J. W. GIBBONS, J. P. GIBBS, G. J. GRAETER, E. B. HARPER, D. J. HOCKING, M. L. HUNTER, D. A. PATRICK, T. A. G. RITTENHOUSE, AND B. B. ROTHERMEL. 2009. Effects of timber harvest on amphibian populations: understanding mechanisms from forest experiments. BioScience 59: 853–862.

STREEBY, L. 1970. Buffer strips—some considerations in the decision to leave. Pages 194–198 *in* J. T. Krygier and J. D. Hall (editors). Proceedings of a Symposium on Forest Land Uses and Stream Environment. Oregon State University, Corvallis, Oregon.

WASHINGTON DEPARTMENT OF NATURAL RESOURCES. 2010. Title 222-30 WAC – Forest practices rules: timber harvesting. Pages 30-1–30-36 *in* Washington forest practices rules (revised 12-06-2010). State of Washington Department of Natural Resources, Olympia, Washington. (Available from: http://www.dnr.wa.gov/Publications/fp_rules_title_222_wac.pdf)

WELSCH, D. J., J. W. HORNBECK, E. S. VERRY, C. A. DOLLOFF, AND J. G. GREIS. 2000. Riparian area management: themes and recommendations. Pages 321–339 *in* E. S. Verry, J. W. Hornbeck, and C. A. Dolloff (editors). Riparian management in forests of the continental eastern United States. CRC Press, Boca Raton, Florida.

Received: 24 March 2011
Accepted: 10 November 2011