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Authors: Naylor, Brian J., Mackereth, Robert W., Kreutzweiser, David P., and Sibley, Paul K.

Source: Freshwater Science, 31(1) : 248-257

Published By: Society for Freshwater Science

URL: https://doi.org/10.1899/11-035.1

Freshwater Science, 2012, 31(1):248–257

DOI: 10.1899/11-035.1
Published online: 24 January 2012

BRIDGES

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

Brian J. Naylor[1,5], Robert W. Mackereth[2,6], David P. Kreutzweiser[3,7], AND Paul K. Sibley[4,8]

[1] *Forest Policy Section, Ontario Ministry of Natural Resources, 3301 Trout Lake Road, North Bay, Ontario, Canada P1A 4L7*

[2] *Centre for Northern Forest Ecosystem Research, Ontario Ministry of Natural Resources, 955 Oliver Road, Thunder Bay, Ontario, Canada P7B 5E1*

[3] *Canadian Forest Service, Natural Resources Canada, 1219 Queen Street East, Sault Ste. Marie, Ontario, Canada P6A 2E5*

[4] *Department of Environmental Biology, University of Guelph, Guelph, Ontario, Canada N1G 2W1*

Abstract. The Crown Forest Sustainability Act stipulates that Ontario's public forests be managed to conserve biological diversity and long-term health by following an emulation of natural disturbance (END) paradigm. Upland forests have been managed following an evolving END approach since the mid-1990s, but operations have been largely excluded from riparian forests. The new Forest Management Guide for Conserving Biodiversity at the Stand and Site Scales attempted to integrate the protection of fish habitat and water quality with the desire to emulate natural disturbance patterns in riparian forests to create a diversity of habitats to support a broad range of riparian plants and animals. Where wildfire is the dominant agent of disturbance, it encourages thoughtfully planned and carefully implemented clearcutting within riparian forest. We provide some examples of how science-based knowledge was used to develop direction to achieve these objectives.

Key words: emulation of natural disturbance, forest management policy, riparian forests, Ontario.

The Crown Forest Sustainability Act (1994) stipulates that the public forests of Ontario be managed to conserve biological diversity and long-term health by following an emulation of natural disturbance (END) paradigm while minimizing adverse effects on a variety of ecosystem goods and services including fish and water. The END approach used in Ontario has been evolving since the mid-1990s. It focuses on providing a diversity of ecosystem conditions at a variety of spatial and temporal scales to meet the habitat needs of a broad range of plants and animals (e.g., OMNR 1998a, 2001a, 2010a). However, operations within riparian forests generally have been discouraged, ostensibly to protect fish habitat and water quality (see OMNR 1988). This practice has created relatively unnatural ribbons and donuts of residual riparian forest adjacent to water features (Buttle 2002, Kreutzweiser et al. 2012).

Planning and implementation of forest management operations on public lands are directed by standards, guidelines, and best management practices (collectively referred to hereafter as *direction*) prescribed in a suite of forest management guides developed by the Ontario Ministry of Natural Resources (OMNR). All direction associated with biodiversity conservation was reviewed recently to ensure it reflected the latest science-based knowledge and would meet OMNR's objectives effectively and efficiently. The review (OMNR 2010b) suggested that direction for riparian areas was often more restrictive than necessary to protect water quality and fish habitat. Moreover, conservative application of past direction was not creating the diversity of ecosystem conditions that

[5] E-mail addresses: brian.naylor@ontario.ca
[6] rob.mackereth@ontario.ca
[7] dave.kreutzweiser@nrcan-rncan.gc.ca
[8] psibley@uoguelph.ca

natural disturbances historically produced in riparian areas. A growing concern was that this failure might adversely affect plants or animals that use riparian forests, especially the American beaver (*Castor canadensis*), a keystone species (Quinn 2004).

Consequently, direction in the Forest Management Guide for Conserving Biodiversity at the Stand and Site Scales (Stand and Site Guide) (OMNR 2010a) was developed to integrate protection of fish habitat and water quality with the desire to emulate natural disturbance patterns in riparian forests to create a diversity of habitats that could support a broad range of riparian plants and animals. Direction was based on a thorough review of existing literature, and discussions with and review by ecological researchers, practitioners, policy makers, stakeholders, and members of the public to ensure that direction would be effective in meeting ecological objectives, while also being feasible to implement and socially palatable. The conclusion of the review was that riparian forests could be managed to achieve a range of ecological objectives without compromising fish habitat or water quality if operations were thoughtfully planned and carefully implemented.

Below we provide some examples of how science-based knowledge was used to develop direction to achieve these objectives. We acknowledge that riparian forests are subject to a variety of disturbance types (Moore and Richardson 2012). However, we focus here on emulation of wildfire because it is the dominant agent of disturbance across most of the province. Some of the discussion (e.g., that addressing careful implementation) applies equally to operations within riparian forests intended to emulate other types of disturbance.

We present this example as a case study that illustrates one approach to incorporating END concepts into riparian forest management. We hope that some components of our approach might be applicable in other jurisdictions in North America.

Thoughtfully Planned

Disturbance of riparian forests must be thoughtfully planned because some operations may be incompatible with other ecological, social, or cultural objectives (sensu Sibley et al. 2012). In Ontario, consideration of special wildlife habitats (OMNR 2010a), resource-based tourism (OMNR 2001b), and cultural heritage (OMNR 2007) normally limits opportunities for disturbance of riparian forest. Moreover, operations in riparian forests can be conducted only where fish habitat and water quality will not be adversely affected because the Fisheries Act (1985) prohibits harmful alteration, disruption, or destruction of fish habitat. All standing and flowing waters contribute to the productive capacity of fish habitat and, thus, are addressed in the Stand and Site Guide. However, the guide adopted a risk-management approach that required us to identify the relative sensitivity of water features to forest management operations and when forest cover adjacent to water is necessary to maintain ecological functions of aquatic systems.

How should potential sensitivity of water features be defined?

Past direction (OMNR 1988) recognized that warm- or cool-water systems usually were less sensitive to disturbance than were cold-water systems. The Stand and Site Guide adopted a framework (Table 1) similar to that proposed by Fisheries and Oceans Canada (DFO 2007). When inventory data are available for individual water features, potential sensitivity (high [HPS], moderate [MPS], or low [LPS]) is defined based largely on the criteria in DFO (2007).

When inventory data are not available, potential sensitivity is estimated using relatively simple measurable criteria based on factors influencing the spatial distribution of sensitive fish species (Table 1). For example, catchment area was used because it is easily modeled, tends to be correlated with stream size, and has a strong influence on fish assemblages (Zorn et al. 2002, Wang et al. 2003). A threshold of 3 km^2 was selected because brook trout (*Salvelinus fontinalis*) generally have a low likelihood of occupying streams (and associated beaver ponds) if upstream catchment area is <3 km^2 (Parker 2006, R. Mackereth, OMNR, unpublished data). A 500-m distance criterion was used because brook trout can travel >500 m up small streams that are connected to water features that support brook trout (Curry et al. 1997, Borwick et al. 2006, R. Mackereth, OMNR, unpublished data). Information on brook trout was used to define thresholds because this species has high socioeconomic importance and generally is considered a sensitive indicator of changes in water temperature, water quality, and groundwater inputs.

When is forest cover adjacent to water necessary to maintain ecological functions?

Wildfires frequently burn to the edge of streams (Landstrom 2003, Lee and Smyth 2003, Nitschke 2005). However, removal of riparian forest may adversely affect thermal regime (see reviews in Steedman and Morash 2001, Steedman et al. 2004), inputs of fine organic matter (Webster and Waide 1982, Webster et al. 1990, Hartman et al. 1996), and recruitment of coarse woody material (Dolloff and

TABLE 1. Classification of water features based on potential sensitivity to forest management operations in Ontario. HPS = high potential sensitivity, MPS = moderate potential sensitivity, LPS = low potential sensitivity.

Sensitivity class	Water feature	Criteria
HPS	Lakes[a]	All
	Ponds[b]	When inventory data are available, HPS ponds are those with $\geq$1 of the following characteristics: • Ponds known to contain fish species that are highly sensitive to perturbations (e.g., brook trout, *Salvelinus fontinalis*) • Ponds known to provide components of fish habitat for which there is a high degree of species' dependence • Ponds known to contain rare habitats or fish that are species at risk • Ponds with low habitat resiliency • Ponds identified as significant habitat by specific fisheries management plans When inventory data are not available, HPS ponds are those with the following characteristics: • Mapped or unmapped open water features ($\leq$25% of surface area covered by emergent vegetation) encountered during operations that are $\geq$0.5 and $<$8 ha in size and are connected to $\geq$1 HPS streams (see below)
	Rivers[c]	All
	Streams	When inventory data are available, HPS streams are those with $\geq$1 of the following characteristics: • Stream segments known to contain fish species that are highly sensitive to perturbations (e.g., brook trout) • Stream segments known to provide components of fish habitat for which there is a high degree of species' dependence • Stream segments known to contain rare habitats or fish that are species at risk • Stream segments with low habitat resiliency • Stream segments identified as significant habitat by specific fisheries management plans When inventory data are not available, HPS streams are those with 1 of the following characteristics: • Mapped large permanent stream segments (catchment area $\geq$3 and $<$50 km^2) • Mapped small permanent stream segments (catchment area $<$3 km^2) $<$500 m (stream distance) from lakes, rivers, mapped large permanent stream segments, or other water features identified as HPS based on inventory data • Recognizable unmapped permanent stream segments $<$500 m from lakes, rivers, mapped large permanent stream segments, or other water features identified as HPS based on inventory data
MPS	Ponds	When inventory data are available, MPS ponds are those with $\geq$1 of the following characteristics: • Ponds known to contain fish species that are moderately resilient to perturbations (e.g., northern pike, *Esox lucius*) • Ponds known to provide components of fish habitat for which there is a moderate degree of species' dependence • Ponds known to contain habitats or fish that have a limited distribution • Ponds with moderate habitat resiliency When inventory data are not available, MPS ponds are those with the following characteristics: • Mapped or unmapped open water features ($\leq$25% of surface area covered by emergent vegetation) encountered during operations that are $\geq$0.5 and $<$8 ha in size and are connected to $\geq$1 MPS streams (see below)

TABLE 1. Continued.

Sensitivity class	Water feature	Criteria
	Streams	When inventory data are available, MPS streams are those with ≥1 of the following characteristics: • Stream segments known to contain fish species that are moderately resilient to perturbations (e.g., northern pike) • Stream segments known to provide components of fish habitat for which there is a moderate degree of species' dependence • Stream segments known to contain habitats or fish that have a limited distribution • Stream segments with moderate habitat resiliency When inventory data are not available, MPS streams are those with 1 of the following characteristics: • Mapped small permanent stream segments that are ≥500 m (stream distance) from lakes, rivers, mapped large permanent stream segments, and other water features identified as HPS based on inventory data • Recognizable unmapped permanent stream segments that are ≥500 m from lakes, rivers, mapped large permanent stream segments, and other water features identified as HPS based on inventory data • Mapped or recognizable unmapped intermittent stream segments <500 m from water features known to support brook trout
LPS	Ponds	• Any pond that does not meet the criteria for an HPS or MPS pond
	Streams	• Any stream segment that does not meet the criteria for an HPS or MPS stream

[a] Water features ≥8 ha in surface area
[b] Water features ≥0.5 but <8 ha in surface area
[c] Streams segments with catchment area ≥50 km^2

Webster 2000, Meleason et al. 2003, Jones and Daniels 2008). Stream temperature typically is influenced by forest within 10 to 30 m of shorelines depending on tree height and canopy density (Barton et al. 1985, Castelle et al. 1994, Sridhar et al. 2004, Wilkerson et al. 2006). More than 80% of allochthonous inputs typically come from vegetation within ~½ tree height of shorelines (Reeves et al. 2006). Thus, the Stand and Site Guide requires retention of mature forest with high canopy closure within 15 m of both sides of HPS or MPS streams (Table 2). Partial harvest within this forest is permitted because moderate levels of canopy removal may emulate small-scale disturbances and increase light availability with minimal effects on water temperature (Zwieniecki and Newton 1999, Mellina et al. 2002, Wilkerson et al. 2006, Kreutzweiser et al. 2009) but with resultant increases in productivity of aquatic systems (Newton and Cole 2005, Wilzbach et al. 2005, Nislow and Lowe 2006). Moreover, partial harvesting may create sufficiently large canopy gaps to attract some wildlife species typically found in young riparian forests (Darveau et al. 1995).

To emulate the conditions created when wildfire burns to the edge of streams, retention of mature riparian forest is not required along HPS or MPS streams when the treed edge is >15 m from the edge of the active channel. Moreover, retention of mature riparian forest is not required along LPS streams (Table 2) because they are typically very narrow, and understory vegetation generally will provide adequate shade (see Blann et al. 2002).

Wildfires also frequently burn to the edge of lakes (see below). Removal of riparian forest appears to have limited effect on littoral water temperature or thermal regime in lakes (Steedman et al. 1998, 2001, Steedman and Kushneriuk 2000). Moreover, allochthonous inputs may be reduced after removal of riparian forest (France 1997), but biological effects appear to be transitory because of rapid regrowth of riparian vegetation (France 1998). However, harvesting of riparian forest may influence future recruitment of coarse woody material into the littoral zones of lakes (Guyette and Cole 1999, Bolgrien and Kratz 2000). Thus, the Stand and Site Guide permits some clearcutting of riparian forest adjacent to standing water (see below) but requires retention of some trees along these shorelines to provide future inputs of coarse woody material (Table 2).

How many riparian trees are necessary to maintain ecological functions?

The Stand and Site Guide requires retention of 10 dominant or codominant trees/100 m of clearcut shoreline to provide future inputs of coarse woody

TABLE 2. Summary of direction designed to emulate natural (wildfire) disturbances in riparian forests while protecting fish habitat and water quality on crown lands in Ontario (see OMNR 2010a for more detailed direction). HPS = high potential sensitivity, MPS = moderate potential sensitivity, LPS = low potential sensitivity.

Variable	Water feature	Direction
Shoreline disturbance	Large lakes (≥1000 ha)	A maximum of 10% of riparian forest may be clearcut
	Medium lakes (100–999 ha)	A maximum of 25% of riparian forest may be clearcut
	Small lakes (8–99 ha) and HPS or MPS ponds	A maximum of 50% of riparian forest may be clearcut
	LPS ponds	Up to 100% of riparian forest may be clearcut
	Rivers	Riparian forest on 1 side of rivers may be clearcut
	HPS or MPS streams	Mature forest with ≥60% canopy cover retained within 15 m of water on both sides of streams
		Remainder of forest in riparian buffer (see below) may be clearcut on 1 side only
	LPS streams	Riparian forest on both sides of streams may be clearcut
Riparian trees	Lakes, rivers, and HPS or MPS ponds	Retain 10 dominant or codominant trees/100 m of clearcut shoreline
Restrictions on harvest, renewal, and tending operations to protect fish habitat and water quality	All water features	No trees felled into water features
		No disturbance of the forest floor within 3 m of water features (no machine travel, no trees felled into or extracted through this zone)
		Minimal disturbance of shrubs and saplings within 3 m of water features
		No ruts within 15 m of water features
		Minimal exposure of mineral soil (<5%) within 15 m of water features
		No ruts that channel water to within 15 m of water features
	All HPS features	No roads[a], landings, or aggregate pits within 30–90 m of water features based on slope (30-, 50-, 70-, and 90-m riparian buffers for slopes of 0–15, 16–30, 31–45, and >45%, respectively)
	All MPS features	No roads[a], landings, or aggregate pits within 30 m of water features
	All LPS features	No roads[a], landings, or aggregate pits within 15 m of water features

[a] Roads permitted if there are no practical or feasible alternatives and appropriate mitigative measures are taken to minimize risk of sediment transport to water features.

material. This number was based on: 1) estimates of the supply of coarse wood in the littoral zone of individual lightly developed lakes in Ontario, Michigan, and Wisconsin (Christensen et al. 1996, Jennings et al. 1999, Mallory et al. 2000, Steedman et al. 2004, Marburg et al. 2006, Sass et al. 2006, B. Cole, OMNR, unpublished data), 2) estimates of the annual input of coarse wood required to balance losses to decay based on mean residence time of coarse wood (Tyrrell and Crow 1994, Guyette et al. 2002), and 3) estimates of the volume of wood that may actually fall into water from trees retained along shorelines based on distance from shore and the likelihood that trees fall toward the water (Robison and Beschta 1990, Bragg et al. 2000, Welty et al. 2002).

The Stand and Site Guide specifies that, ideally, retained trees should be within ½ tree height of water and leaning toward the water. Conifers are preferred because coniferous logs have a longer residence time in water than do hardwood logs (Cole et al. 2003). Moreover, conifers typically have a more complex branching structure that provides better cover for schooling fish (Newbrey 2002) and more complex bark that supports a higher diversity of invertebrates (Bowen et al. 1998).

How much riparian forest would be altered by natural disturbances?

Following an END paradigm suggests that the amount of riparian forest disturbed by forest management operations should be similar to that altered by natural disturbances, such as wildfire. Considerable empirical evidence exists to indicate that fire can play an important role in the dynamics of riparian forests (Russell and McBride 2001, Dwire and Kauffman 2003, Pettit and Naiman 2007), but only a few studies provide detailed quantitative information on the amount of shoreline burned during disturbances. For example, Landstrom (2003) studied 23 large fires in northwestern Ontario and found that fire burned ~60% of the riparian forest adjacent to lakes and streams.

The pattern of riparian disturbance around >1800 lakes within 42 wildfires in the boreal and transition forests of Ontario was examined to provide more empirical information to support direction in the guide (OMNR 2010b). Overall, the median percent of riparian area burned around lakes averaged ~50%. However, variation was quite large and values for individual lakes ranged from <10 to >90%. Thus, up to 50% of the shoreline of HPS or MPS ponds and small lakes may potentially be clearcut to reflect the average amount of riparian disturbance observed in our analysis and the literature (Table 2). The actual amount of riparian forest that can be clearcut around individual water features will vary considerably given constraints imposed by other direction (e.g., special wildlife habitats, cultural features), operability or marketability considerations, and land ownership. More of the shoreline of LPS ponds and less of the shoreline of larger lakes may potentially be clearcut to capture some of the variation inherent in the natural pattern (Table 2). This approach largely reflects our observation that the median percent of riparian area burned tended to be inversely related to the size of water features (OMNR 2010b).

Carefully Implemented

The Fisheries Act (1985) prohibits the deposition of deleterious substances, including sediment, into water. In this regard, the most significant concern is that forest management operations may expose mineral soil and facilitate transport of sediment in runoff and subsequent deposition in water (see reviews in Steedman and Morash 2001, Steedman et al. 2004, Croke and Hairsine 2006). Most jurisdictions prescribe riparian buffers within which forest management operations are prohibited or restricted to minimize the risk of sediment entering water (Lee et al. 2004, Richardson et al. 2012).

Roads, landings, and water crossings are the major potential sources of sediment in forest management operations (see reviews in Stafford et al. 1996, Steedman and Morash 2001, Steedman et al. 2004). Smaller amounts of mineral soil exposed by mechanical site preparation (Steedman and Morash 2001) or skidding (Stafford et al. 1996) are also a potential (but minor) source of sediment.

What restrictions are necessary for major potential sources of sediment?

Past direction (OMNR 1988) restricted major potential sources of sediment within 30 to 90 m of water based on the slope-dependent distance required to attenuate sediment movement in a small study conducted in New Hampshire (Trimble and Sartz 1957). More recent literature suggests that smaller buffers (15–60 m wide) generally may be adequate to slow surface water flow and trap suspended sediment from major sources of exposed mineral soil (see reviews in Clinnick 1985, Castelle et al. 1994, Croke and Hairsine 2006). The relationship between the length of sediment tracks originating from forest access roads and slope was modeled, pooling data available from the literature, to evaluate whether past direction was still appropriate (see OMNR 2010b). Slope was a highly significant predictor of the length of sediment tracks. Buffers of 30, 40, and 50 m were generally predicted to attenuate ~95% of sediment tracks when slope was 15, 30 and 45%, respectively. This result suggested that the 30- to 90-m model proposed by Trimble and Sartz (1957) probably is effective but somewhat conservative. The 30- to 90-m slope-based buffer has been used for >20 y in Ontario and appears to be effective, so it was prescribed for HPS water features. However, narrower buffers were prescribed for MPS and LPS features because the 30- to 90-m buffer probably is conservative.

What restrictions are necessary for minor potential sources of sediment?

Numerous studies suggest that effects of skid trails can be mitigated by applying careful operating practices (e.g., Martin and Hornbeck 1994, Martin et al. 2000, Macdonald et al. 2003). For example, Kreutzweiser and Capell (2001) found no significant input of sediment when machine travel was >3 m from streams and harvesting equipment did not create channeled flow paths. Plamondon (1982) suggested that effects of skidding could be mitigated by retaining 10 to 15 m of undisturbed forest floor adjacent to water features. Therefore, past direction (OMNR 1998b) that prohibited disturbance of the forest floor within 3 m of water features was retained. Moreover, the literature and discussions with experts suggested that additional restrictions on site disturbance would further minimize the risk of sediment transport and deposition associated with machine travel (Table 2).

Ephemeral streams that channel runoff from snowmelt or rainfall events directly into water features can be significant conduits for movement of sediment (Haupt and Kidd 1965, Kreutzweiser and Capell 2001, Maine Forest Service 2004). Moreover, when springs, seeps, and other areas of shallow groundwater discharge enter water features they can create important habitat for cold-water fish, such as brook trout (Biro 1998, Ridgway and Blanchfield 1998, Borwick et al. 2006). Thus, the Stand and Site Guide prohibits disruption of water movement within these features when associated with other water features.

Looking Ahead

Growing recognition that riparian disturbance may contribute to biodiversity conservation is encouraging various jurisdictions to incorporate riparian disturbance into their forest management practices (e.g., Manitoba Conservation 2008, OMNR 2010a). Recently, Sibley and Gordon (2010) developed a decision-support system to help forest managers plan disturbance thoughtfully in riparian areas. We hope that some components of the approach described in our case study may be applicable to other jurisdictions that have similar natural disturbance regimes, planning and operational frameworks, types of aquatic and terrestrial values, and social receptivity (Sibley et al. 2012).

Looking ahead, Ontario faces 3 main challenges to incorporating END concepts into riparian forest management. First, although the Stand and Site Guide incorporates the best science-based information available at the time of development, uncertainties still exist about the effects of emulating natural disturbance in riparian forests on aquatic systems and the effectiveness of mitigative direction (Sibley et al. 2012). Thus, OMNR continues to promote, conduct, support, or monitor hypothesis-driven studies examining the effects of forest management operations on ecological functions within aquatic systems as part of an adaptive management approach. Knowledge gained from these studies will be used to inform future versions of the Stand and Site Guide, which is reviewed and potentially revised every 5 y.

Second, the Stand and Site Guide defines the maximum amount of riparian forest that can be clearcut within individual harvest areas. The frequency with which this direction is applied ultimately determines the mosaic of young and old riparian forest across landscapes. However, OMNR currently does not provide END-based guidance for riparian management at the landscape scale (see Moore and Richardson 2012 for a discussion of END-related landscape-scale considerations).

Last, despite the new direction, some forest managers have been reluctant to clearcut to the shore of water features. This reluctance reflects a number of factors including stakeholder resistance. Stakeholder resistance largely reflects the perception that riparian management is driven by economic considerations and that operations in riparian areas cannot be conducted carefully. Perceptions are changing as messages about the ecological benefits of riparian disturbance are being shared with stakeholder groups. In our experience, the best way to influence perception is to combine messaging with tours of harvest areas that include riparian management so stakeholders can see the results for themselves. We anticipate that END-based management of riparian forests will become more common across the province as forest managers and stakeholders become more comfortable planning and implementing operations in riparian areas.

Acknowledgements

We gratefully acknowledge the many researchers, practitioners, policy makers, stakeholders, and members of the public who contributed to the development of the Stand and Site Guide. We extend special thanks to the individuals involved in a previous attempt to revise the 1988 Timber Management Guidelines for the Protection of Fish Habitat. Their work formed the basis for much of the riparian direction in the Stand and Site Guide. Joe Churcher and 2 anonymous referees provided constructive comments on various drafts of this manuscript.

Literature Cited

BARTON, D. R., W. D. TAYLOR, AND R. M. BIETTE. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. North American Journal of Fisheries Management 5: 364–378.

BIRO, P. A. 1998. Staying cool: behavioral thermoregulation during summer by young brook trout in a lake. Transactions of the American Fisheries Society 127:212–222.

BLANN, K., J. F. NERBONNE, AND B. VONDRACEK. 2002. Relationship of riparian buffer type to water temperature in the Driftless Area Ecoregion of Minnesota. North American Journal of Fisheries Management 22:441–451.

BOLGRIEN, D. W., AND T. K. KRATZ. 2000. Lake riparian areas. Pages 207–218 *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.

BORWICK, J., J. BUTTLE, AND M. S. RIDGWAY. 2006. A topographic index approach for identifying groundwater habitat for young-of-the-year brook trout (*Salvelinus fontinalis*) in the land-lake ecotone. Canadian Journal of Fisheries and Aquatic Sciences 63:239–253.

BOWEN, K. L., N. K. KAUSHIK, AND A. M. GORDON. 1998. Macroinvertebrate communities and biofilm chlorophyll on woody debris in two Canadian oligotrophic lakes. Archiv für Hydrobiologie 141:257–281.

BRAGG, D. C., J. L. KERSHNER, AND D. W. ROBERTS. 2000. Modeling large woody debris recruitment for small streams of the central Rocky Mountains. General Technical Report RMRS-GTR-55. US Department of Agriculture Forest Service, Washington, DC.

BUTTLE, J. M. 2002. Rethinking the donut: the case for hydrologically relevant buffer zones. Hydrological Processes 16:3093–3096.

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

CHRISTENSEN, D. L., B. R. HERWIG, D. E. SCHINDLER, AND S. R. CARPENTER. 1996. Impacts of lakeshore residential development on coarse woody debris in north temperate lakes. Ecological Applications 6:1143–1149.

CLINNICK, P. F. 1985. Buffer strip management in forest operations: a review. Australian Forestry 48:34–45.

COLE, W. G., K. E. SMOKOROWSKI, T. C. PRATT, E. C. MALLORY. 2003. Riparian forest and nearshore fish habitat in Ontario: so close and yet so far. Pages 17–19 *in* L. J. Buse AND A. H. Perera (compilers). 2003. Meeting emerging ecological, economic, and social challenges in the Great Lakes region. Forest Research Information Paper No. 155. Ontario Forest Research Institute, Ontario Ministry of Natural Resources, Ottawa, Ontario.

CROKE, J. C., AND P. B. HAIRSINE. 2006. Sediment delivery in managed forests: a review. Environmental Review 14: 59–87.

CURRY, R. A., C. BRADY, D. L. G. NOAKES, AND R. G. DANZMANN. 1997. Use of small streams by young brook trout spawned in a lake. Transactions of the American Fisheries Society 126:77–83.

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.

DFO (DEPARTMENT OF FISHERIES AND OCEANS). 2007. Practitioner's guide to the risk management framework for DFO habitat management staff. Habitat Management Program, Department of Fisheries and Oceans Canada, Ottawa, Ontario. (Available from: http://www.dfo-mpo.gc.ca/habitat/role/141/1415/14155/risk-risque/index-eng.asp)

DOLLOFF, C. A., AND J. R. WEBSTER. 2000. Particulate organic contributions from forests to streams: debris isn't so bad. Pages 125–138 *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.

DWIRE, K. A., AND J. B. KAUFFMAN. 2003. Fire and riparian ecosystems in landscapes of the western USA. Forest Ecology and Management 178:61–74.

FRANCE, R. L. 1997. Potential for soil erosion from decreased litterfall due to riparian clearcutting: implications for boreal forestry and warm- and cool-water fisheries. Journal of Soil and Water Conservation 52:452–455.

FRANCE, R. L. 1998. Colonization of leaf litter by littoral macroinvertebrates with reference to successional changes in boreal tree composition expected after riparian clearcutting. American Midland Naturalist 140:314–324.

GUYETTE, R. P., AND W. G. COLE. 1999. Age characteristics of coarse woody debris (*Pinus strobus*) in a lake littoral zone. Canadian Journal of Fisheries and Aquatic Sciences 56:496–505.

GUYETTE, R. P., W. G. COLE, D. C. DEY, AND R.-M. MUZIKA. 2002. Perspectives on the age and distribution of large wood in riparian carbon pools. Canadian Journal of Fisheries and Aquatic Sciences 59:578–585.

HARTMAN, G. F., J. C. SCRIVENER, AND M. J. MILES. 1996. Impacts of logging in Carnation Creek, a high-energy coastal stream in British Columbia, and their implications for restoring fish habitat. Canadian Journal of Fisheries and Aquatic Sciences 53(Supplement 1):237–251.

HAUPT, H. F., AND W. J. KIDD. 1965. Good logging practices reduce sedimentation in central Idaho. Journal of Forestry 63:664–670.

JENNINGS, M. J., M. A. BOZEK, G. R. HATZENBELER, E. E. EMMONS, AND M. D. STAGGS. 1999. Cumulative effects of incremental shoreline habitat modification on fish assemblages in north temperate lakes. North American Journal of Fisheries Management 19:18–27.

JONES, T. A., AND L. D. DANIELS. 2008. Dynamics of large woody debris in small streams disturbed by the 2001 Dogrib fire in the Alberta foothills. Forest Ecology and Management 256:1751–1759.

KREUTZWEISER, D. P., AND S. S. CAPELL. 2001. Fine sediment deposition in streams after selective forest harvesting without riparian buffers. Canadian Journal of Forest Research 31:2134–2142. (see also Erratum, Canadian Journal of Forest Research 32:1108)

KREUTZWEISER, D. P., S. S. CAPELL, AND S. B. HOLMES. 2009. Stream temperature responses to partial-harvest logging in riparian buffers of boreal mixedwood forest watersheds. Canadian Journal of Forest Research 39: 497–506.

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.

LANDSTROM, J. 2003. Shoreline forest disturbance rates in natural and managed forests of northwestern Ontario. MSc Thesis, Lakehead University, Thunder Bay, Ontario.

LEE, P., AND C. SMYTH. 2003. Riparian forest management: paradigms for ecological management and practices in Alberta. Final Report No. 1. Northern Watershed Project, Alberta Research Council (Vegreville, Alberta) and Alberta Conservation Association (Edmonton, Alberta). (Available from: http://www.ab-conservation.com/go/default/index.cfm/publications/conservation-reports/report-series/details/?reportID=61CA67BE-BCD6-BFDD-5D1158CC86ADAD10)

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

MACDONALD, J. S., P. G. BEAUDRY, E. A. MACISAAC, AND H. E. HERUNTER. 2003. The effects of forest harvesting and best management practices on streamflow and suspended sediment concentrations during snowmelt in headwater streams in sub-boreal forests of British Columbia, Canada. Canadian Journal of Forest Research 33: 1397–1407.

MAINE FOREST SERVICE. 2004. Best management practices for forestry: protecting Maine's water quality. Maine Department of Conservation, Augusta, Maine. (Available from: http://www.maine.gov/doc/mfs/pubs/bmp_manual.htm)

MALLORY, E. C., M. S. RIDGWAY, A. M. GORDON, AND N. K. KAUSHIK. 2000. Distribution of woody debris in a small headwater lake, central Ontario, Canada. Archiv für Hydrobiologie 148:587–606.

MANITOBA CONSERVATION. 2008. Forest management guidelines for riparian management areas. Manitoba Conservation, Forestry Branch, Winnipeg, Manitoba. (Available from: http://www.gov.mb.ca/conservation/forestry/practices/guidelines.html)

MARBURG, A. E., M. G. TURNER, AND T. K. KRATZ. 2006. Natural and anthropogenic variation in coarse wood among and within lakes. Journal of Ecology 94:558–568.

MARTIN, C. W., AND J. W. HORNBECK. 1994. Logging in New England need not cause sedimentation of streams. Northern Journal of Applied Forestry 11:17–23.

MARTIN, C. W., J. W. HORNBECK, G. E. LIKENS, AND D. C. BUSO. 2000. Impacts of intensive harvesting on hydrology and nutrient dynamics of northern hardwood forests. Canadian Journal of Fisheries and Aquatic Sciences 57(Supplement 2):19–29.

MELEASON, M. A., S. V. GREGORY, AND J. P. BOLTE. 2003. Implications of riparian management strategies on wood in streams of the Pacific Northwest. Ecological Applications 13:1212–1221.

MELLINA, E., R. D. MOORE, S. G. HINCH, J. S. MACDONALD, AND G. PEARSON. 2002. Stream temperature responses to clearcut logging in British Columbia: the moderating influences of groundwater and headwater lakes. Canadian Journal of Fisheries and Aquatic Sciences 59: 1886–1900.

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.

NEWBREY, M. G. 2002. Morphological and meristic characteristics of lacustrine coarse woody structure as fish habitat. MS Thesis, University of Wisconsin, Stevens Point, Wisconsin.

NEWTON, M., AND E. C. COLE. 2005. Linkage between riparian buffer features and regeneration, benthic communities, and water temperature in headwater streams, western Oregon. Pages 81–101 *in* C. A. Harrington and S. H. Schoenholtz (editors). Productivity of western forests: a forest products focus. General Technical Report PNW-GTR-642. US Department of Agriculture Forest Service, Washington, DC.

NISLOW, K. H., AND W. H. LOWE. 2006. Influences of logging history and riparian forest characteristics on macroinvertebrates and brook trout (*Salvelinus fontinalis*) in headwater streams (New Hampshire, U.S.A). Freshwater Biology 51:388–397.

NITSCHKE, C. R. 2005. Does forest harvesting emulate fire disturbance? A comparison of effects on selected attributes in coniferous-dominated headwater systems. Forest Ecology and Management 214:305–319.

OMNR (ONTARIO MINISTRY OF NATURAL RESOURCES). 1988. Timber management guidelines for the protection of fish habitat. Ontario Ministry of Natural Resources, Queen's Printer for Ontario, Toronto, Ontario. (Available from: http://www.mnr.gov.on.ca/en/Business/Forests/Publication/STEL02_179028.html)

OMNR (ONTARIO MINISTRY OF NATURAL RESOURCES). 1998a. A silvicultural guide for the tolerant hardwood forest in Ontario. Ontario Ministry of Natural Resources, Queen's Printer for Ontario, Toronto, Ontario. (Available from: http://www.mnr.gov.on.ca/en/Business/Forests/Publication/MNR_E000396P.html)

OMNR (ONTARIO MINISTRY OF NATURAL RESOURCES). 1998b. Code of practice for timber management operations in riparian areas. Ontario Ministry of Natural Resources, Queen's Printer for Ontario, Toronto, Ontario. (Available from: http://www.mnr.gov.on.ca/en/Business/Forests/Publication/MNR_E000494P.html)

OMNR (ONTARIO MINISTRY OF NATURAL RESOURCES). 2001a. Forest management guide for natural disturbance pattern emulation. Ontario Ministry of Natural Resources, Queen's Printer for Ontario, Toronto, Ontario. (Available from: http://www.mnr.gov.on.ca/en/Business/Forests/Publication/MNR_E000509P.html)

OMNR (ONTARIO MINISTRY OF NATURAL RESOURCES). 2001b. Management guidelines for forestry and resource-based tourism. Ontario Ministry of Natural Resources, Queen's Printer for Ontario, Toronto, Ontario. (Available from: http://www.mnr.gov.on.ca/en/Business/Forests/Publication/STEL02_179025.html)

OMNR (ONTARIO MINISTRY OF NATURAL RESOURCES). 2007. Forest management guide for cultural heritage values. Ontario Ministry of Natural Resources, Queen's Printer for Ontario, Toronto, Ontario. (Available from: http://www.mnr.gov.on.ca/en/Business/Forests/Publication/MNR_E000505P.html)

OMNR (ONTARIO MINISTRY OF NATURAL RESOURCES). 2010a. Forest management guide for conserving biodiversity at the stand and site scales. Ontario Ministry of Natural Resources, Queen's Printer for Ontario, Toronto, Ontario. (Available from: http://www.mnr.gov.on.ca/en/Business/Forests/Publication/272847.html)

OMNR (ONTARIO MINISTRY OF NATURAL RESOURCES). 2010b. Forest management guide for conserving biodiversity at the stand and site scales: background and rationale for direction. Ontario Ministry of Natural Resources, Queen's Printer for Ontario, Toronto, Ontario. (Available from: http://www.mnr.gov.on.ca/en/Business/Forests/Publication/272847.html)

PARKER, S. A. 2006. The influence of local and landscape scale factors on the presence, relative abundance and characteristics of brook trout (*Salvelinus fontinalis*) in beaver ponds. MSc Thesis, Lakehead University, Thunder Bay, Ontario.

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

PLAMONDON, A. P. 1982. Augmentation de la concentration des sédiments en suspension suite à l'exploitation forestière et durée de l'effet. Canadian Journal of Forest Research 12:883–892.

QUINN, N. W. S. 2004. The presettlement hardwood forests and wildlife of Algonquin Provincial Park: a synthesis of historic evidence and recent research. Forestry Chronicle 80:705–717.

REEVES, G. H., P. A. BISSON, B. E. RIEMAN, AND L. E. BENDA. 2006. Postfire logging in riparian areas. Conservation Biology 20:994–1004.

RICHARDSON, J. S., R. J. NAIMAN, AND P. A. BISSON. 2012. How did fixed-width buffers become standard practice for protecting freshwaters from forest harvest practices? Freshwater Science 31:000–000.

RIDGWAY, M. S., AND P. J. BLANCHFIELD. 1998. Brook trout spawning areas in lakes. Ecology of Freshwater Fish 7: 140–145.

ROBISON, E. G., AND R. L. BESCHTA. 1990. Identifying trees in riparian areas that can provide coarse woody debris to streams. Forest Science 36:790–801.

RUSSELL, W. H., AND J. R. MCBRIDE. 2001. The relative importance of fire and watercourse proximity in determining stand composition in mixed conifer riparian forests. Forest Ecology and Management 150:259–265.

SASS, G. G., J. F. KITCHELL, S. R. CARPENTER, T. R. HRABIK, A. E. MARBURG, AND M. G. TURNER. 2006. Fish community and food web responses to a whole-lake removal of coarse woody habitat. Fisheries 31:321–330.

SIBLEY, P. K., AND A. M. GORDON. 2010. Managing riparian forests: a decision support system. Sustainable Forest Management Network, Edmonton, Alberta. (Available from: http://www.ales.ualberta.ca/forestry/Sustainable_Forest_Management/Publications/SynthesisReports.aspx#Authors'%20with%20last%20name%20starting%20with%20M)

SIBLEY, P. K., D. P. KREUTZWEISER, B. J. NAYLOR, J. S. RICHARDSON, AND A. M. GORDON. 2012. Emulation of natural disturbance (END) for riparian forest management: synthesis and recommendations. Freshwater Science 31:258–264.

SRIDHAR, V., A. L. SANSONE, J. LAMARCHE, T. DUBIN, AND D. P. LETTENMAIER. 2004. Prediction of stream temperature in forested watersheds. Journal of American Water Resources Association 40:197–213.

STAFFORD, C., M. LEATHERS, AND R. BRIGGS. 1996. Forestry-related nonpoint source pollution in Maine: a literature review. Miscellaneous Report 399. Maine Agricultural and Forest Experimental Station, Orono, Maine. (Available from: http://www.umaine.edu/mafes/elec_pubs/miscrepts/mr399.pdf)

STEEDMAN, R. J., C. J. ALLAN, R. L. FRANCE, AND R. S. KUSHNERIUK. 2004. Land, water, and human activity on boreal watersheds. Pages 59–85 *in* J. M. Gunn, R. J. Steedman, and R. A. Ryder (editors). Boreal shield watersheds. CRC Press, Boca Raton, Florida.

STEEDMAN, R. J., R. L. FRANCE, R. S. KUSHNERIUK, AND R. H. PETERS. 1998. Effects of riparian deforestation on littoral water temperatures in small boreal forest lakes. Boreal Environment Research 3:161–169.

STEEDMAN, R. J., AND R. S. KUSHNERIUK. 2000. Effects of experimental clearcut logging on thermal stratification, dissolved oxygen, and lake trout (*Salvelinus namaycush*) habitat volume in three small boreal forest lakes. Canadian Journal of Fisheries and Aquatic Sciences 57(Supplement 2):82–91.

STEEDMAN, R. J., R. S. KUSHNERIUK, AND R. L. FRANCE. 2001. Littoral water temperature response to experimental shoreline logging around small boreal forest lakes. Canadian Journal of Fisheries and Aquatic Sciences 58: 1638–1647.

STEEDMAN, R. J., AND P. R. MORASH. 2001. Effects of forest regeneration practices on aquatic ecosystems. Pages 541–556 *in* R. G. Wagner and S. J. Colombo (editors). Regenerating the Canadian forest. Fitzhenry and Whiteside, Markham, Ontario.

TRIMBLE, G. R., AND R. S. SARTZ. 1957. How far from a stream should a logging road be located? Journal of Forestry 53: 339–341.

TYRRELL, L. E., AND T. R. CROW. 1994. Dynamics of dead wood in old-growth hemlock-hardwood forests in northern Wisconsin and northern Michigan. Canadian Journal of Forest Research 24:1672–1683.

WANG, L., J. LYONS, P. RASMUSSEN, P. SEELBACH, T. SIMON, M. WILEY, P. KANEHL, E. BAKER, S. NIEMELA, AND P. M. STEWART. 2003. Watershed, reach, and riparian influences on stream fish assemblages in the Northern Lakes and Forest Ecoregion, U.S.A. Canadian Journal of Fisheries and Aquatic Sciences 60:491–505.

WEBSTER, J. R., S. W. GOLLADAY, E. F. BENFIELD, D. J. D'ANGELO, AND G. T. PETERS. 1990. Effects of forest disturbance on particulate organic matter budgets of small forest streams. Journal of the North American Benthological Society 9:120–140.

WEBSTER, J. R., AND J. B. WAIDE. 1982. Effects of forest clearcutting on leaf breakdown in a southern Appalachian stream. Freshwater Biology 12:331–344.

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.

WILKERSON, E., J. M. HAGAN, D. SIEGEL, AND A. A. WHITMAN. 2006. The effectiveness of different buffer widths for protecting headwater stream temperature in Maine. Forest Science 52:221–231.

WILZBACH, M. A., B. C. HARVEY, J. L. WHITE, AND R. J. NAKAMOTO. 2005. Effects of riparian canopy opening and salmon carcass addition on the abundance and growth of resident salmonids. Canadian Journal of Fisheries and Aquatic Sciences 62:58–67.

ZORN, T. G., P. W. SEELBACH, AND M. J. WILEY. 2002. Distributions of stream fishes and their relationship to stream size and hydrology in Michigan's Lower Peninsula. Transactions of the American Fisheries Society 131:70–85.

ZWIENIECKI, M. A., AND M. NEWTON. 1999. Influence of streamside cover and stream features on temperature trends in forested streams in western Oregon. Western Journal of Applied Forestry 14:106–113.

Received: 29 March 2011
Accepted: 2 November 2011