Emulation of natural disturbance (END) for riparian forest management: synthesis and recommendations

Authors: Sibley, Paul K., Kreutzweiser, David P., Naylor, Brian J., Richardson, John S., and Gordon, Andrew M.

Source: Freshwater Science, 31(1) : 258-264

Published By: Society for Freshwater Science

URL: https://doi.org/10.1899/11-094.1

Freshwater Science, 2012, 31(1):258–264

DOI: 10.1899/11-094.1
Published online: 24 January 2012

BRIDGES

Emulation of natural disturbance (END) for riparian forest management: synthesis and recommendations

Paul K. Sibley[1,5], David P. Kreutzweiser[2,6], Brian J. Naylor[3,7], John S. Richardson[4,8], AND Andrew M. Gordon[1,9]

[1] *School of Environmental Sciences, University of Guelph, Guelph, Ontario, Canada N1G 2W1*
[2] *Great Lakes Forestry Centre, Canadian Forest Service, 1219 Queen Street East, Sault Ste. Marie, Ontario, Canada P6A 2E5*
[3] *Forest Policy Section, Ontario Ministry of Natural Resources, 3301 Trout Lake Road, North Bay, Ontario, Canada P1A 4L7*
[4] *Department of Forest Sciences, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z4*

Abstract. Designing management strategies based on the emulation of natural disturbance (END) to promote long-term sustainability of riparian forests and their adjacent aquatic ecosystems is an evolving process. Conceptually, the goal of END in riparian forest management is to mimic, to the extent possible, natural disturbance processes within the range of natural variability of the ecosystem while accounting for both temporal (frequency) and spatial (size) scales of the disturbance. The application of END in riparian forests has been evaluated in a limited but growing number of studies. From these studies, the idea has emerged that END could be used as a *tool* to enhance forest complexity and resilience capacity through carefully implemented management strategies. In practice, however, this tool presents a formidable challenge, constrained by scientific and social uncertainty. In this *BRIDGES* cluster we have critically examined: 1) the historical, scientific, and practical foundations of applying END in riparian forest management as an alternative to fixed-width buffers, and 2) the extent to which mimicking natural disturbance and renewal processes can protect aquatic ecosystems through conservation of riparian and aquatic biodiversity. In this synthesis paper, we identify some of the outstanding questions and uncertainties that constrain the integration of END into riparian forest management, provide some initial guiding principles for applying END in riparian areas, and offer recommendations for future research.

Key words: riparian forests, management, emulation of natural disturbance, aquatic systems.

Forest management has undergone significant change over the past few decades. Most notable among these changes has been the movement away from management practices focused solely on wood production (Hebert 2004, Swanson et al. 2011) to those that integrate a more complete range of watershed and landscape values (Naiman et al. 2005, Richardson et al. 2012). This change has led to a gradual shift from stand-level forest-management practices to those that explicitly integrate management across spatial and temporal scales and that incorporate ecosystem-based perspectives. Congruent with this new perspective is the idea that harvesting should be conducted in a manner that emulates natural disturbance patterns (Perera and Cui 2010, Swanson et al. 2011), i.e., Emulation of Natural Disturbance (END), with the goal of ensuring that the historical ranges of natural variation are maintained in future states of ecosystem structure and function (Kimmins 2004). Application of END in forest management has elicited much debate, but some jurisdictions in Canada currently use END principles in sustainable forest-management practices (McNicol and Baker 2004, Manitoba Conservation 2009) or policy (OMNR 2010, Naylor et al. 2012). From this beginning has emerged the concept that END can and should be applied as a management *tool* whereby

[5] E-mail addresses: psibley@uoguelph.ca
[6] dave.kreutzweiser@nrcan-rncan.gc.ca
[7] brian.naylor@ontario.ca
[8] john.richardson@ubc.ca
[9] agordon@uoguelph.ca

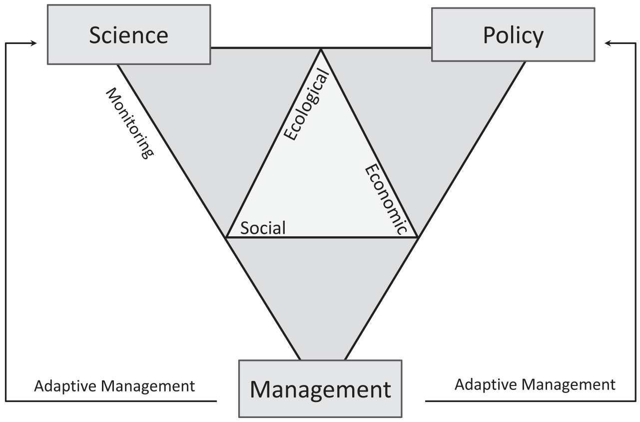

FIG. 1. Conceptual framework for the incorporation of emulation of natural disturbance (END) in riparian forest management. In this approach, the tripartite relationship between science, management, and policy forms the foundation for adaptive decision making, within which ecological, social, and economic values are explicitly considered.

carefully planned and implemented silvicultural strategies that emulate natural disturbance patterns are used as the basis for sustainable riparian forest management (Naylor et al. 2012). Intentional disturbance via carefully planned harvesting in riparian areas is guided by a desire to increase habitat complexity at multiple spatial and temporal scales thereby conserving and enhancing riparian and aquatic biodiversity (Kreutzweiser et al. 2012, Naylor et al. 2012).

In this *BRIDGES* cluster, we have critically examined the historical, scientific, and practical application of END in riparian forest management as an alternative to fixed-width buffers to address the question: Can emulating natural watershed disturbance and renewal processes sustain riparian and aquatic ecosystems and their biodiversity? Herein, we provide a synthesis of these ideas to identify some of the outstanding questions and uncertainties constraining the integration of END into riparian forest management, provide some initial guiding principles to facilitate the application of END in riparian forests, and offer recommendations for future research.

Uncertainties, Outstanding Questions, and Possible Solutions when Applying END

Scientific understanding of how riparian areas and their associated aquatic systems respond to natural disturbances has improved tremendously in recent decades, and this understanding has led to an increasing number of studies evaluating the application of END to meet ecological objectives in riparian forest management (Bouchard et al. 2008, Jackson and Sullivan 2009, Kardynal et al. 2009, Arkle and Pilliod 2010, Holmes et al. 2010, Kreutzweiser et al. 2010, Sarr et al. 2011). These studies indicate that END can be applied in some situations but that it must be applied in a manner that clearly integrates other riparian values (e.g., provision of ecosystem services, preservation of sociocultural attributes) in the decision-making process (National Research Council 2002, Naiman et al. 2005). Figure 1 illustrates such an integrative planning approach. A tripartite relationship between science, management, and policy forms the foundation for adaptive decision making, within which ecological, social, and economic values are explicitly considered when applying END in riparian forest management. The extent to which such integrative approaches can be applied successfully will depend on the success with which the uncertainties that currently constrain the broader application of END in riparian forest management can be addressed. Some of these uncertainties include: 1) the degree to which habitats created through END-based management practices truly mimic naturally disturbed habitats (i.e., how closely can we emulate natural disturbance?), 2) the time scale over which convergence between natural and emulated disturbances will be acceptable, 3) the extent to which END can be applied in light of potential negative societal perceptions, 4) acceptance by the forest industry under economic constraints, and 5) the need to consider cumulative effects of other activities on the landscape when planning END approaches.

Ecological uncertainties in the application of END

Uncertainties associated with the ecological premise of END approaches are a significant constraint to the broader application of END in riparian forest management. From an ecological standpoint, the goal of END in riparian forest management is to mimic disturbance within the range of natural variability, thereby enhancing riparian forest complexity and resilience capacity (Drever et al. 2006, Odion and Sarr 2007, Long 2009, Mori 2011). END is based on the assumptions that biodiversity is a critical element for long-term ecosystem persistence and that natural disturbance plays an essential role in generating compositional and functional heterogeneity at multiple scales (Drever et al. 2006). Kreutzweiser et al. (2012) contend that periodic large-scale disturbances in riparian and upland forests may be required for long-term sustainability of riparian and aquatic communities because they have evolved in the presence of both terrestrial (e.g., fires, mass wasting, disease, windthrow, etc.) and hydrological (e.g., flooding) disturbance regimes (St. Onge and Magnan 2000, Tonn et al. 2003, 2004, Cott et al. 2010) that determine the trajectory and outcome of successional patterns and support biodiversity. Although natural disturbance regimes on the landscape often affect riparian areas, the current practice to protect aquatic systems from effects of forest management is to retain largely unnatural, undisturbed, fixed-width buffers (Buttle 2002, MacDonald et al. 2004, Richardson et al. 2012). In the absence of periodic stand-replacing (fire) or smaller-scale (gap creation) disturbances that favor growth of new tree species or a range of seral stages of existing species, buffer-based riparian areas can experience a loss of structural and functional heterogeneity and eventually will encompass only a subset of the natural range of structural and functional diversity that would otherwise exist (Kreutzweiser et al. 2012). Lower heterogeneity decreases the probability that the system will be able to resist unexpected events that can lead to catastrophic regime shifts (Drever et al. 2006).

The goal of applying END in riparian forest management is to increase the resilience capacity of riparian areas and, by virtue of ecohydrological coupling, to protect aquatic systems. Growing empirical evidence indicates that habitats created by management actions can function similarly (though not identically) to natural habitats for some taxa, but the extent to which such findings can be generalized across all species and habitats remains uncertain (Niemela 1999, Nitschke 2005). How much additional understanding of natural disturbance regimes is required for END to serve as an effective management tool is often questioned (Long 2009). A key consideration is how to address the issue of scale because riparian forests experience disturbance regimes (e.g., fire, pest outbreaks, windthrow) across a range of spatiotemporal scales, sometimes simultaneously. Scale-dependent responses to disturbance across aquatic–terrestrial ecotones must be explicitly considered in the application of END if it is to be effectively applied in riparian forest management (Moore and Richardson 2012), although complex, nonlinear changes in ecosystem condition are difficult to manage for a desired future state. Should END be applied in a manner that reflects the true stochastic nature of disturbances or based on the long-term average frequency of occurrence, intensity, and size of disturbance on the landscape? The latter would be easier from a management standpoint but might be less realistic than the former. In landscapes dominated by a particular disturbance regime, management practices would be largely directed toward emulating that regime. For example, riparian areas in boreal shield forests have evolved largely under a fire disturbance regime. Recent studies have shown that prescribed fires in riparian areas can increase biodiversity compared to unburned fixed-width buffers and yield riparian forests that more closely resemble natural post-burned states (Kardynal et al. 2009, Arkle and Pilliod 2010). However, public resistance to the use of prescribed fires in forest management is strong (Arkle and Pilliod 2010), and use of a combination of clear cutting and prescribed fire or clear cutting alone to emulate the natural effects of fires in riparian areas may be more acceptable (Nitschke 2005). The potential importance of small-scale disturbances in riparian areas also must be considered. For example, gap-opening windthrow events may favor the growth of small trees required by beaver, a keystone species in boreal forests (Naiman et al. 1994).

Addressing the ecological uncertainties of END, including how best to integrate this understanding into a practical framework for decision making, is a significant future challenge in riparian forest management (Sibley and Gordon 2010). Some ideas are presented in the future research section below. However, successful application of END as a management tool in riparian forests also will depend on how well we can address societal uncertainties.

Sociocultural considerations and economic constraints

Social acceptance is a potentially significant obstacle to implementation of END in riparian forest management (Long 2009). Klenk et al. (2008, 2009) suggested that societal resistance to END reflects a poor understanding of its scientific basis, but, when END allows access to the previously unavailable riparian timber (Naylor et al. 2012), negative public perception also may stem from mistrust of industry actions, which are often viewed as financially rather than environmentally motivated. The public often perceives proposals to increase access to riparian timber as a wood grab motivated by a desire to maximize profits. However, current forest management practices and policies increasingly incorporate integrative and sustainable approaches (Naylor et al. 2012), and such thinking may be more indicative of outdated historical perceptions than an understanding of current practices. Forest companies today must consider multiple competing values of riparian areas in the decision-making process (Sibley and Gordon 2010). They must be willing to accept trade-offs between wood allocation and other features (e.g., ecologically sensitive habitats or hydrologically vulnerable areas), and possibly, to forego opportunity costs related to timber (McKenney et al. 2004).

Social acceptance of END practices can be significantly enhanced if the public is provided an opportunity to participate in development of END practices. For example, during the creation of Ontario's new forest guidelines, the proposal to include large (e.g., hundreds to thousands of hectares) clearcuts to emulate large-scale forest fires was rejected by some segments of the public (McNicol and Baker 2004, Naylor et al. 2012). This rejection led to restriction of most (80%) boreal forest clearcuts to <260 ha. Larger clearcuts are allowed 20% of the time if appropriately rationalized, but the concession to public perception undoubtedly will constrain the extent to which the upper range of natural disturbance can be emulated by END practices. At the smaller end of the spatial spectrum, small cut blocks (<1 ha), which could mimic small-scale disturbances, such as windthrow (a common form of disturbance in riparian areas), may be filtered out by forest companies because the cost of developing road access may not be offset by the small wood volumes obtained.

Public perception also is influenced by a poor understanding of how END should be applied in the context of competing land uses that can exacerbate impacts on landscapes already under intense pressure (e.g., cumulative effects). The relative importance of this issue will vary by region. For example, in boreal shield forests, where forestry is the dominant industry, other landuse activities may be relatively unimportant, but in the boreal plains, forestry is but one of several industries (e.g., agriculture, mining, and oil and gas extraction) that can negatively affect the landscape (Schneider et al. 2003). Large road networks are required for exploration, access, and removal of resources, and the impacts of roads on aquatic systems are well documented (Mattson et al. 2000, McGarigal et al. 2001). Forest management regulations in most jurisdictions are meant to mitigate impacts from roads by reducing their number or optimizing their location on the landscape. However, in Alberta, despite numerous regulations governing seismic exploration, the cumulative density of seismic lines and associated roads is not limited (Schneider et al. 2003). On landscapes where impacts from other industries are significant, the effectiveness of applying END approaches may be significantly constrained.

The public is likely to be more receptive to riparian management practices that incorporate smaller-scale harvesting disturbances, have a lower probability of compromising ecosystem services, and explicitly consider other potential values. Thus, in practice, only a subset of the potential spectrum of actual disturbance regimes may be emulated in most habitats because other disturbances are either socially unacceptable or economically infeasible. One way to address the uncertainties associated with END is to establish a set of guiding principles that can be applied in an adaptive-management framework.

Guiding principles for END applications

When Perera et al. (2004) reviewed the applications of END in North American forest management, no explicit, generally accepted guidelines existed on how to implement END principles practically. However, some principles of END (e.g., creation of forest gaps by partial harvesting, large openings by clear cutting) have been implicit in forest management guidelines for decades, and refined approaches to forest management based on END have been successful (Bouchard et al. 2008). Recently, several field studies (Kreutzweiser et al. 2005, 2010, Kardynal et al. 2009), a meta-analysis (Nitschke 2005), a decision-support system (Sibley and Gordon 2010), and revised forest management direction (OMNR 2010, Naylor et al. 2012) have been published that focus on new configurations or implications for riparian forest buffers based on END principles. On the basis of the perspectives provided in this series of publications, a few generalizations emerge that we think can be offered as initial guiding principles for END applied to forest watersheds.

1) Most natural forest disturbances make incursions into riparian areas to varying degrees.
2) Forest harvesting configurations designed to emulate natural disturbance patterns will depend on the forest type and regional disturbance patterns. END may be applicable as a model for riparian forest management in many regions and forest types, but it is unlikely to work everywhere, and the limits to where it may be applicable will need to be cautiously assessed (Moore and Richardson 2012).
3) Forest management operations may have to include a range of realistic disturbance intensities. A key objective of END is to maintain structural and functional heterogeneity within the range of natural variation in riparian forests, so management approaches based on END will have to be applied with consideration of forest type and expected regional and local disturbance patterns (Moore and Richardson 2012). In forest types that require periodic large, stand-replacing disturbances to sustain natural forest structure and processes, emulation should incorporate clearcut silviculture within riparian forests. Conversely, in forest types that regenerate

through smaller gap disturbances, emulation should incorporate silviculture based on partial/selective harvesting systems within riparian forests.

4) The key is complexity (Puettmann et al. 2009). The overall objective is to maintain riparian and upland heterogeneity in forest structure within the range of natural, and ideally within socially acceptable, variation to produce a myriad of conditions in support of biodiversity and ecosystem function.

5) All operations within riparian forests must be thoughtfully planned and carefully implemented to ensure that the appropriate type and amount of disturbance (and subsequent renewal and tending) is conducted in locations where it will be operationally feasible and where it will not compromise aquatic systems and other ecological or social values.

Recommendations for Future Research

A growing body of theoretical and practical literature supports the idea that END can be used as a management tool, but empirical testing of the END model and its underlying assumptions has been limited in the context of operational riparian forest management. One of the biggest questions faced by governments and forest managers implementing END is how to decide when the application of END has been successful, i.e., how close is close enough? If managed habitats have the same list of species as natural habitats, is that close enough? How comparable does the abundance of each species between natural and END-managed systems need to be? Should we measure the success of END-based management on functional or structural endpoints? To answer these questions, the limits (i.e., type and degree) of disturbance (e.g., harvesting) that achieve a desired future forest state (e.g., enhanced biodiversity, preservation of other values, etc.) will have to be clearly defined.

The management guidelines recently introduced for the province of Ontario (OMNR 2010) may present an excellent opportunity to develop and test specific hypotheses related to the operational application of END in riparian forests with an adaptive-management framework. In the context of complex systems, adaptive-management frameworks address uncertainties by using proposed management actions as experiments to test socially and scientifically defensible management options for the protection of ecosystems (Holling and Gunderson 2002, Olsson et al. 2004, 2006, Walker et al. 2004, Folke 2006; Fig. 1). In Ontario, guidance is provided to forest managers for clearcut harvesting, which mimics larger-scale disturbances, and partial harvesting, which mimics smaller-scale disturbances, for timber removal in riparian areas (OMNR 2010). Based on this direction, site-specific riparian harvesting scenarios (different types of management actions that emulate natural disturbances) could be implemented in carefully planned experimental designs (e.g., Before-After-Control-Impact) and monitored to determine if the desired (hypothesized) outcomes have been achieved over acceptable spatial and temporal scales. Ideally, separate studies would be conducted in different regions of North America to account for regional differences in riparian forest responses to END approaches and should differentiate between lentic and lotic riparian ecosystems because these 2 types of aquatic ecosystems may not respond comparably to END management approaches. Such a "management by hypothesis" approach (Holling 1978) would go a long way toward defining the limits with which END can/should be applied in riparian forest management and could serve as an excellent model for contributing to the evolving process of improving forest management practices.

Use of intentional disturbance in riparian and upland forests as a management approach to sustain riparian and aquatic ecosystems is an evolving practice. It has been logically rationalized in terms of ecological principles like resiliency, but a strong need remains for empirical evidence that it can be applied in a practical and effective manner. END could be a model for riparian forest management to sustain and protect aquatic systems, but it may not work everywhere because regional patterns of natural disturbance, operational feasibility, consideration of nonaquatic values, and social receptivity will constrain and direct its application. Where END is being implemented, a need exists to monitor effectiveness to determine the relative success of implemented disturbance-based management options and for hypothesis-driven research based on adaptive management to answer more specific questions about how the structure and function of both riparian and aquatic ecosystems will respond to disturbance-based management.

Literature Cited

Arkle, R. S., and D. S. Pilliod. 2010. Prescribed fires as ecological surrogates for wildfires: a stream and riparian perspective. Forest Ecology and Management 259:893–903.

Bouchard, M., D. Kneeshaw, and Y. Bergeron. 2008. Ecosystem management based on large-scale disturbance pulses: a case study from sub-boreal forests of western

Quebec (Canada). Forest Ecology and Management 256: 1734–1742.

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

COTT, P. A., B. A. ZAJDLIK, K. J. BOURASS, M. LANGE, AND A. M. GORDON. 2010. Effects of forest fire on young-of-the-year northern pike, *Esox lucius*, in the Northwest Territories. Canadian Field Naturalist 124:104–112.

DREVER, C. R., G. PETERSON, C. MESSIER, Y. BERGERON, AND M. FLANNIGAN. 2006. Can forest management based on natural disturbance maintain ecological resilience? Canadian Journal of Forest Research 36:2285–2299.

FOLKE, C. 2006. Resilience: the emergence of a perspective for social-ecological systems analysis. Global Environmental Change 16:253–267.

HEBERT, D. 2004. Consequences of emulating natural forest disturbance: a Canadian forest perspective. Pages 200–208 *in* A. H. Perera, L. J. Buse, and M. G. Weber (editors). Emulating natural forest landscape disturbance. Columbia University Press, New York.

HOLLING, C. S. 1978. Adaptive environmental assessment and management. John Wiley and Sons, Hoboken, New Jersey.

HOLLING, C. S., AND L. H. GUNDERSON. 2002. Resilience and adaptive cycles. Pages 25–62 *in* L. H. Gunderson and C. S. Holling (editors). Panarchy: understanding transformations in human and natural systems. Island Press, Washington, DC.

HOLMES, S. B., D. P. KREUTZWEISER, AND P. S. HAMILTON. 2010. Operational and economic feasibility of logging with forested riparian zones. Forestry Chronicle 86:601–606.

JACKSON, B. K., AND S. M. SULLIVAN. 2009. Influence of wildfire severity on riparian plant community heterogeneity in an Idaho, USA wilderness. Forest Ecology and Management 259:24–32.

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.

KIMMINS, J. P. 2004. Emulating natural forest disturbance. What does this mean? Pages 8–28 *in* A. H. Perera, L. J. Buse, and M. G. Weber (editors). Emulating natural forest landscape disturbance. Columbia University Press, New York.

KLENK, N. L., G. Q. BULL, AND D. COHEN. 2008. What is the "END" (emulation of natural disturbance) in forest ecosystem management? An open question. Canadian Journal of Forest Research 38:2159–2168.

KLENK, N. L., G. Q. BULL, AND J. I. MACLELLAN. 2009. The "emulation of natural disturbance" (END) management approach in Canadian forestry: a critical evaluation. Forestry Chronicle 85:440–445.

KREUTZWEISER, D. P., S. S. CAPELL, AND K. P. GOOD. 2005. Macroinvertebrate community responses to selection logging in riparian and upland areas of headwater catchments in a northern hardwood forest. Journal of the North American Benthological Society 24:208–222.

KREUTZWEISER, D. P., E. A. MUTO, S. B. HOLMES, AND J. M. GUNN. 2010. Effects of upland clearcutting and riparian partial-harvesting on leaf pack breakdown and aquatic invertebrates in boreal forest streams. Freshwater Biology 55:2238–2252.

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.

LONG, J. N. 2009. Emulating natural disturbance regimes as a basis for forest management: a North American view. Forest Ecology and Management 257:1868–1873.

MACDONALD, E., C. J. BURGESS, G. J. SCRIMGEOUR, S. BOUTIN, S. REEDYK, AND B. KOTAK. 2004. Should riparian buffers be part of forest management based on emulation of natural disturbance? Forest Ecology and Management 187:185–196.

MANITOBA CONSERVATION. 2009. Forest management guidelines for riparian management areas. Manitoba Conservation, Winnipeg, Manitoba. (Available from: http://www.manitoba.ca/conservation/forestry/forest-practices/practices/fpp-guideline-pdfs.html)

MATTSON, J. A., J. E. BAUMGRAS, C. R. BLINN, AND M. A. THOMPSON. 2000. Harvesting options for riparian areas. Pages 255–272 *in* E. S. Verry, J. W. Hornbeck, and C. A. Dolloff (editors). Riparian management in forests. Lewis Publishers, New York.

MCGARIGAL, K., W. H. ROMME, M. CRIST, AND E. ROWORTH. 2001. Cumulative effects of roads and logging on landscape structure in the San Juan Mountains, Colorado (USA). Landscape Ecology 16:327–349.

MCKENNEY, D., A. MUSSELL, AND G. FOX. 2004. An economic perspective on emulation forestry and a case study on woodland caribou–wood production trade-offs in northern Ontario. Pages 209–218 *in* A. H. Perera, L. J. Buse, and M. G. Weber (editors). Emulating natural forest landscape disturbance. Columbia University Press, New York.

MCNICOL, J. G., AND J. A. BAKER. 2004. Emulating natural disturbance: from policy to practical guidance in Ontario. Pages 251–262 *in* A. H. Perera, L. J. Buse, and M. G. Weber (editors). Emulating natural forest landscape disturbance. Columbia University Press, New York.

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.

MORI, A. S. 2011. Ecosystem management based on natural disturbances: hierarchical context and non-equilibrium paradigm. Journal of Applied Ecology doi: 10.1111/j.1365-2664.2010.01956.x

NAIMAN, R. J., H. DECAMPS, AND M. E. MCCLAIN. 2005. Riparia: ecology, conservation, and management of streamside communities. Elsevier Academic Press, New York.

Naiman, R. J., G. Pinay, C. A. Johnston, and J. Pastor. 1994. Beaver influences on the long-term biogeochemical characteristics of boreal forest drainage networks. Ecology 75:905–921.

National Research Council. 2002. Riparian areas. Functions and strategies for management. National Academy Press, Washington, DC.

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: 247–256.

Niemela, J. 1999. Management in relation to disturbance in the boreal forest. Forest Ecology and Management 115: 127–134.

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.

Odion, D. C., and D. A. Sarr. 2007. Managing disturbance regimes to maintain biological diversity in forested ecosystems of the Pacific Northwest. Forest Ecology and Management 246:57–65.

Olsson, P., C. Folke, and F. Berkes. 2004. Adaptive co-management for building resilience in social-ecological systems. Environmental Management 34:75–90.

Olsson, P., L. H. Gunderson, S. R. Carpenter, P. Ryan, L. Lebel, C. Folke, and C. S. Holling. 2006. Shooting the rapids: navigating transitions to adaptive governance of social-ecological systems. Ecology and Society 18 (Available from: http://www.ecologyandsociety.org/vol11/iss1/art18/)

OMNR (Ontario Ministry of Natural Resources). 2010. Forest management guide for conserving biodiversity at the stand and site scales. Queen's Printer for Ontario, Toronto, Ontario.

Perera, A. H., and W. Cui. 2010. Emulating natural disturbances as a forest management goal: lessons from fire regime simulations. Forest Ecology and Management 259:1328–1337.

Perera, A. H., and L. J. Buse. 2004. Emulating natural disturbance in forest management: an overview. Pages 3–7 *in* A. H. Perera, L. J. Buse, and M. G. Weber (editors). Emulating natural forest landscape disturbances: concepts and applications. Columbia University Press, New York.

Perera, A. H., L. J. Buse, and M. G. Weber. 2004. Emulating natural forest landscape disturbances. Columbia University Press, New York.

Puettmann, K. J., K. D. Coates, and C. Messier. 2009. A critique of silviculture: managing for complexity. Island Press, Washington, DC.

Richardson, J. S., R. J. Naiman, and P. A. Bisson. 2012. How did fixed-width buffers become standard practice for protecting freshwaters and their riparian areas from forest harvest practices? Freshwater Science 31:232–238.

Sarr, D. A., D. E. Hibbs, J. P. A. Shatford, and R. Momsen. 2011. Influences of life history, environmental gradients, and disturbance on riparian tree regeneration in Western Oregon. Forest Ecology and Management 261: 1241–1253.

Schneider, R. R., J. B. Stelfox, S. Boutin, and S. Wasel. 2003. Managing the cumulative impacts of land uses in the western Canadian sedimentary basin: a modeling approach. Conservation Ecology 7:8–14.

Sibley, P. K., and A. M. Gordon. 2010. Managing riparian forests: a decision support system. Sustainable Forest Management Network, Edmonton, Alberta. (Available from: P. Sibley, School of Environmental Sciences, University of Guelph, Guelph, Ontario, Canada N1G 2W1).

St. Onge, I., and P. Magnan. 2000. Impact of logging and natural fires on fish communities of Laurentian shield lakes. Canadian Journal of Fisheries and Aquatic Sciences 57:165–174.

Swanson, M. E., J. F. Franklin, R. L. Beschta, C. M. Crisafulli, D. A. DellaSala, R. L. Hutto, D. B. Lindenmayer, and F. J. Swanson. 2011. The forgotten stage of forest succession: early-successional ecosystems on forest sites. Frontiers in Ecology and the Environment 9:117–125.

Tonn, W. M., S. M. Boss, P. K. M. Aku, G. J. Scrimgeour, and C. A. Paszkowski. 2004. Fish assemblages in subarctic lakes: does fire affect fish–environment relations in northern Alberta? Transactions of the American Fisheries Society 133:132–143.

Tonn, W. M., C. A. Paszkowski, G. J. Scrimgeour, P. K. M. Aku, M. Lange, E. E. Prepas, and K. Westcott. 2003. Effects of forest harvesting and fire on fish assemblages in boreal plains lakes: a reference conditions approach. Transactions of the American Fisheries Society 132: 514–523.

Walker, B., C. S. Holling, S. R. Carpenter, and A. Kinzig. 2004. Resilience, adaptability, and transformability in social–ecological systems. Ecology and Society 9. (Available from: http://www.ecologyandsociety.org/vol9/iss2/art5)

Received: 26 July 2011
Accepted: 21 November 2011