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BRIDGES

Introduction and a theoretical basis for using disturbance by forest management activities to sustain aquatic ecosystems

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Abstract. Emulation of natural disturbance (END) is an emerging paradigm for modern, ecosystem-based forest management in North America. On the premise that periodic disturbance is an integral part of natural, determinative processes on forest landscapes, managing forests by emulating natural disturbance is thought to produce landscape patterns that resemble those arising from natural disturbances and that are known to maintain critical processes and habitat for conserving biodiversity. Applying END principles to forest watersheds has implications for the protection of aquatic ecosystems because END can include intentional logging disturbance near water to emulate natural riparian disturbance. Literature shows that logging in watersheds, and especially in riparian areas, can lead to negative abiotic and biotic effects in aquatic ecosystems. However, an integration of the current understanding of land–water linkages in forest watersheds with general disturbance ecology would suggest that periodic watershed and riparian disturbances may be natural renewal processes that are required for long-term sustainability of aquatic ecosystems. Previous syntheses of END in forestry failed to consider the implications for aquatic ecosystems, and most forest-management guidelines default to the protection of water resources by systematic riparian (shoreline) buffers. This paper introduces the concepts of END and provides a theoretical basis for using intentional riparian forest disturbance to sustain aquatic habitat complexity and ecosystem integrity.

Key words: natural disturbance emulation, forest watershed, logging impacts, aquatic ecosystem sustainability.

Forest management policies and practices are evolving in North America. Policymakers and practitioners are increasingly adopting whole ecosystem-based management principles as a means to attain sustainable forest management (Kimmins 2004). The assumption is that ecosystem-based management will simultaneously provide the required habitat for most species across the landscape and thereby sustain biodiversity and critical ecosystem processes within their natural range of variation (Hunter 1999, Lindenmayer et al. 2006). An emerging paradigm that underpins ecosystem-based management for forests is the emulation of natural disturbance, or END (Long 2009). On the premise that periodic disturbance is an integral part of natural, determinative processes on forest landscapes, managing forests to emulate natural disturbance is thought to achieve the goals of ecosystem-based management by providing landscape patterns resembling those that result from natural disturbances and that are known to renew and maintain critical processes and habitat for conserving biodiversity (OMNR 2001). This practice means creating spatial patterns across managed forest landscapes that are similar in size and forest structure to patterns arising from natural disturbance. It is generally accepted that forest ecosystem resilience has evolved in part from a legacy of natural disturbance in the sense that disturbance ultimately fosters the structural and functional complexity of forest

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landscapes (Gunderson 2000). Under END, management goals seek to sustain forest ecosystem structure and function across a number of spatial scales thereby retaining a capacity for renewal, maintaining desired ecological goods and services, and reducing the probability of shifting to an undesirable state (Drever et al. 2006).

Perera and Buse (2004, p. 4) define END as ‘‘an approach in which forest managers develop and apply specific management strategies and practices, at appropriate spatial and temporal scales, with the goal of producing forest ecosystems as structurally and functionally similar as possible to the ecosystems that would result from natural disturbances and that incorporate the spatial, temporal, and random variability intrinsic to natural systems’’. Fire is currently the most common disturbance agent being modeled for END in forest management (Hunter 1993), but it is not the only disturbance type that is useful or appropriate in this context. Other disturbances being considered for effectiveness as forest management models include insect defoliation (MacLean 2004), gap phase processes from natural mortality (Seymour et al. 2002), windthrow (Kneeshaw et al. 2011), debris flows (Rood 2006), and a combination of disturbances (Suffling and Perera 2004). Natural disturbance emulation is applicable to any forest system that is disturbance-influenced to varying degrees, ranging from stand-replacing events (like fire) to gap openings from natural mortality. However, END probably will be applied to mimic disturbance-generated features only on landscapes with frequent and moderate disturbances because emulating very large, severe, or infrequent disturbances probably would meet with societal and political resistance regardless of their ecological relevance (Kimmins 2004). Therefore, the application of END through forest management is particularly relevant to disturbance-prone systems, such as the boreal forest, where stand-replacing events can occur at temporal scales of decades to centuries (Hunter 1993).

Implications of Natural Disturbance Emulation for Aquatic Ecosystems

The END approach in forest watersheds has implications for the protection of aquatic ecosystems because water bodies are ubiquitous across most forest regions and are integral parts of forest ecosystems (Richardson and Danehy 2007). Forest water bodies are strongly linked to their surrounding terrestrial catchments (Hynes 1975), so forest management activities that alter the forest structure and other watershed features can influence aquatic ecosystems. Numerous studies have assessed the impacts on aquatic ecosystems of watershed disturbances from forest management over the past few decades (see reviews by Webster et al. 1992, Prepas et al. 2003, Fortino et al. 2004, Kreutzweiser et al. 2008b, Richardson 2008, Buttle et al. 2009). In general, these studies show that tree removal, ground disturbances, changes in watershed nutrient cycling and export, and road construction can affect receiving waters and their biotic communities and that the magnitude of effects is site- or context-specific. Effects can include reduced canopy cover and shading, increased water temperatures, increased fine-sediment deposition, increased nutrient concentrations, reduced inputs of large wood and fine organic matter, and restricted fish movement, all of which have implications for aquatic ecosystem sustainability. As a result, best management practices for forest operations have been developed and refined to mitigate aquatic impacts of forest management (Table 1) (Vowell and Frydenborg 2004, Schilling 2009, Ice et al. 2010, Richardson et al. 2012).

One of the most broadly applied best management practices in North America for protecting forest water bodies is retention of riparian (shoreline) buffers in which logging operations are prohibited or restricted around water bodies (Phillips et al. 2000, Lee et al. 2004). Forested riparian buffers are usually effective for mitigating many forest management impacts on aquatic systems, particularly those associated with near-water canopy removal or ground disturbance (Barling and Moore 1994, Broadmeadow and Nisbet 2004, Hickey and Doran 2004), but not necessarily those impacts that arise from watershed-level effects (i.e., significant changes in water quality or biotic responses were detected even with intact riparian buffers) (Prepas et al. 2003, Martel et al. 2007, Kreutzweiser et al. 2008a, Lecerf and Richardson 2010).

The systematic application of riparian buffers around water bodies leads to unnatural, linear patterns of older-growth forests across the landscape resulting in ribbons along streams and donuts around lakes (Buttle 2002, Steedman et al. 2004). Protection of riparian forests in managed watersheds could suppress natural riparian forest renewal because the adjacent upland areas contain young, regenerating stands that are less prone to disturbances like fire, wind, and insect infestations that could otherwise cross into riparian areas. In the absence of periodic disturbance and regeneration, riparian habitat heterogeneity probably will decrease (riparian areas will become more homogeneous) and, as a result, structural and functional riparian diversity may decrease to a condition that is less than the natural range of variability (Degraaf and Yamasaki 2000, Swanson

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TABLE 1. Examples of forestry best management practices (BMPs) intended to mitigate potential impacts on water resources.

BMP	Protection goals	Operational applications
Appropriate operational timing	Minimize soil disturbance, rutting, water diversion in wet areas	Harvest under frozen, snow-covered, or dry conditions
Roads and stream crossings	Minimize erosion, sediment runoff, water diversion; avoid fish movement barriers	Locate roads and crossings to avoid wet soils when possible, minimize water flow disruption; use course surfacing and back-fill materials, other sediment retention or diversion techniques; proper bridge and culvert installations, avoid culverts perched above stream beds
Landings	Minimize erosion, soil disturbance, sediment runoff	Keep number and size of landings to minimum; avoid wetlands, steep, or unstable slopes; keep out of riparian areas; use appropriate ditches, outsloping to keep landings dry
Skidding and skid trails	Minimize erosion, soil disturbance, sediment runoff	Avoid low-lying or wet areas; skid across slopes and parallel to shorelines or stream channels; divert water by lead-off ditches; avoid concentrated and repeated skidder movement on wet or shallow or organic soils
Stabilize exposed soils on slopes	Prevent soil damage; minimize sediment and nutrient runoff	Use appropriate equipment such as low ground pressure tires; smooth out ruts on slopes to prevent channeling; promote revegetation as quickly as possible; apply stabilizing ground cover such as branches, mulch, cobble
Riparian buffer strips or management zones	Retain shoreline stability, shade, litter and wood inputs, terrestrial and semiaquatic habitats; intercept sediment and nutrient runoff; minimize near-water soil compaction or disturbance	Restricted or modified harvesting in buffers, restricted machine movement; specified tree retention
Proper equipment fuelling and maintenance	Avoid contaminating water bodies with fuels, lubricants, other contaminants	Place fuelling and maintenance areas away from water sources; provide waste containers on site; conduct regular checks for leaks or wear

et al. 2011). The unnatural landscape patterns created by these riparian buffers may not be consistent with the goals of forest management based on END patterns (Macdonald et al. 2004, Holmes et al. 2010) because natural disturbances often occur in riparian areas (Andison and McCleary 2002, Nitschke 2005).

Unnatural landscape patterns arising from the systematic retention of no-logging buffers are resulting in changes or proposed changes to riparian forest management guidelines in Canada (Morissette and Donnelly 2010, Sibley and Gordon 2010). Several recent studies or guidelines have incorporated intentional shoreline disturbance by careful near-water logging to create more natural riparian forest conditions (Kardynal et al. 2009, Kreutzweiser et al. 2010, OMNR 2010, Naylor et al. 2012). This approach seems counterintuitive for the protection of water resources and aquatic ecosystem integrity. The forest management guidelines that focus on the retention of riparian buffers are intended to prevent or mitigate disturbances to shoreline areas, thereby protecting aquatic ecosystems. The intended outcomes from these buffer guidelines often are not clearly defined by specific, quantitative targets (Richardson and Thompson 2009), but the premise generally has been protection of aquatic systems by avoiding or minimizing change from prelogging (baseline) or nearby no-logging (reference) conditions. Changes induced by forest management operations from these baseline or reference conditions usually have been construed as undesirable impacts (see the reviews on forestry impacts listed above). However, in forests that have evolved over a range of disturbances, using baseline or reference conditions defined over a short time period (often only a few years) to represent the natural range of variability in forests and their water bodies over longer periods (decades or more) may be inappropriate. If the target for management under END is "no change beyond the range of natural disturbance" (Long 2009), then short-term changes from reference conditions or sites may be acceptable. Therefore, applying END to riparian forest management (i.e., intentional disturbance of some riparian forests) may require redefining acceptable and unacceptable changes in aquatic ecosystems using specific conservation targets based on mimicking natural disturbance (Richardson and Thompson 2009, Moore and Richardson 2012).

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Empirical studies are clearly needed to develop and assess relevant conservation targets for applying END to riparian forests. Studies should be done to determine the effects of intentional shoreline disturbance under END and the extent to which riparian logging emulates or modifies the effects of natural disturbances (Nitschke 2005). These studies also should establish the bounds of natural variability in forest water bodies to help determine when logging-induced changes become unacceptable impacts or simply natural (or emulated) pulses in longer-term renewal processes of a disturbance-based ecosystem. This approach differs from the historical assessments of intensive logging to shorelines that have demonstrated impacts on aquatic communities (e.g., Ely and Wallace 2010), because shoreline harvesting under END principles will follow careful harvesting practices under specific guidelines. For example, although the goal is to mimic natural disturbance patterns as closely as possible, shoreline harvesting would be constrained in some places by restrictions on machine movement or ground disturbance in wet areas, residual forest requirements for special wildlife habitats, and downed wood, inoperable terrain, cultural heritage sites, or other values (Naylor et al. 2012).

A Theoretical Basis for Applying END to Riparian Forest Management

Forest ecologists have long regarded natural disturbance regimes as critical factors in structuring and sustaining diverse forest communities (reviewed by McCarthy 2001), but the role of disturbance in enhancing spatial heterogeneity and sustaining aquatic communities has been recognized increasingly in more recent years (Lake 2000, Lepori and Hjerdt 2006, Lepori and Malmqvist 2007). The emphasis in our paper is on streams, but the principles of disturbance effects would apply to other aquatic ecosystems as well. General disturbance theory postulates that spatial heterogeneity in biotic communities, patchiness, and temporal dynamics arise in large part from disturbance and that the absence of this disturbance-mediated temporal and spatial variability would preclude the existence of many species (Sousa 1984). Disturbance in ecology is variously defined, but White and Pickett's (1985, p. 7) definition of "any relatively discrete event in time that disrupts ecosystems, community, or population structure, and changes resources, substrate availability, or the physical environment" is useful. The simplified premise of disturbance theory is that disturbance increases habitat heterogeneity and complexity by destroying some patches (conditions) while creating others, thereby changing the colonization, habitation, and succession patterns of biota and influencing community structure. The resultant different-sized patches under varying conditions support a higher biodiversity than is supported in more homogeneous systems.

Disturbance theory has been successful in explaining or predicting community structure in aquatic systems. The effects of natural disturbances on aquatic communities can be scale- and context-dependent, but disturbances promote habitat heterogeneity that underpins the continuance of diverse aquatic communities (Reice 1994, Lepori and Hjerdt 2006). The interactive effects of disturbances and patch dynamics on biotic communities are complex, but in general, major disturbances like floods and drought create new patterns of patchiness that regulate biotic community structure by varying resource availability and use (Lake 2000).

Disturbances are of particular importance to forest watersheds and riparian areas where land–water linkages connect terrestrial and aquatic ecosystems because they can play a role in establishing and sustaining those linkages. Nakamura et al. (2000) demonstrated this importance by focusing on the sequencing or cascading of geomorphological disturbances down the gravitational flow paths of stream networks and their riparian systems in mountainous landscapes. The same principles should be applicable to other landscapes. They suggest that streams and their riparian zones are networks containing a shifting mosaic of disturbance patches that are linear and parallel, linking riparian conditions to stream conditions in the context of disturbance. Swanson et al. (2011) pointed out that natural recovery processes in forest ecosystems that promote succession, renewal, complexity and stability also occur in riparian areas and influence aquatic ecosystems.

Thus, it follows that disturbances to forested watersheds are important natural determinants of aquatic habitat conditions and communities because of the strong ecological linkages between forest water bodies and their terrestrial watersheds. Natural disturbances in riparian and upland forests can influence these ecological linkages and induce changes in receiving waters. For example, insect defoliation of riparian forests can change stream water chemistry through elevated nitrification in riparian soils and leaching of nutrients and labile C from insect frass and green litterfall (Lewis and Likens 2007). Wildfire can induce large changes in aquatic ecosystems and their communities through canopy removal, increased runoff, altered biogeochemical processes, nutrient fluxes, sediment delivery, and other influences (Bisson

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et al. 2003, Spencer et al. 2003, Neary et al. 2008, Malison and Baxter 2010, Moore and Richardson 2012). Forest gap generation by windthrow can influence instream light availability and periphyton communities via increased spatial variability in canopy structure (Stovall et al. 2009).

It appears then, that natural forest disturbances in watersheds will promote aquatic habitat heterogeneity and, therefore, natural patterns in biological diversity. Disturbance is a significant ecological process that maintains biodiversity and ecosystem integrity (Mori 2011). Therefore, forest watershed disturbances may be required for long-term aquatic ecosystem stability. One could argue that restricting natural riparian and upland disturbances through fire suppression, insect control, or no-logging buffers could conceivably constrain these natural disturbance and renewal processes and their effects on aquatic habitats and communities. No-logging buffers cannot accommodate the natural range of variability in riparian forest composition and function, and they disregard the fact that disturbance is a natural part of riparian forests (Palik et al. 2000, Sibley and Gordon 2010). This logic suggests that intentional disturbances by carefully planned and implemented forest management operations (e.g., Naylor et al. 2012) could be used to emulate natural disturbances in watersheds and riparian forests to sustain aquatic ecosystems over the long term, recognizing that some short-term alterations (potentially perceived as impacts) could be incurred. However, this suggestion is largely untested in forest watersheds.

Conclusions

Previously published forums on END in forestry (Kuuluvainen 2002, Mitchell et al. 2002, Perera et al. 2004) have not considered implications for watershed and riparian management or for conservation of aquatic biodiversity and ecosystem integrity. Jurisdictions that have implemented some END principles for riparian forest management usually have done so to create complexity through early-successional regeneration (Swanson et al. 2011) in shoreline habitats to support terrestrial and semiaquatic biodiversity (Kreutzweiser et al. 2005, 2010, Kardynal et al. 2009, Naylor et al. 2012), while striving to avoid adverse effects on aquatic systems. We now suggest, based on disturbance ecology and the recognized land–water linkages in forest watersheds, that END in forest management can also be applied to sustain aquatic biodiversity and ecosystem integrity by mimicking natural riparian and watershed disturbances and renewal processes. This suggestion does not imply unrestrained riparian logging in all areas, but rather carefully planned and implemented logging in some riparian forests under science-based guidelines (Morissette and Donnelly 2010, Sibley and Gordon 2010, Moore and Richardson 2012, Naylor et al. 2012, Sibley et al. 2012). However, much of this idea is untested and many uncertainties remain around the application of END to forest watersheds. The subsequent papers in this *BRIDGES* cluster explore some of the outstanding issues.

Our intent is for this cluster to promote an exchange of ideas on how, why (or why not), when, and where to apply END in riparian forests. Using intentional riparian disturbance by forest management to emulate natural disturbance patterns and processes is a new and evolving concept in forestry, and the potential implications for aquatic ecosystems have not been explored. Indeed, this paucity of information on the implications of END for aquatic ecosystems was the impetus for exploring this topic through a *BRIDGES* cluster in hope of generating advanced discussion and study. We have drawn on established disturbance theory to provide a theoretical basis for using intentional riparian disturbance as a management tool because few empirical studies are available. Our group has notionally embraced the concept of applying END to riparian forest management, but we recognize the need to move on to empirical testing. Discussions arising from this cluster should advance and direct that process.

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