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Does forest harvesting emulate fire disturbance? A comparison of effects on selected attributes in coniferous-dominated headwater systems

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Abstract

The emulation of natural disturbances is seen by many as an important management paradigm for achieving sustainable ecosystem management. To successfully emulate natural disturbances, managers must first have an understanding of the complex interactions that occur to the biophysical and chemical attributes of an ecosystem for both the natural and the ‘‘emulating’’ disturbance. The management of riparian ecosystems is an important issue faced by managers since the type of harvesting treatment can have a significant influence on the aquatic component. The removal or retention of riparian forests can have a direct influence on water quality and quantity, particularly on the smaller systems that are found at the headwaters of catchments, but do these treatments invoke a similar response as wildfire? To determine if emulation occurs, the affects of forest harvesting treatments and wildfire on temperature, water chemistry, summer stream flow, and sedimentation in headwater systems were compared using a meta-analysis. A statistically significant difference was found for temperature response between partial/selective harvesting and wildfire, but not after clear-cut harvesting. Water chemistry showed statistically significant differences for 11 out of 14 tested attributes, with dissolved organic carbon exhibiting the most marked difference. A significant difference was identified between clear-cut harvesting and wildfire for summer stream flow but not between wildfire and partial/selective harvest systems. Forest harvesting operations were found to emulate sedimentation through forest roads but not harvest treatment. Partial/selective harvest systems may offer the greatest emulation congruency versus clear-cut harvest systems in terms of overall headwater response and recovery. Partial/selective harvest systems combined with prescribed burning may provide managers with the best solution when attempting to emulate wildfire in headwater systems and reduce the detrimental impact of perturbation on these systems.

Keywords: Headwater systems; Wildfire; Harvesting; Temperature; Summer stream flow; Water chemistry; Sedimentation; Meta-analysis; North America; Coniferous

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1. Introduction

New strategies in forest management practices are based on the assumption that emulating natural disturbances, such as natural fires, will sustain forest dynamics and biodiversity (Hunter, 1993). As a consequence of these assumptions, management of forests is moving toward emulating natural disturbance patterns through forest harvesting (Prepas et al., 2001); especially as harvesting shifts from lowland forests to upland forests. The notion of emulating natural disturbance has been seen as a method for reducing the risk associated with management decisions designed to protect ecosystem values and meet sustainability requirements while allowing harvesting on forest landscapes (Elkie and Rempel, 2001). Forest managers in many regions of North America have begun to examine how emulation of natural disturbance could guide management (Perera and Buse, 2004). For example, in the province of British Columbia, Canada, a biodiversity guidebook for managing forest ecosystems based on natural disturbance patterns was developed to mimic landscape-level processes through the emulation of natural disturbance (Andison and Marshall, 1999). In Ontario, the policy of natural disturbance emulation has led to the development of the Forest Management Guide for Natural Disturbance Pattern Emulation (McNicol and Baker, 2004). In the future, the interactions between harvesting and headwaters will certainly continue to increase. As a result of this increasing interface and a shift to ecosystem management, there is a need to determine how natural disturbances affect aquatic systems, particularly the smaller headwater systems that tend to show the greatest change in abiotic and biotic structure when subjected to disturbance (Minshall et al., 1997). Harvesting practices that emulate wildfire must also meet the requirement of public acceptability, which can be a difficult task (see McNicol and Baker, 2004). Finding a balance between ecologically effective emulation and social acceptability will require an understanding of how congruent different harvesting techniques are with wildfire.

Traditional management strategies applied to headwater systems, such as clear-cutting the riparian area or leaving a predetermined buffer width have left these systems with little residual protection from the original riparian forest (Moore and Richarson, 2003). Coupling the fact that there is an incomplete knowledge of the ecological functions of headwater systems (Moore and Richarson, 2003), with the importance of headwater systems as sources of sediments, water, and nutrients to downstream systems (Gomi et al., 2002) it has become important to determine the resilience of these systems to disturbances. The identification of ‘‘resilience thresholds’’ in these systems may allow for sustainable tradeoffs, between management that emulates wildfire or allows natural processes to drive management, to be determined. Adoption of the principles surrounding the emulation of natural disturbance means that managers must have a comprehensive knowledge of the effects of harvesting and wildfire on headwater systems. Only with a comprehensive knowledge will managers be able to determine if management decisions are truly emulating nature’s processes. Perera and Buse (2004) stated that the body of scientific knowledge surrounding disturbance regimes must be expanded; particularly, in terms of which management strategies emulate natural disturbance with the greatest congruency. The objective of this paper is to provide some insight into the comparative nature of harvesting and wildfire, with the hope of providing direction for management decisions around headwater systems that are both ecologically sustainable and socially acceptable.

The effects of forest harvesting on aquatic systems have been studied (for example, Moring and Lantz, 1975; Keppeler, 1998; Steedman, 2000) for many years and not until more recently have researchers begun to study the effects of natural disturbances on aquatic systems, in particular, wildfire (Minshall et al., 1997; Minshall, 2003; also see Young et al., 2003). Coinciding with this research is a more recent interest in comparison studies between harvesting and wildfire and their effects on aquatic systems. Research in these areas has been conducted most notably by Carignan et al. (2000), Lamontagne et al. (2000), Steedman (2000), and Prepas et al. (2001).

The ability of wildfire to dramatically alter watersheds either through stand-maintaining events and especially through stand-replacing events has presented the argument that since fire removes large tracts of forest then harvesting that utilizes silvicultural systems, such as clear-cutting, green tree retention, seed tree, and shelterwood systems, can somewhat mimic these disturbances (Angelstam, 1998; Lieffers et al., 2003). Studies have attempted to quantify these assumptions; however, these studies are limited and focused on non-riparian forests and grasslands (Romme et al., 2004; Zasada et al., 2004). The ability to study the effects of wildfire is limited by the stochastic nature of wildfire; as a result, research on wildfire impacts has been concentrated within perturbed areas. The concentration of research has produced narrowly focused results in some areas that are typically separated from corresponding studies.

The following issues were addressed by conducting a meta-analysis of research related to impacts caused by wildfire and harvesting within headwater systems. By conducting such a review and analysis the goal was to test the following hypotheses:

(1) Harvesting emulates the natural disturbance of fire in headwater systems.
(2) Harvesting is more detrimental to headwater systems.
(3) Headwater systems recover faster from harvesting compared to wildfire.

2. Methods

Due to the stochastic nature of wildfire, there are few opportunities to study the impacts of the perturbation on particular systems; therefore, most research undertaken has been opportunistic in nature. Even rarer than studying wildfire effects on headwater systems is the opportunity to conduct comparative analysis between wildfire and harvesting within the same landscape. In contrast, the study of harvesting impacts on headwater systems has been widespread, both temporally and spatially. Fig. 1 identifies regions in North America where studies have been undertaken to look at the effects of forest practices, wildfire and comparison studies on headwater systems. An unweighted meta-analysis between studies involving harvesting, wildfire, and comparative studies was used

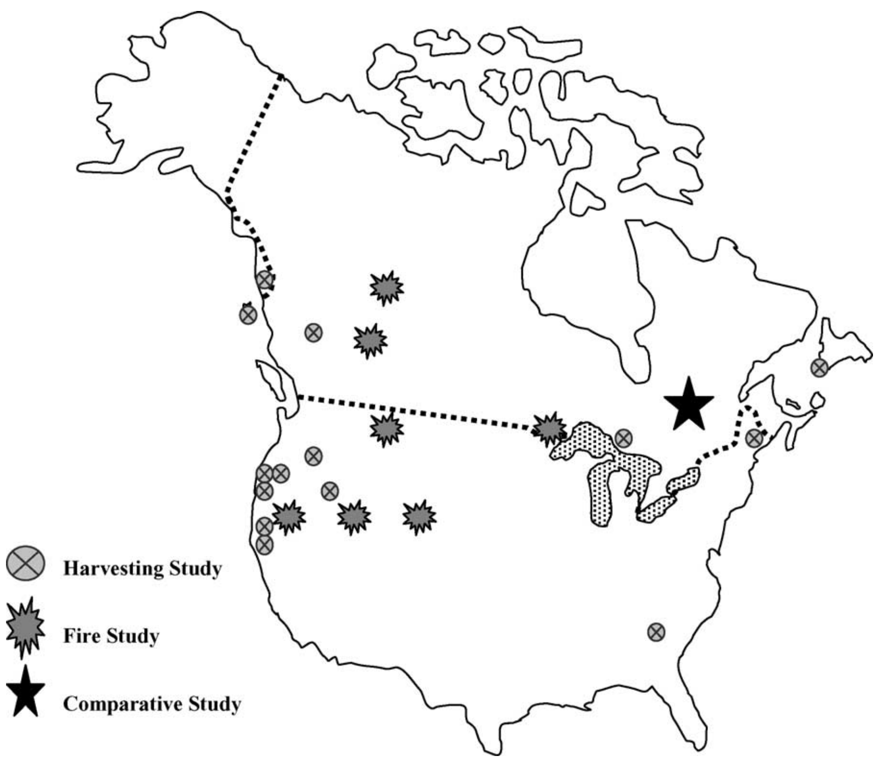

Fig. 1. Location of studies used in meta-analysis. Studies identified with: (✹) indicate a wildfire study; (⊗) indicate a harvesting study; (★) indicate a comparative study between harvesting and wildfire.

to identify any potential similarities and differences. See Olkin (1990) and Wachter and Straf (1990) for a description of meta-analyses. In the study by Parmesan and Yohe (2003), an unweighted meta-analysis was used because the variances from all the studies were not available. Facing a similar challenge as Parmesan and Yohe, an unweighted meta-analysis was used in this study to compare forest harvesting to wildfire. As well, to deal with any issues of non-independent data, all findings in studies were treated independently with the average findings from a study used where applicable. According to Wolf (1990) these steps will reduce the influence of non-independent findings in the analyses. The analyses were conducted on relevant literature up to February 2003, the literature that was used as case studies are presented in this paper (see Table 1).

An unweighted, single factor analysis of variance (ANOVA) was used to determine if the differences identified are significant due to the inability to incorporate variances from the studies used in this analysis. ANOVA was used to calculate any significance differences in the response of temperature, chemistry, summer stream flows and sedimentation between wildfire and harvesting. Three comparisons were made in this study: (1) wildfire versus total forest harvesting, (2) wildfire versus clear-cut harvesting, and (3) wildfire versus partial/selection harvesting. To compare studies that used different levels of precision in the presentation of their data, a generalization approach was used to create a common scale. With the exception of the comparisons of temperature and recovery attributes, which used degrees Celsius and years, respectively, the remaining attributes were generalized to represent the percent increase or decrease of the attribute. This generalization approach thus created a common scale from which to compare from.

Many of the studies have focused on more narrow objectives while others have touched on a broad array. To incorporate these differences, the impacted attributes of the headwater systems will be analysed and discussed separately, with the overall impacts summarised to addresses the objectives outlined for this paper.

3. Results

The results of the meta-analysis are summarised in Tables 2–4. Table 2 summarises the comparison between wildfire and total forest harvesting (TFH) while Tables 3 and 4 summarise the effects of wildfire versus clear-cut harvesting (CH) and partial/selection harvesting (PSH), respectively. The analysis was conducted on the temperature, chemistry, summer stream flow, and sedimentation attributes of headwater systems. It should be noted that within some of the studies more than one headwater system was studied.

Table 1
Studies used in the meta-analyses are based on wildfire, forest harvesting or are comparative studies that measured temperature, sedimentation, summer stream flow, and/or water chemistry

Wildfire studies	Harvesting studies	Comparative studies
Amaranthus et al. (1989)	Brown and Krygier (1970)	Carignan et al. (2000)
Bayley et al. (1992)	Brown and Krygier (1971)	Garcia and Carignan (2000)
Beaty (1994)	Brown et al. (1973)	Lamontagne et al. (2000)
Bozek and Young (1994)	Curry et al. (2002)	
McEachern et al. (2000)	Hall and Lantz (1969)	
Minshall et al. (1997)	Hewlett and Fortson (1982)	
Hall and Lantz (1969)	Hicks et al. (1991)	
Prepas et al. (2001)	Johnson and Jones (2000)	
Wondzell and King (2003)	Keppeler (1998)	
Minshall (2003)	Kreutzweiser and Capell (2001)	
	Martin et al. (2000)	
	Mellina et al. (2002)	
	Moring (1975)	
	Ringler and Hall (1975)	
	Robinson and Runyon (2003)	
	Steedman (2000)	

Table 2
Summary of ANOVA results for wildfire vs. total forest harvesting (TFH) (clear-cut and partial/selection harvesting combined)

Comparison attributes	Wildfire			TFH			Values	
	n	Mean	S.D.	*n*	Mean	S.D.	*P*	*F*
Maximum temperature (°C)	3	6.9	1.5	5	4.97	3.5	0.074	3.536
Diurnal flux (°C)	1	7.2	0.0	5	6.4	4.2	0.87	0.031
Nitrate (%Δ)	9	529.9	465	8	50.97	160	3.5^{-6***}	25.62
Ammonium (%Δ)	9	69.7	57.1	8	−20	2	0.017^{*}	7.068
Total phosphorous (%Δ)	9	207.4	171.1	8	65.4	24.3	2^{-4***}	15.54
Total nitrogen (%Δ)	9	76.6	35.4	8	73.3	71.2	0.797	0.067
Mercury (%Δ)	9	26.1	2.3	8	79	3.7	$<0.001^{***}$	65535
Calcium 2+ (%Δ)	9	53.67	34.6	8	19.24	21.9	5^{-5***}	19.45
Magnesium 2+ (%Δ)	9	69.5	50.2	8	7.18	12.0	1.64^{-7***}	36.54
Potassium + (%Δ)	9	167.8	226.8	8	273.5	185.5	0.0613	3.652
Chloride − (%Δ)	9	131.2	105.5	8	125.6	87.3	0.833	0.0446
Sulphate 2− (%Δ)	9	165.7	41.5	8	−6.04	7.3	2.1^{-18***}	237.13
Sodium +	9	19.73	10.8	8	54.55	30.2	8.04^{-7***}	32.12
Dissolved organic C (%Δ)	9	36.7	17.6	8	83.9	38	2.26^{-7***}	35.7
Chlorophyll (%Δ)	9	8.3	1.6^{-7}	8	25	2.6	1.1^{-84***}	1.56^{+16}
Light extinction coefficient	9	40.76	2.0	8	87	3.1	1.4^{-48***}	40833
Summer stream flow increase (%Δ)	3	68.3	16.2	4	101	61.4	0.42	0.773
Summer low flow recovery (years)	3	5.33	0.58	4	9.5	4.4	0.17	2.58
Summer low flow decrease (%Δ)	2	0.0	0.0	3	−8.33	14.4	0.5	0.6
Sedimentation increases (%Δ)	4	1050	694	8	178.6	217	0.007^{**}	11.41
Sedimentation recovery time (years)	4	5.25	1.5	8	2.25	0.27	2^{-4***}	33.103
Sedimentation: harvesting w/o roads (%Δ)	4	1050	694	5	97.3	79	0.017^{*}	9.61
Sedimentation: forest roads only (%Δ)	4	1050	694	3	314	329	0.16	2.795

The table provides the mean values and corresponding standard deviations of each attribute studied. The *P*-values and *F*-values are provided to show significance of response. Levels of significance: (*) 0.05, (**) 0.01, and (***) 0.001.

This study focuses predominantly on harvesting and wildfire in coniferous forests, though some of the forests in the studies did contain small deciduous components (e.g. Hewlett and Fortson, 1982). These studies show similar responses as the other studies analysed.

3.1. Temperature

In the comparison of wildfire to TFH, no statistical differences were found in the response of maximum temperature and diurnal flux. When the analysis was scaled down and conducted on CH and PSH, different findings were identified (see Tables 2 and 3, respectively). No statistical difference was found in the response between wildfire and CH on maximum temperature and diurnal flux. It should be noted that although there was no statistically different response, the mean for CH was higher and showed greater variation. In contrast, a statistically significant difference was found between wildfire and PSH for

Table 3
Summary of ANOVA results for wildfire vs. clear-cut harvesting (CH)

Comparison attributes	Wildfire			CH			Values	
	n	Mean	S.D.	*n*	Mean	S.D.	*P*	*F*
Maximum temperature (°C)	3	6.9	1.5	3	7.1	3.8	0.899	0.0165
Diurnal flux (°C)	1	7.2	0.0	2	7.7	2.4	0.893	0.0288
Summer stream flow increase (%Δ)	3	68.3	16.2	2	153.5	7.8	0.0068^{**}	44.68
Summer low flow recovery (years)	3	5.33	0.58	2	7.5	0.71	0.032^{*}	14.49
Summer low flow decrease (%Δ)	2	0.0	0.0	1	−25	0.0	$<0.001^{***}$	65535
Sedimentation increases (%Δ)	4	1050	694	1	175.3	0	0.342	1.271

The table provides the mean values and corresponding standard deviations of each attribute analysed. The *P*-values and *F*-values are provided to show significance of response between wildfire and clear-cut harvest treatments. Levels of significance: (*) 0.05, (**) 0.01, and (***) 0.001.

Table 4
Summary of ANOVA results for wildfire vs. partial/selection harvesting (PSH)

Comparison attributes	Wildfire			PSH			Values	
	n	Mean	S.D.	*n*	Mean	S.D.	*P*	*F*
Maximum temperature (°C)	3	6.9	1.5	5	3.71	3.0	0.0048**	10.32
Diurnal flux (°C)	1	7.2	0.0	3	5.53	5.4	0.813	0.072
Summer stream flow increase (%Δ)	3	68.3	16.2	2	48.5	14.8	0.262	1.90
Summer low flow recovery (years)	3	5.33	0.58	2	11.5	6.4	0.166	3.325
Summer low flow decrease (%Δ)	2	0.0	0.0	2	0.0	0.0	0.000	65535
Sedimentation increases (%Δ)	4	1050	694	4	77.8	76	0.032*	7.76

The table provides the mean values and corresponding standard deviations of each attribute analysed. The *P*-values and *F*-values are provided to show significance of response between wildfire and partial/buffer harvest treatments. Levels of significance: (*) 0.05, (**) 0.01, and (***) 0.001.

maximum temperature response ($P < 0.01$). No statistical difference was found in the comparison of PSH to wildfire for diurnal flux response.

3.2. Water chemistry

In the comparison of the response of headwater systems to wildfire and TFH perturbations, the greatest numbers of statistically significant responses were identified for the entire study. It should be noted that no finer comparison was possible between CH/wildfire, and PSH/wildfire in this analysis. Of the 14 attributes tested, 11 showed statistically significant differences in their response to wildfire and harvesting. Total P, NO_3, Hg, Ca^{2+}, Mg^{2+}, SO_4^{2-}, NH_3, dissolved organic carbon (DOC), chlorophyll, and light extinction coefficient (LEC) all showed statistically significant differences in their responses to wildfire and forest harvesting ($P < 0.05$–0.001). The three attributes that showed no significant statistical difference in the proportional change were total N, K, and Cl. The direction of response varied between attributes, with some showing significant increases after harvesting, while others decreasing significantly in comparison to their response after wildfire. Concentrations of NO_3, NH_3, total P, Ca^{2+}, Mg^{2+}, and SO_4^{2-} all showed statistically significant decreases after harvesting compared to wildfire, while concentrations of Hg, Na, DOC, chlorophyll, and LEC all showed statistically significant increases.

3.3. Summer stream flows

The three summer stream flow attributes that were analysed in the comparison of wildfire to forest harvesting were: increase in summer stream flow, decrease in summer low flow, and low flow recovery time. The analysis of these three attributes identified that no statistically significant differences existed between wildfire and TFH. When the comparison was conducted on CH and PSH, different results emerged from the analysis. In the comparison of wildfire to CH, statistically significant differences were identified for all three attributes. Summer stream flow increases ($P < 0.01$) and low flow recovery time ($P < 0.05$) were found to increase after CH, while summer low flow decreases were found to be significantly greater compared to the responses observed after wildfire ($P < 0.001$). Statistically different responses were not observed between wildfire and PSH for all three attributes.

3.4. Sedimentation

Wildfire significantly increased sedimentation in headwater systems compared to harvesting by six-fold ($P < 0.001$). Wildfire also showed statistically significant increases in recovery times; approximately 3 years over harvested systems ($P < 0.001$). Interestingly, when wildfire was compared to harvesting treatments without roads, the difference in the rate of sedimentation was reduced, though the difference still remained statistically significant ($P < 0.05$). Comparing wildfire to only forest roads found that no significant statistical difference could be detected in the rate of sedimentation. In terms of sedimentation, forests roads, not harvesting, may be the component of forest operations that emulates wildfire with the greatest congruency.

A subset comparison was conducted to compare increases in sedimentation between harvest treatment and wildfire. In the comparison of CH to wildfire, no statistically significant difference was found between the two disturbances. It should be noted that this analysis included forest roads because they typically play an integral and economically important role in CH treatments. In contrast, headwater systems subjected to PSH received statistically less sediment ($P < 0.05$) compared to headwater systems perturbed by wildfire.

4. Discussion

4.1. Temperature

Silvicultural systems that remove streamside vegetation from headwater systems lead to increase maximum stream temperatures; however, when buffer strips are left temperature increases are minimal (Kiffney et al., 2003). The results suggest that forest harvesting can have a similar effect on stream temperatures as wildfire. Systems affected by wildfire typically have increased maximum temperatures and diurnal fluctuations compared to PSH that retain portions of the riparian zone. When wildfire is compared to CH treated systems, lower mean maximum temperature increases and reduced diurnal fluctuations are observed. The difference in temperatures between wildfire affected systems and CH treated systems could possibly be attributed to the presence of fire-killed trees. The ability of the fire-created snags to reduce sensible and latent heat flux losses, and long-wave radiation losses at night could result in lower increases of maximum temperatures and less diurnal fluctuation. Amaranthus et al. (1989) found that dead standing vegetation (trees) can provide up to 57% of the post-fire shading and that shading by fire-killed trees can have a significant influence on stream temperature in relation to topography and residual live vegetation, such as shrubs and herbs. An impact that occurs during wildfire, but not during harvesting, is the immediate response of stream temperatures during the perturbation. Minshall et al. (1997) found that stream temperatures, in first- and second-order headwater systems, were significantly greater in burned systems then unburned reference systems, often surpassing the tolerance levels for salmonids with average temperatures >20 °C. Spencer et al. (2003) observed mortality of small Westslope cutthroat trout (*Oncorhynchus clarki lewisi*) (less than 10 cm in length) due to elevated stream temperatures during the Red Bench wildfire in Glacier National Park, Montana. Hall and Lantz (1969) found that the stream temperatures for Needle Creek incurred the highest temperatures during a subsequent slash burn. The stream temperature rose from 13 °C to over 28 °C, leading to high mortality rates for juvenile salmonids and sculpins (*Cottus* spp.). In an adjacent headwater catchment, Hall and Lantz (1969) found that a headwater stream subjected to partial harvesting and subsequent fire showed no effects of burning due to the protection afforded by a riparian buffer.

It appears that harvest treatments, such as PSH, that retain structure within the riparian zone do not emulate intense, stand replacing fires because the treatment does not provide the same magnitude of temperature increases due to the greater degree of shading that the live trees provide over dead trees. Amaranthus et al. (1989) found that intense fire reduced shading down to 30% while retention harvesting that removes 50% of the canopy cover still provides, on average, about 50% shading (Mellina et al., 2002). Though leaving buffers or using retention systems does not mimic high intensity fires, it may emulate lower intensity burns that typically leave portions of the overstorey intact. Though the results suggest that CH may emulate wildfire in riparian zones, this may not be necessarily true for many reasons. For example, Amaranthus et al. (1989) found that less than 5% of headwater systems burn at high intensities; however, Minshall et al. (1997) found that on average 75% of headwater catchment areas burn during intense fires. This appears to be contradictory, but the studies represent two distinct climatic regimes, maritime and continental, respectively. The difference in climatic regime means that the fires between regions will vary in size and severity due to the influence of climatic conditions on the fire return interval (Miller and Urban, 1999). It is important to note that the intensity of fire around streams and within the catchment are two separate issues since riparian areas are usually the wettest sites within an ecosystem and as a result, require higher intensity fires to burn them completely. Irregardless of the fire regime, if CH removes even 90% of the forest adjacent to a headwater stream, it will not provide on average, the same conditions that regulate temperatures as found after intense wildfire. Amaranthus et al. (1989) found that headwater systems increased in temperature more dramatically over shorter distances compared to the increases caused by wildfire. The legacies left in wildfire affected areas, snags and residual live trees; reduce the rate of temperature increase compared to systems subjected to CH. The implications of this mechanism are quite important. If a manager was truly trying to emulate wildfire by CH the equivalent wildfire affected area within a catchment, an even bigger discrepancy between temperatures may be observed.

It is important for managers to understand the predominant intensity of a fire and the legacies a fire leaves behind within a management area, in order to emulate the affect wildfire can have on temperature. It is also important for managers to understand some of the possible impacts increased stream temperature can have on stream biota. For example, Moring and Lantz (1975) found that increased temperatures, due to CH, led to a decline in the populations of some salmonid species over a 7 year period because of the increased competitive ability of other salmonid species better adapted to the warmer temperatures. These changes have not been reported after wildfire.

The comparison of the impacts of wildfire and TFH on temperature attributes of headwater systems suggests that certain harvesting treatments may be able to emulate wildfire. Even though systems subjected to PSH were found to have statistically significant different response than occurs after wildfire, the level of retention could be altered over time to create congruent shading conditions. For example, Macdonald et al. (2003) found that maximum temperatures and diurnal variation remained higher in harvested headwater systems than in control systems for 5 years, irregardless of the harvest treatment. Over 3 years, windthrow was found to gradually reduce the cover provided by a high retention system to a state that mirrored a low retention system. The change from high to low retention resulted in an increase in temperatures that were observed in the original low retention system. Since no significant statistical difference was found between wildfire and CH it could be argued that this treatment emulates wildfire. Amaranthus et al. (1989), however, observed that streams in harvested headwater systems heat up faster and over shorter distances than streams in wildfire affected systems. Though systems subjected to CH increase in temperature much more rapidly, the impacts of the perturbation may be localised (Story et al., 2003). Story et al. (2003) found that the temperatures of systems that are only partially affected along their length by harvesting can recover rapidly back to post-disturbance levels through groundwater inputs and hyporheic exchange as the system re-enters a closed forest. This suggests that some headwater systems may have a natural resilience that will localise either harvesting or wildfire disturbance, causing minimal downstream impacts.

4.2. Water chemistry

Harvesting and wildfire affect the water chemistry of headwater systems in different ways. The most significant contrasts are between the magnitude and direction of change for NO_3, NH_3, total P, DOC, LEC, Hg, Ca^{2+}, Mg^{2+}, $SO_4{}^{2-}$, and Na^+. The attribute that exhibited the most striking difference between the treatments was $SO_4{}^{2-}$. After harvesting, $SO_4{}^{2-}$ decreased by 16.3% while after wildfire it increased by 126.7%. Carignan et al. (2000) identified the partial combustion of the LFH layer and B-horizon during a wildfire as a possible cause for this observed trend since these layers can contain up to 30 times more S then above ground biomass. During a wildfire, if the LFH layer is partially combusted, the $SO_4{}^{2-}$ ion will be released resulting in an increase as observed in this analysis. Martin et al. (2000) identified that harvesting facilitates the nitrification and mineralization of N by increasing H^+ ions (increases up to 132.5%). Increases in H^+ ions will acidify the forest soil and soil water resulting in an increase of the adsorption capacity of the soil's B horizon, possibly accounting for the decrease in $SO_4{}^{2-}$ observed after harvesting.

Wildfire causes increases in total N, in particular total P. Harvesting, while increasing both total N and P, has the largest impact on the residence time of total P in comparison with total N. Carignan et al. (2000) identified that total P evolves at longer time scales then total N and when coupled with increases in DOC and LEC they have negative impacts on aquatic ecosystems. The P:N ratio was also different between the two treatments with wildfire creating a ratio of 3:1 and harvesting a 1:1 ratio (2.4:1 with outlier added). Lamontagne et al. (2000) identified that P loading is a key determinant of total primary production, P:N ratio influences algal populations. Another important difference between harvesting and wildfire perturbations is on the composition of total N. Wildfire increases the total N that is composed of both organic and mineral forms while harvesting increases the total N composed of predominately organic forms. N and P are limiting nutrients in most aquatic systems (Prepas et al., 2001) and since wildfire, in comparison to harvesting, provides a higher loading of both nutrients it may promote increased primary production.

Harvesting does not cause the same magnitude of response in cations and anions when compared to wildfire. Compared to harvesting, the base cations Ca^{2+} and Mg^{2+} showed statistically significant increases ($P < 0.001$), while Na^{+} showed an increase that was statistically less ($P < 0.001$) after wildfire. An important caveat, noted by Lamontagne et al. (2000), is that observed concentrations of Ca^{2+} and Mg^{2+} may be more comparable to wildfire if whole tree harvesting was not used because the loss of these cations are usually doubled under this treatment. Carignan et al. (2000) identified that after wildfire, the increases in these cations are only short-lived with concentrations returning to pre-disturbance levels within 5–6 years. The same pattern was identified for NO_3 and NH_3 concentrations, which occur as short-term, high magnitude pulses after wildfire that decline as vegetation re-establishes. In contrast, Martin et al. (2000) found that Ca^{2+}, Mg^{2+}, and NO_3 had not returned to pre-harvest levels after 27 years and at year 20, NO_3 net losses began to increase well above pre-harvest levels. In comparison to harvesting, wildfire increases the concentrations of NO_3 ($P < 0.01$) and NH_3 ($P < 0.05$). After harvesting, NH_3 was found to decrease by 20% compared to a 70% increase after harvesting; NO_3 increased 530% after wildfire versus 50% after harvesting. Based on the analysis it could be argued that wildfire may provide a greater quantity of NO_3 and NH_3 to headwater systems. Increases in NO_3 and NH_3 inputs after wildfire should provide the N required for increasing the primary production of non-toxic algae species. Increases in N and primary production within an aquatic ecosystem can help mitigate changes in cyanobacteria concentrations (Prepas et al., 2001). In N-limited systems, cyanobacteria can increase the toxicity of the aquatic ecosystem to the detriment of many organisms. In systems that are not N-limited, but are P-limited, algae that do not produce harmful toxins tend to be more dominant. Though harvesting increases NO_3 to aquatic systems the magnitude of response in primary production may be dampened because it will supply less NO_3 and NH_3 compared to wildfire. For this reason, emulation of wildfire will most likely not occur if harvesting alone is the only treatment.

Compared to wildfire, a statistically significant increase in DOC ($P < 0.001$) was identified after harvesting. The increase in DOC may have the most influential and detrimental affects on a headwater system. Carignan et al. (2000) identified that the differences in DOC between harvesting and wildfire are related to the partial combustion of the organic floor and near complete loss of organic carbon sources that occur after a fire. After a wildfire, large quantities of DOC are absorbed by the residual charcoal left on the forest floor. The absorption of DOC to charcoal accounts for the reduction in observed DOC after wildfire compared to harvesting. After harvesting, large quantities of easily leached and/or decomposed organic material are left on the perturbed area. This organic material is responsible for the increased DOC recorded in headwater systems after harvesting (Carignan et al., 2000). Increases in DOC are positively correlated with increases in LEC and chlorophyll, which increases watercolour. The increase in these attributes can have cascading effects on aquatic ecosystems. Carignan et al. (2000) found that LEC and watercolour will continually increase after harvesting as DOC is leached from the humic layer in the upper soil horizons of a perturbed area. A part from statistically significant responses in DOC concentrations, it is important to note that the mechanisms for DOC leaching into headwater systems are mediated by completely different processes. Because wildfire and harvesting cause significantly different responses in headwater systems it could be argued that there is a lack of "emulation congruency" between the two perturbations. It should be noted that McEachern et al. (2000) found that wildfire in headwater systems dominated by peat and/or organic soils can cause increases in DOC compared to systems that are not peat/organic soil dominated. Increases in fire-origin DOC occur in these headwater systems because of increases in humic runoff that occurs after wildfire. McEachern et al. (2000) still observed that DOC increased after harvesting compared to wildfire in these peat/organic soil dominated watersheds.

The increase in DOC after harvesting, in comparison to wildfire, can be viewed as a detrimental impact on headwater systems. Increases in DOC can reduce the thermo cline depth at which photosynthesis occurs by decreasing water clarity through an increase in the LEC and watercolour. Increases in DOC after harvesting can also offset the increase in other nutrients, such as N and P, by restricting potential increases in primary production. Decreases in algal and plankton communities responsible for primary production have been observed in relation to increases in DOC during the first 3 years post-harvest (Patoine et al., 2000; Planas et al., 2000). In comparison to harvested systems, wildfire affected systems seem to respond with higher and more sustained productivity (Bayley et al., 1992; McEachern et al., 2000). To minimize these negative impacts PSH may offer the best management alternative. Molot and Dillon (1997) found that DOC inputs were 50% lower in systems where 10 m buffers were retained compared to systems subjected to CH. PSH treatments that leave buffers >10 m, likely buffers that are at a minimum 20–30 m wide, could reduce the concentrations of DOC to less detrimental levels and may allow for closer ‘‘emulation congruency’’ with wildfire, though this requires further study.

Increased DOC is causally linked to the statistically significant increases in mercury (Hg) concentrations in harvested systems compared to wildfire affected systems ($P < 0.001$). Increased DOC loads can disrupt the cycling of Hg within an ecosystem. Garcia and Carignan (2000) found that extensive harvesting caused increases in Hg, which bio-accumulated through the trophic structures of headwater systems and raised the Hg levels in the aquatic biota beyond the advisory limit set by the World Health Organization.

The major impacts of harvesting on water chemistry attributes are the significant increases in long-term factors combined with lower increases in short-term factors, this is opposite in the case of wildfire. Harvesting creates a situation of extreme responses within headwater systems where recovery appears to be much more difficult because a return to a state of equilibrium must occur over a greater distance. It is important to remember that wildfire on average, affects greater areas of the catchment then harvesting (Amaranthus et al., 1989; Carignan et al., 2000; Lamontagne et al., 2000), hence, the changes in water chemistry after harvesting occurs from a smaller area. If an equivalent area of the catchment was harvested as is typically disturbed by wildfire the differences could be even more significant. Minshall et al. (1997) found that small headwater systems show greater responses; this appears to hold true for the response of water chemistry attributes. Prepas et al. (2001) stated that wildfire and forest harvesting have divergent effects on water chemistry and this divergence could have potentially substantial consequences on biodiversity in aquatic systems. Carignan et al. (2000) found that DOC, LEC and total P are long-term problems associated with harvesting in headwaters and it may take decades before these attributes are able to return to pre-disturbance conditions within affected headwater systems. For this attribute, it appears that harvesting does not emulate wildfire. The impacts over the long-term could be significant if management decisions do not take into account water chemistry attributes.

4.3. Summer stream flows

It appears that wildfire and PSH yield similar responses for all three summer stream flow attributes. In complete contrast, CH was found to yield statistically significant differences compared to wildfire. CH increased summer stream flow by 2.25-fold ($P < 0.01$) and statistically extended low flow recovery times ($P < 0.05$). The most important finding was that CH statistically decreased summer low flows by up to 25% below base conditions ($P < 0.001$) over extended periods of time. Hicks et al. (1991) found that CH increased summer stream flows by 159% for 8 years, which was then followed by 25% deficit in summer low-flows, which had not returned to pre-harvest levels after 18 years. The study also observed a 59% increase in summer flows after partial harvesting which lasted for 16 years. Hicks et al. (1991) identified that summer flows in the PSH treated system were not significantly different than the control after 16 years; this was not observed in the CH treated system. The differences between the two treatments are attributed to the differences in riparian vegetation that occupied the riparian area after disturbance. The riparian area in the CH treated system became dominated by hardwoods, while the PSH treated system remained predominantly coniferous. Hicks et al. (1991) found that the hardwoods transpired more water then softwoods and this was a major cause for the decrease in summer low flows after CH.

Increases in summer stream flow during the critical summer months can have many positive implications for stream biota in a headwater system. Amaranthus et al. (1989) found that increased summer stream flows can mitigate increases in stream temperature after disturbances by providing greater volumetric area to warm and higher water velocity which decreases the residence time of water in the system. The high air temperatures associated with summer low flows can increase stream temperatures above the critical survival threshold for many species of fish (Moring, 1975), particularly, if water volume is too low and/or residence time is too high. Increases in water volume may also create habitat for biota by promoting fast water habitats, such as riffles, which usually increase the dissolved oxygen content in the water. This is important particularly for raising the quality of pool habitats within a system. Lower temperatures after disturbance may help maintain dissolved oxygen levels; this will increase survival rates of salmonids, particularly juveniles and fry which have been found to be affected more strongly by disturbance then adults (Hanson and Waters, 1974). The results suggest that CH adjacent to streams without substantial buffering appears to be detrimental in the long-term for stream biota due to its impact on summer low flows. PSH appears to be a beneficial treatment for headwater systems because it increases summer stream flows, over longer periods of time, without a net loss after recovery. Though CH and PSH do not emulate wildfire exactly, PSH appears to emulate it with a greater congruency by increasing summer flows and maintaining similar recovery times. On the other hand, CH provides a false truth by increasing low flows for a longer period then wildfire, but then placing the system on a potentially detrimental trajectory for stream biota by reducing summer low-flows below base conditions. For these reasons, it can be argued that PSH emulates wildfire with sufficient congruency while CH shows a "divergent congruency" over the long-term.

4.4. Sedimentation

Wildfire increases sedimentation more than harvesting. Though CH increases sedimentation more than PSH, all studies identified roads and/or unrestricted skid trails as the primary cause of the increase (Brown and Krygier, 1971; Moring, 1975; Kreutzweiser and Capell, 2001). Kreutzweiser and Capell (2001) identified that reduced road networks, designated skid trails, and careful harvesting practices can result in insignificant increases in sediment yield even if selective harvesting occurs right up to stream banks. Wildfire on the other hand, can cause significant increases in sediment yield and thus appears to be more detrimental than harvesting systems but not the roads used for forest operations. Wildfire disturbs larger areas of catchments, in comparison to harvesting (Carignan et al., 2000) in turn; more soil is exposed and subjected to erosion processes, such as mass wasting events. Wondzell and King (2003) found that severe fires can increase the frequency and magnitude of episodic mass-wasting events, particularly debris slides and debris flows, while Johnson and Jones (2000) found that mass-wasting events occurred with increased frequency after harvesting. Rood (1984) found that CH in steep watersheds can increase mass wasting frequencies and magnitudes by 29-fold. Hicks et al. (1991) found that the majority of mass wasting events following harvesting are initiated from poor forest road design and construction. Mass wasting events can contribute significantly to post-disturbance sediment influxes into headwater systems. The impacts of the increased sediment yields in the systems have been directly correlated with the emergent survival of salmonids. Increases in sediment fines can severely reduce emergent survival rates (Phillips et al., 1975; Ringler and Hall, 1975; Newcomb and Flagg, 1983; St-Onge and Magnan, 2000; Shaw and Richardson, 2001) and can cause adult mortality (Bozek and Young, 1994).

The major difference between harvesting and wildfire is the presence of forest roads, which can provide a continuous source of fine sediments. Beaty (1994) found that this continuous source of fine sediments does not occur from a burnt headwater catchment, due to the reduction in erodible substrates over time. In comparison, harvesting will likely result in increased sedimentation due to the need to access more areas for harvesting. This could particularly be

Table 5
Summary of harvest treatment's ability to emulate wildfire (CH: clear-cut harvesting; PSH: partial/selective harvesting)

Treatment	Temperature		Water chemistry, all attributes	Summer stream flow, all three attributes	Sedimentation, w/o roads
	Maximum temperature	Diurnal flux			
CH	Yes[a]	Yes	No	No	No[c]
PSH	No	Yes	Possibly[b]	Yes	No[c]

[a] Systems that are subjected to CH heat up over shorter distances then wildfire affected systems.
[b] Studies have identified less divergent responses when limited retention of riparian forest occurs.
[c] Forest roads emulate wildfire in the short-term not harvest treatment.

the case if CH is used in conjunction with methods that expose mineral soil in riparian areas and/or the adjacent uplands. Harvesting with limited roads, either by CH or PSH, actually has less of an impact than wildfire in the short-term. Forest road construction and maintenance does appear to emulate wildfire in the short-term; however, the fact that forest roads provide a long-term source of sediment does differ from wildfire and this must be considered by forest managers. It is important to build high quality roads with stable and sufficient crossing structures on streams to reduce sedimentation. Road networks should also be planned in a manner that reduces the need to build secondary roads into headwater catchments. All the studies used in this analysis identified secondary roads as the main cause of sedimentation. Harvest operations should also use designated skid trails to minimize mineral soil exposure and provide buffers in clear-cut treated areas to reduce riparian soil disturbance or use PSH systems adjacent to headwater streams. To answer the question, in relation to sedimentation, does harvesting emulate wildfire? The answer is no, but this appears to be beneficial if roads are limited or are of high quality and properly maintained. Because roads are the key to economic viability of harvesting, an interesting conundrum exists; do managers increase construction costs to emulate wildfire with greater congruency or do managers minimize cost and risk affecting the system over the long-term in a manner that is not congruent with wildfire?

5. Conclusion

Though some attributes are emulated, it is clear that no matter the harvest intensity/system wildfire will not be emulated with 100% congruency. The most detrimental differences between harvesting and wildfire are associated with changes in water chemistry and summer stream flow. In terms of sedimentation, it is the forest roads that may have the most significant impact because of the constant source of sediment they can provide over the life time of the road network. When all attributes are considered it appears that CH does not emulate wildfire and may have a more detrimental impact on headwater systems in both the short and long-term. PSH systems appear to recover along a more congruent trajectory with wildfire while CH does not appear to follow the same temporal recovery for summer stream flow and water chemistry. Overall, the results suggest that harvesting does not emulate wildfire, particularly CH. A lower intensity harvest system, such as PSH, provides hope since this system appears to emulate the majority of the attributes and offers equivalent recovery times in comparison to wildfire (see Table 5). Because of its increased congruency, PSH systems may offer a compromise between wildfire and CH systems. Reducing road networks and using prescribed under-burning after PSH may provide managers with a solution for emulating the effects of wildfire on water chemistry changes while still maintaining congruency with temperature, summer stream flow, and sedimentation attributes. This could be particularly true in ecosystems where wildfire is the primary disturbance agent.

The only way to develop harvest strategies that emulate wildfire is to evaluate multiple attributes of headwater systems that are affected by both disturbance types. This study has followed this philosophy in an attempt to address the complex interactions that occur when ecosystems are subjected to disturbance. Statistically significant differences were still found despite problems that should have existed due to the large geographic variation covered in this study. These significant differences were observed due to the differences in responses outweighing the variation. The fact that statistically significant findings can be identified over such a large geographic area suggests that coniferous ecosystems in North America may be exhibiting similar biophysical-chemical responses to disturbances. This may allow the results of this study to be generally applied to a wide range of coniferous-dominated ecosystems in the temperate and Boreal regions of North America, Europe, or Asia.

It is important for forest managers to consider the complex affects that harvest treatments can have on headwater systems if they are going to successfully practice ecosystem management and achieve sustainable forest management. It is also important for managers to understand that there are many other attributes to be considered. In particular, the ability of harvest treatments to emulate wildfire in regards to peak flows, organic matter inputs, large woody debris recruitment, channel morphology, and stream biota response. Due to the inability to statistically analyse these attributes they were not incorporated into the scope of this paper. Managers can potentially emulated wildfire with acceptable congruency through tailoring their harvest treatments to balance the impacts of each attribute with the harvest system that offers the greatest overall emulation congruency.

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