HYDROLOGICAL IMPLICATIONS OF FOREST BIOMASS USE

Final Report

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1. Introduction

This report is a literature review of the impacts of intensive wood (or biofibre) harvesting practices for bioenergy production on the hydrology and biogeochemistry of the boreal and Great Lakes-St. Lawrence forests in the vicinity of the Atikokan Generation Station, Ontario. It is the final deliverable for the project "*Hydrological impacts of using woody biomass for heat and/or electricity production in the context of a biomass LCA in the Atikokan power generating station supply area*", completed for Environment Canada by the Institute for Watershed Science at Trent University. The report addresses the following components:

i. Factors relevant to the general hydrological characteristics of the Atikokan region.
ii. The general impacts of forest management on hydrological and biogeochemical processes, including a review of studies that have examined the hydrologic and hydrochemical effects of forest disturbance in northwestern Ontario, a focus on the hydrological significance of logging slash, and a discussion of the specific hydrologic and biogeochemical impacts of the selected forest management scenarios that may apply to biofibre harvesting for bioenergy production in the Atikokan region.
iii. Knowledge gaps in our understanding of the impacts of biofibre harvesting for bioenergy production on hydrology and biogeochemistry in general and in the specific context of the Atikokan region.
iv. Recommendations regarding hydrologically- and biogeochemically-relevant aspects of Life Cycle Assessment (LCA) of biofibre harvesting for bioenergy production, and environmental metrics that may be relevant in assessing the impacts of this harvesting on hydrological and biogeochemical properties and processes.

2. Factors relevant to the general hydrological characteristics of the Atikokan region

The landscape of the Atikokan region of northwestern Ontario comprises numerous ridges, gullies, lakes and streams. Much of the area consists of bare rock and thin soils. The bedrock geology of the Atikokan region consists of Precambrian Shield (igneous, sedimentary, metamorphic rocks); granitic gneiss, with some metavolcanic and metasedimentary rocks are present (Senes Consultants 2004). Surficial geological deposits are largely bouldery till (Senes Consultants 2004). Soils are predominantly humo-ferric podzols, with lesser amounts of rockland and orthic eutric brunisols and orthic gray luvisols (Clayton et al. 1977).

The mean annual air temperature of the Atikokan region is 1.6°C, with a mean monthly minimum in January of -18.1 °C and a mean monthly maximum in July of 17.7 °C. Thirty-year normals of mean annual precipitation (*P*), rainfall and snowfall are 740 mm, 568 mm and 220 cm, respectively. There is a marked annual cycle in monthly *P* which is typical of northwestern Ontario, with a Winter minimum (25 mm in February) and a Summer maximum (103 mm in June). Snow generally begins to accumulate in late October and ablates by the end of April.

Mean annual lake evaporation (*E*) and mean annual evapotranspiration (*ET*) are both between 500 and 600 mm (Anon. 1984). Schindler et al. (1976) used a water balance approach to estimate *ET* from terrestrial surfaces and lake *E* in the Experimental Lakes Areas 60 km east of Kenora, Ontario and west of Atikokan. The former ranged from 449 – 670 mm while latter ranged from 285 – 562 mm during a four year period. Frisbee et al. (2007) also used a water balance approach to estimate *ET* for hillslopes east of the Atikokan region, and obtained an annual value of 470 – 480 mm for 2003.

Mean annual runoff in the Atikokan region is ~250 mm (Anon. 1984). Annual *P* exceeds annual potential *ET* (*PET*) by 200 – 400 mm on average. According to Devito et al. (2005) this suggests the potential for lateral water flow from uplands to receiving waters. These values are consistent with measurements made for small basins in the Experimental Lakes Areas 60 km east of Kenora, Ontario and west of Atikokan (Schindler et al. 1976), where annual runoff during a four year period ranged between 223 – 354 mm. The annual runoff regime for the region has highest flows for the weeks following Spring snowmelt, a decline in flows during Summer and a second but smaller increase in flows in the Fall before the development of continuous snowcover due reduced *ET* in the Fall. Groundwater flows in an east – west direction (Senes Consultants 2004), and is generally confined to near-surface unconfined aquifers. Allan and Roulet (1994) examined runoff processes in headwater basins on the Precambrian Shield in the Experimental Lakes Area west of Atikokan. The study landscape is similar to that in the Atikokan area (patches of forest on thin soil surrounded by bedrock outcrops). They observed overland flow from bedrock surfaces, subsurface flow in forest stands with some instances of saturation overland flow when the perched water table reached the surface of soil “islands”. Basins were dry or frozen for about 70% of the year and runoff was only generated during and immediately following snowmelt and/or rainfall. Frisbee et al. (2007) studied hydrologic characteristics of two zero-order basins on the Precambrian Shield east of the Atikokan area. Depressions in the bedrock surface were found to lead to considerable depression storage on slopes. These depressions can contribute runoff downslope when the water level rises above the bedrock sill (the “fill-and-spill” mechanism, Spence and Woo 2003). Subsurface water was observed to flow along the soil-bedrock interface and also via buried channels of glacial cobble.

3. Hydrologic impacts of forest management

3.1. General impacts of forest management on hydrological processes

Much of the following material is a reworking of reviews of the hydrological effects of forest harvesting provided by Buttle et al. (2000) and Buttle (2011).

3.1.1. Interception of precipitation

Forest cover and stand characteristics, such as tree species, leaf area and canopy density, have a significant influence on the amount of precipitation that is partitioned between interception storage (which is subsequently evaporated back to the atmosphere) and net precipitation that reaches the forest floor (Winkler et al. 2009). The percentage of rain that is intercepted by a forest is also dependent on storm intensity, duration, and weather conditions. On an annual basis interception loss from an undisturbed coniferous forest typically ranges between 1- to 50% (Roth et al. 2007). Forest harvesting generally increases the net precipitation reaching the ground surface due to reduced interception. This reduction in interception occurs for both rainfall and snowfall. In warmer and moisture forest landscapes a portion of the intercepted snowfall may melt and subsequently reach the snowpack surface; however, in the cold dry boreal forests of central Canada most of the intercepted snowfall is sublimated back to the atmosphere (Pomeroy et al. 1998, 2002).

3.1.2. Snow accumulation and melt

Studies in coniferous and deciduous forests have shown that forest harvesting can increase snow accumulation (Murray and Buttle 2003, Winkler et al. 2005). In coniferous forest the increases in snow accumulations in clearings five tree-heights or more in diameter have been shown to be 5 to 70% higher than under mature forest canopies (Winkler et al. 2005). The differences are the result of the efficient ability of conifers to intercept snow, and subsequent sublimation of intercepted snow back to the atmosphere.

Studies have also documented that the removal of forest canopy leads to an increase in snowmelt rates. This occurs as a result of greater inputs of solar radiation to the snowpack surface, and larger turbulent fluxes of sensible and latent heat. As a result, melt rates are typically 30 to 100% higher in clearcuts than in adjacent forests (Moore and Wondzell 2005). The net result is that more meltwater is delivered at a faster rate to the soil surface in disturbed locations relative to inputs in undisturbed forests (Murray and Buttle 2003). The impact of the modified delivery of melt water relative to undisturbed forests is discussed in the streamflow response section of this paper. Recognition of the role of forest disturbance in modifying snow accumulation and melt regimes has influenced forest management practices in some parts of Canada. One example is the H_{60} method that has been adopted as a watershed assessment guideline in the southern interior of British Columbia. This method assumes that the upper 60%

of a mountainous watershed is snow-covered and is contributing meltwater to streamflow during times of peak flows. Therefore, harvesting in locations with elevations greater than the elevation above which 60% of the basin (the H_{60} contour) lies has a much greater impact on changes that occur to streamflow following harvest. Forest harvesting above the H_{60} contour is thought to have a much greater impact on changes to snow accumulation and melt patterns compared to harvesting at lower elevations of the watershed. The British Columbia Interior Watershed Assessment Procedure provides a weighting mechanism that limits harvesting proposed in zones above the H_{60} contour (British Columbia Ministry of Forests and Ministry of the Environment 1999, Gluns 2001).

3.1.3. Evaporation and evapotranspiration

Forest harvesting can result in dramatic reductions in transpiration (Amiro 2001). Removal of the forest canopy also leads to greater direct evaporation from the soil surface relative to undisturbed forest stands, due to larger inputs of solar radiation, greater warming of the soil, and increased wind speeds immediately above the soil surface (Sun et al. 2001). However, this increase only partly counterbalances the reduction in transpiration losses due to tree removal.

3.1.4. Soil water and groundwater recharge

The combination of increased inputs and decreased evapotranspiration outputs that arise from forest harvest means increased water inputs to the soil. This occurs under both snowmelt and rainfall conditions. The result is greater soil water contents (e.g. Elliot et al. 1997, Murray and Buttle 2005), and increased groundwater recharge in harvested areas relative to undisturbed forests (Bent 2001). Forest harvesting often promotes a rise in water table levels (Dubé et al. 1995, Roy et al. 1997), with important implications for regeneration and site productivity. Increased soil water recharge also leads to enhanced potential for lateral flow on slopes where soils overlie less-conductive horizons or bedrock surfaces (e.g. Murray and Buttle 2005). In thin-soil landscapes, such as those found in the Atikokan area, groundwater flow is often through perched saturated layers above the soil-bedrock interface (Buttle et al. 2004, Frisbee et al. 2007). Increased recharge following harvesting should lead to increases in this shallow subsurface flow to receiving waters (e.g. streams, lakes, wetlands). This is consistent with the frequently-reported increase in low flows following harvesting (see below). Often this groundwater discharges at discrete locations along the lake or wetland boundary. Along lake margins these discharge sites may form key spawning and rearing habitat for fish (Borwick et al. 2005).

3.1.5. Streamflow response

3.1.5.1. Water yield

The increase in net water delivery to soils and potential for more rapid lateral transfer of these inputs to receiving waters means that forest disturbance often (but not always) results in increased annual streamflow (water yield) from drainage basins. There is abundant evidence from around the world to indicate that increased removal of forest canopy results in increased water yield for both deciduous and coniferous forest types (Bosch and Hewlett 1982, Sahin and Hall 1996). However, the wide range in climatic, geologic, pedologic, topographic, vegetation and disturbance conditions associated with these studies means that there is considerable scatter in the relationship between canopy removal and water yield increase, such that this relationship cannot be used with any real confidence to predict the water yield response to forest disturbance for a particular drainage basin. Nevertheless, reviews of studies of water yield response to forest disturbance provide strong evidence for the contention that significant increases in water yield appear to occur only when at least 20% of the forest cover has been removed. It is important to note that syntheses of studies that have led to the suggested 20% basin harvested threshold for observable increases in water yield have largely been based on measurements conducted within the first several years of harvesting (e.g. within 5 years of harvesting, Bosch and Hewlett 1982). The limited number of studies on the recovery of water yield following forest regeneration (e.g. Bosch and Hewlett 1982, Thomas 1990) suggests that 10 – 20 years or more may be needed (depending on such factors as forest type and climate) before forest regeneration results in a return of water yields to pre-harvest conditions. There is a long-standing assumption that the effects of forest disturbance on water yield are greatest at the small-basin scale, and that these effects become subsumed by downstream water storage and the runoff response of undisturbed portions of larger basins such that they cannot be detected with confidence at larger spatial scales (Keenan and Kimmins 1993). This assumption is supported when water yield response is plotted against basin size for data aggregated at the national (Stednick 1996) or global level (Bosch and Hewlett 1982). However, examination of data at the regional scale (e.g. Stednick 1996) shows that in some instances water yield response to forest disturbance may remain relatively consistent or even increase with basin scale. This issue is particularly relevant for efforts to assess the cumulative impacts of forest disturbance for large drainage basins, and requires further study (e.g. Krezek et al. 2008).

3.1.5.2. Peak flows

Due to increased potential for lateral flow within the soil and above the soil surface on disturbed slopes, a greater fraction of incoming water (snowmelt, rainfall) can reach receiving waters (wetlands, lakes, streams) more rapidly than under natural conditions. However, previous studies provide “mixed messages about peak flow responses” (Thomas and Megahan 1998, p. 3402) to forest disturbance. Thus, the literature provides evidence for increased peak flows across a range of event sizes (Verry et al. 1983, Jones and Grant 1996), increases for only small peak flows (Thomas and Megahan 1998), decreased peak flows (Harr and McCorisin 1979), or no significant changes in peak flows following harvesting (Thomas and Megahan 1998). Buttle and Metcalfe (2000) note that this wide variation in peak flow response to disturbance arises from intersite differences in runoff generation, climate, geology, topography, vegetation, soils, and the nature of forest disturbance. This highlights the need to consider the landscape-specific properties and processes that may govern the hydroecological responses to processes in Canada's varied forest ecozones under both natural and disturbed conditions. The equivocal literature results for peak flow response to forest disturbance are echoed to some extent by Guillemette et al.'s (2005) summary of studies of peak flow response to forest harvesting. They used bankfull discharge as their index of peak flow, and found that there was general increase in bankfull flow with increasing fraction of basin harvested. Nevertheless, there was considerable scatter in the relationship, similar to the water yield – fraction of basin harvested relationship referred to above. As with the water yield data, there appears to be a decrease in bankfull flow response to harvesting with increasing basin scale (0.0 → 1000 ha); however, no clear relationship between bankfull flow response and scale emerges when only basins experiencing complete clearcutting are considered. As noted in the context of water yield, the relationship between scale and streamflow response to disturbance requires further study, particularly for forest ecozones that have not previously been examined (Buttle et al. 2000).

3.1.5.3. Low flows

The increased soil water and groundwater recharge that usually accompanies disturbance of the forest cover is generally assumed to result in increased low flows during periods when *PET* may approach or even exceed *P* inputs (e.g. mid-to-late Summer). Pomeroy et al. (1997) noted that the wetter conditions that accompany removal of the forest canopy mean that Summer rainfalls that may not generate streamflow response in forested basins may produce small-to-moderate flows in disturbed basins. Increased streamflow during periods that are normally associated with low flows under undisturbed conditions can have important ecological implications, in terms of such factors as habitat availability and water temperature. However, some research has shown that elevated low flows may persist for only short period of time, and that subsequent colonization of disturbed areas by plant species with higher water demand than the original forest cover may reduce low flows to below pre-disturbance levels (e.g. Martin et al. 2000).

3.1.5.4. Streamflow timing

In snowmelt-dominated hydrologic regimes, disturbance effects on snow accumulation and melt can lead to de-synchronization of flows from disturbed and undisturbed parts of the basin. Thus, rather than observing a single large peak streamflow event due to basin-wide snowmelt, there may be several smaller peak streamflows as disturbed areas lose their snowcover before forested areas (Verry et al. 1983).

3.1.6. Erosion and sediment transport

Forest disturbance has been found to increase sediment mobilization. Nitschke (2005) presented a meta-analysis of data from studies of sediment fluxes from disturbed forested basins in Canada and the US. He showed that wildfire disturbance increases sediment generation in the short-term, while roads associated with harvesting can provide long-term sediment sources. Road crossings and near-stream landings have been found to provide important point-sources of sediment associated with forest harvesting (Macdonald et al. 2003). In high-relief forest landscapes, mass movement processes such as landslides may serve as the major means by which sediment enters receiving waters (Sidle and Wu 2001). Forest harvesting has been found to lead to increased piezometric heads on slopes in coastal British Columbia due to reduced evapotranspiration losses noted earlier (Dhakal and Sidle 2004). Harvesting may also affect slope stability by reducing the cohesion associated with tree roots (Sidle and Wu 2001). However, landslides in the Pacific Northwest are typically caused by large Winter rainstorms, when the magnitude of water inputs to the soil surface would exert a greater influence on mass movement potential than the role of forest harvesting. Dhakal and Sidle (2004) contended that harvesting in temperate forests enhances hydrologic response and increases mass movement potential only during small and moderate storms.

3.1.7. Biogeochemical processes

Forest harvesting has been shown to disrupt natural biogeochemical processes in soils and the way in which these associated dissolved nutrients are delivered to receiving waters (Kreutzweiser et al. 2008). Increases in soil temperature and soil moisture caused by forest harvesting are generally associated with increased microbial activity in soils (Hazlett et al. 2007). This in turn can covert nutrients from non-mobile to mobile forms (Buttle et al. 2005, Kreutzweiser et al. 2008). Mobile nutrients are more readily exported to receiving waters as water tables rise and saturation of the soil occurs (Buttle et al. 2005).Nutrients can move through both surface and subsurface pathways in solution, or attached to particulate matter. The following discussion provides more detailed reviews on the impacts of forest harvesting on concentrations and fluxes of some of the key elements associated with the biogeochemistry of forest ecosystems: carbon, nitrogen, phosphorus and mercury.

3.1.7.1. Carbon

Forests are considered to be carbon (C) sinks since they fix more C than they release via respiration. The excess C is incorporated into the forest biomass. In the boreal forest large stores of C are found in trees, roots, plant litter, humus and heterotrophic organisms in the ground (Natural Resources Canada 2009). From a hydrological perspective the most significant change that occurs to C cycling following forest harvesting is an increase in dissolved organic C (DOC) production. DOC production rates may increase in harvested areas as a result of increased organic matter decomposition of residues left behind on the forest floor following harvesting (Lamontagne et al. 2000). Increased DOC production can result in increased DOC export to receiving waters such as streams or lakes. Higher water tables in clearcut areas can result in increased DOC exports as hydrological flowpaths may favour near surface pathways (Laudon et al. 2009).

The result is increased water flow through organic-rich upper soil layers and the bypassing of mineral soils where DOC can be sorbed and stabilized (Lamontagne et al. 2000 Kreutzweiser et al. 2008). Kreutzweiser et al. (2008) report that the majority of studies on DOC exports to receiving waters in the boreal forest showed increases in the range of 200% to 500% shortly after clear-cut harvesting, followed by declining DOC exports 3 to 5 years after harvesting. These DOC exports to receiving waters are unlikely to cause harmful changes to aquatic systems in the boreal forest and may help protect aquatic habitat and biological productivity through the attenuation of UV radiation, reduction of thermocline depths and augmentation of basal energy resources (Kreutzweiser et al. 2008).

3.1.7.2. Nitrogen

Nitrogen (N) is a growth limiting factor in the boreal forest (Tamm 1982). The N cycle in undisturbed boreal forest is relatively closed, with most of the N cycled within the soil-microbe-plant system (Futter et al. 2010). N-fixing bacteria in the soil convert atmospheric nitrogen (N_2) into ammonia (NH_3), and bacteria and soil microbes convert NH_3 to nitrite (NO_2^-) and NO_2^- to nitrate (NO_3^-). This mineralization makes the N bioavailable and the bulk of this N is taken up by forest biota. Total input of N to the soil from N fixation and atmospheric deposition is small. However, losses from the system through denitrification and leaching are generally smaller than inputs, resulting in net accumulation (Tamm 1982). Although the boreal forest contains large amounts of organically bound N, the rate of decomposition and mineralization is low in undisturbed forests.

Forest harvesting can disrupt the N-cycle by altering soil temperatures, soil moisture, organic debris, plant uptake and decomposition, all of which have the potential to affect N cycling and losses of N from harvested sites. The changes caused by harvesting can affect N uptake rates, microbial communities, mineralization, nitrification, denitrification and immobilization processes. Nitrate (NO_3^-) is highly mobile, and is the form of N most likely to be lost from forest soils by leaching (Kreutzweiser et al. 2008). Excess NO_3^- leaching occurs when plant uptake rates are lower than the rate of organic N transformation to NO_3^-, or when water transports NO_3^- away before it can be utilized by forest biota (Futter et al. 2010). Elevated concentrations of NO_3^- can persist for several years following harvesting in the boreal forest (Futter et al. 2010), and can cause increases in NO_3^- concentrations in groundwater and receiving surface waters (Kubin 1998, Henriksen and Kirkhusmo 2000, Kreutzweiser et al. 2008). Nitrogen losses by leaching and transport can contribute to the nutrient enrichment of forest water bodies (Kreutzweiser et al. 2008). This nutrient enrichment can result in excessive growth of plants and algae (eutrophication).

The response of boreal forest N pools and cycling to forest harvesting is variable and nearly impossible to predict or model (Kreutzweiser et al. 2008). The magnitude and timing of changes to the processes that impact N cycling are highly site specific. N responses to forest harvesting are variable across and within the landscape as the result of micro-site level differences in soil properties, site conditions, biological interactions, topography, etc. Responses will depend on the type of harvesting, the time of year the harvesting is conducted, and the post harvesting conditions such as weather patterns and soil moisture.

3.1.7.3. Phosphorus

The cycling of phosphorus (P) is influenced by many of the same factors that control the cycling of N (Kreutzweiser et al. 2008). The wetter and warmer soil conditions that are induced by harvesting may lead to increased P mineralization, and therefore an increase in P availability (Macrae et al. 2004). Disturbance of the mineral soil layer can result in increased weathering of P from this layer. P adsorbs readily to mineral soils, and any hydrological event that results in the movement of mineral soils via surface or surbsurface pathways could increase the loading of P to receiving waters (Macrae et al. 2004, Kreutzweiser et al. 2008). P can also adsorb to DOC, which increases the solubility, mobility and export of P (Kreutzweiser et al. 2008). Therefore, the processes described in Section 3.1.7.1 that increase DOC exports following harvesting could also increase the export of P.

Nevertheless, the effect of forest harvesting on dissolved P exports from forest soils in the boreal forest are not well understood, and have not been studied as intensely as other nutrients (Kreutzweiser et al. 2008). The studies that have been conducted show variable results, with some reporting increases in P exports and concentrations in receiving waters following harvesting (Devito et al. 2000, Lamontagne et al. 2000, Kreutzweiser et al. 2008), and others reporting decreases in P exports (Evans et al. 2000, Lindo and Visser 2003). Like N, the impact of forest harvesting on P cycling is variable and highly site specific; however, the impact of forest harvesting on P cycling and exports in the boreal forest is likely not as great as on N cycles (Macrae et al. 2004, Kreutzweiser et al. 2008).

3.1.7.4. Mercury

The soils of the boreal forest are rich in organic matter, and readily adsorb and accumulate mercury (Hg) from dry and wet atmospheric deposition (Desrosiers et al. 2006). Sulphate-reducing bacteria are primarily responsible for converting Hg in boreal forest soils to methylmercury (MeHg), which is the form of mercury that that is most readily bioaccumulated in aquatic fauna (Sørensen et al. 2009). Forest harvesting can enhance the methylation of mercury by raising soil temperatures, increasing the supply of C from decomposing logging debris, and raising the water table (thus depleting oxygen in the soil), creating conditions that are favourable for the sulphate-reducing bacteria (Sørensen et al. 2009). The export of MeHg from soils to receiving waters is largely controlled by the export of organic matter (Porvari and Verta 2003). Like phosphorus, MeHg readily adsorbs to DOC. Therefore any increase in DOC exports following harvesting could also increase the export of MeHg.

Many studies have demonstrated that forest harvesting in the boreal forest results in increased loading of MeHg to receiving waters, and increases in the amount of Hg found in the aquatic fauna downstream of the harvested area. Zooplankton and northern pike in the boreal forest of Quebec have increased MeHg concentrations in lakes where forest harvesting has been conducted within the contributing terrestrial basin compared to adjacent lakes with unharvested basins (Garcia and Carignan 1999, Garcia and Carignan 2000). In the boreal forest of Finland Porvari et al. (2003) measured MeHg concentrations in soils and concluded that harvesting and subsequent soil treatment significantly increased MeHg exports to receiving waters.. It is estimated that between 10% and 25% of the Hg in lakes in the Swedish boreal forest entered the aquatic ecosystem as a result of forest harvesting (Sørensen et al. 2009).

However, there are studies that have found that MeHg does not always follow these patterns. Schuster et al. (2008) found insignificant increases in MeHg following harvest in a Swedish boreal forest, citing a winter harvest that resulted in very little disturbance of the forest soils. Site specific factors such as soil type and topography also appeared to reduce the sensitivity of the site to impacts induced by forest harvesting that result in increased MeHg exports following harvest. Topography has also been shown by others to influence MeHg export upland-peatland, and Mitchel et al. (2009) found that watershed geomorphology played an important role in the fluxes of MeHg into peatlands in Minnesota. This suggests that it may be possible to reduce the impacts of forest harvesting on MeHg exports by minimizing site disturbance, and selecting optimal sites for harvesting.

3.2. Studies of the hydrologic effects of forest disturbance in northwestern Ontario

There have been few studies of the hydrologic impacts of forest disturbance (e.g. fire, harvesting) on hydrological processes in northwestern Ontario that could be readily translated to the Atikokan region. Schindler et al. (1980) and Bayley et al. (1992) examined the hydrochemical response to fire for small basins in the ELA area of northwestern Ontario, and provided a brief description of impacts on basin hydrology. Steedman (2000) examined the effects of clearcutting on lake water quality in the Atikokan region, but did not address the impacts of harvesting on the streams draining to the lakes or other aspects of the terrestrial hydrology. Thus, there is a lack of knowledge of the specific impacts that biofibre harvesting may have on the hydrology of the Atikokan region, and any efforts to assess these impacts will necessitate the transfer of findings from forest landscapes in Canada and the US that are similar to that of the Atikokan landscape. Krezek et al. (2008) discuss some of the prospects and challenges facing that knowledge transfer. For example, there have been a number of studies of the hydrologic and biogeochemical consequences of forest harvesting in the Canadian boreal forest, and the findings could potentially be used to predict the water quantity and quality impacts of various bioenergy harvesting scenarios in the Atikokan region. Nevertheless, it is uncertain whether the hydrologic processes that operated in these studies function in the same manner as in the Atikokan landscape, and Devito et al. (2005) illustrate how an incorrect conceptual model of the hydrologic processes operating in a region increases the risk of applying inappropriate mitigation strategies. Differences in spatial scale between that of the relatively small experimental basins used to document the hydroecological consequences of forest harvesting and that of the larger basins in the Atikokan region that may be subjected to harvesting for bioenergy production also poses a challenge. Harvesting may produce impacts on water quantity and quality in headwater systems that are undetectable in larger basins (e.g. Buttle and Metcalfe 2000). Since the latter are often the systems that are monitored for streamflow and water quality, the absence of a detectable change in these properties for larger basins may lead managers to conclude (possibly incorrectly) that harvesting has no hydrologic or biogeochemical consequences.

3.3. Hydrological significance of logging slash

Biofibre harvesting for bioenergy production often involves the recovery of portions of the tree (tops, branches and bark) that are generally not removed in commercial harvesting. This material is commonly known as slash, and there is little information on how downed woody material (which would include slash left on site after harvesting) affects water quality and quantity (Evans 2011). Nevertheless, there are certain aspects of the hydrologic role played by slash that have been identified in the literature.

Slash has a substantial water holding capacity (Fraver et al. 2002); this implies that slash removal would increase net precipitation reaching the soil surface. Kelliher et al. (1992) found that slash that covered 60% of the ground intercepted 11% of rainfall in a thinned *Pinus radiata* stand in New Zealand. Slash on this site intercepted 3.6 times less water per unit leaf area than lives trees. Reid and Lewis (2007) used this study to justify and quantify increased litter interception values into their model that predicts pre-logging peakflows from below-canopy rainfall. Makoto et al.'s (2005) study of the influence of slash on soil moisture also reported that slash acted to intercept precipitation, but did not provide any information on the magnitude of this interception loss.

The presence of slash may alter snow accumulation and snowmelt processes, since slash is an important roughness element in harvested areas. Snow is generally redistributed from harvested areas into adjacent forested areas (Murray and Buttle 2003); presence of slash would encourage retention of snow in harvested areas (Winkler et al. 2010), at least until the snowpack depth exceeded the depth of the slash layer after which redistribution would increase. Thus, presence of slash would increase the amount of water potentially available to infiltrate or runoff during Spring snowmelt relative to sites with no slash. The presence of slash would provide some shading of the snowpack surface during the snowmelt period; however, this reduction in energy input would likely be more than compensated for by the increased turbulent fluxes and enhanced downward longwave radiative flux to the snowpack as the slash protrudes above the snowpack surface (Buttle et al. 2005). Thus, melt rates in harvested areas retaining slash may exceed rates in areas where slash has been removed. The net result is a greater input rate of a greater total amount of water in areas retaining slash during Spring snowmelt. Murray and Buttle (2005) found that this would promote greater infiltration of water into the soil profile and enhanced water and nutrient fluxes from harvested slopes to receiving water bodies.

Zabowski et al. (2000) studied the impacts of residue treatment on the microclimate and soils of harvested blocks in the Cascade Mountains of Washington State for two years post forest harvest. In treatments where the slash residue was burned or removed, soil temperatures were consistently higher during the growing season compared to areas where the residue was left on site. Similar findings were found by Fowler and Helvey (1981) in the Blue Mountains of Oregon. The result of these increased energy inputs would be greater evaporation at sites where residues are removed compared to those where it is left on site. Makoto et al. (2005) reported that slash in a Hinoki forest in Japan reduced evaporation from the ground surface. In the Atikokan region, both *PET* and *P* are greatest during the Summer, although there is a Summer soil water deficit (*PET* > *P*). This suggests that slash removal will lead to increased loss of water via evaporation from the soil surface that will exceed increases in net precipitation. These losses would be driven by increased inputs of solar radiation and higher wind speeds at the soil surface at sites on which the slash was removed relative to those where the slash is left on site.

It is expected that forest harvesting scenarios in which slash is left on the cut blocks will have lower net precipitation rates relative to sites where the slash is recovered for biofibre, or removed to the roadside. The decrease in net precipitation rates is expected to be partly offset by decreases in evaporation losses from the ground surface as a result of decreased energy inputs to the soil surface by solar radiation (shading) and turbulent fluxes caused by the slash. The net result may be that slash management has little impact on soil moisture contents of clearcut soils. Nevertheless, *in situ* retention of residual biomass following harvesting has been shown to have a positive effect on long-term soil organic matter levels (Powers 1991). In certain cases, retention of slash residues has also been shown to conserve soil moisture (Smethurst and Nambiar 1990, O’Connell et al. 2004). Thus, greater organic matter contents associated with on-site slash retention should sustain higher soil moisture content relative to plots where slash is removed.

Based on the assumption that the retention of slash within the cut block would support higher soil moisture content (depending on soil characteristics), this could potentially promote greater rates of lateral water movement of water over and through the soil (interflow). In the specific case of the Atikokan area, the implications of slash retention or removal upon near-surface soil water contents and surface runoff during Spring snowmelt can be significant given the region’s cold climate and potential for development of concrete frost during soil freezing.

Freezing of near-saturated soils in the Fall prior to development of a deep insulating snowcover can lead to creation of concrete frost at the soil surface that can severely reduce infiltration rates and promote overland flow during snowmelt and rain-on-snow events (Proulx and Stein 1997).

Slash left in the cut block also serves to protect the mineral soil from erosion by reducing overland flow in forests (McIver and Starr 2001, Wu et al. 2005). This has the added effect of reducing sediment transport to streams from harvested slopes, while slash that is retained in small stream channels may also promote sediment trapping and reduce downstream sediment loading (Hart 2003). The physical process of removing slash can displace the soil's duff layer, thus exposing the mineral soil to erosion by wind, rain and overland flow (Elliot 2010).

Slash piles left at the roads side are expected to have minor impacts on nutrients fluxes compared to areas where the slash piles are removed for biofibre processing. Rosén and Lundmark-Thelin (1987) studied leachate from slash piles in Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) dominated forests in central Sweden, and found increased N leaching from the piles. This increase was caused by higher moisture content in the humus layer underneath slash piles, which results in increased mineralization coupled with a decrease in N demand in the soils under the slash piles due to the lack of vegetation. Gotou and Nishimura (2002) studied leachate from piles of slash dominated by Japanese cypress (*Chamacecyparis obtuse*) and Japanese cedar (*Cryptomeria japonica*) for four years following harvesting. They found that leachate from the slash piles carried water-soluble nutrients into the soil approximately 5 to 7 m from the pile after four years. The pH of the soil near the slash piles decreased, and several minerals, particularly Ca (Japanese cedar is a Ca –rich species), also increased near the pile. They concluded that although the piles did increase soluble nutrients in the area under and surrounding the slash piles, the piles did not have an impact on nutrient fluxes at larger scales (Gotou and Nishimura 2002).

4. Selected forest management scenarios that may apply to biofibre harvesting for bioenergy production in the Atikokan region

4.1. Forest management scenarios

4.1.1. Scenario BH0 (existing practice)

This scenario is currently the standard harvesting practice in northwestern Ontario. Harvesting is conducted at the historical harvest rate, targeting conifer-dominated stands with incidental poplar harvested. Unmerchantable and unmarketable wood is left standing. A minimum of 25 trees/ha (including unmarketable trees) are left standing for biodiversity purposes. Full-tree-to-roadside is the dominant harvesting method, with the exception of sites with sensitive or shallow soils where cut-to-length methods are used. Approximately 50% of the slash is left on the cut-blocks, and 50% is piled at the roadside. The roadside slash is placed in piles, and these piles are occasionally burned.

4.1.2. Scenario BH1 (residue recovery)

This scenario follows the same harvesting practice as scenario BH0 (Section 4.1.1); however, roadside slash piles are collected for biofibre from currently planned harvesting operations (i.e. no additional harvest for biofibre). The slash piles created from the full-tree-to-roadside method are recovered for biofibre at an average recovery rate of 75% of the piled residues. Residues left in the cut-block during full-tree-to-roadside and cut-to-length harvesting are not recovered.

4.1.3. Scenario BH2 (increased hardwood harvest)

This scenario follows the same harvesting practice as scenario BH0 (Section 4.1.1), plus the additional full-tree harvesting of unmarketable or unmerchantable trees with grapple skidding and delimber-debarker-chipper operations at the roadside, to produce hardwood chips for white pellet production. Conifer dominated stands are targeted as a priority, but stands with greater hardwood content are also harvested. Hardwood utilization is approximately 73% of the annual allowable cut (AAC). Residue is recovered for bioenergy production.

4.1.4. Scenario BH3 (full hardwood harvest)

This scenario sees both conifer and hardwood dominated stands targeted, with hardwood that is additional to current harvested amounts being used for biofibre for pellet production. Hardwoods that are unmarketable or unmerchantable for conventional forest products, but can be used for white pellet production, are harvested using full-tree to roadside harvesting methods. Hardwood utilization is approximately 95% of AAC for hardwoods.

5. Comparison of the selected forest management practices and an explanation of their different hydrological impacts.

The hydrological impacts of forest harvesting have been well documented. Each of the four scenarios that are considered in this report generally result in similar modifications to hydrologic processes, including changes in net precipitation, interception, evapotranspiration, soil moisture, and streamflow. The magnitude of the changes may change from scenario to scenario. How slash residues are handled can have an influence on some hydrological processes.

From a hydrological perspective it is likely that the percentage of area harvested would have the largest role in determining the impacts of each of the four harvesting scenarios. Scenario BH3 has the highest percentage of the area harvested at 95% of the AAC, followed by BH2 at 85% of the AAC, and BH0/BH1 at 70% of the AAC (Cormier and Reynolds 2011). The percentage of the basin that is harvested increases from BH0/BH1 through to BH3. As the percentage of the basin harvested increases it would generally be expected that interception losses and transpiration decrease as a result of canopy removal. Evaporation from the forest floor would increase due to increased exposure to incoming solar radiation and turbulent energy fluxes. A slight increase in snow accumulation and melt rates would also be expected. The cumulative expected results of these changes would be increased soil water contents and a rise in water table levels. The magnitude of these changes would be influenced by the percentage of the basin harvested. However, these processes are highly variable, and are influenced not only by forest harvesting but also by such factors as forest stand characteristics, the biophysical characteristics of the watershed such as soil properties and topography, climatic variables, season of harvest, etc.

The hydrological implications of slash management are not well studied. In the studies outlined in Section 3.3 it is shown that slash management can influence rainfall interception, evaporation, soil moisture, erosion sediment transport, and biogeochemical fluxes. However, the magnitude of changes to these hydrological processes is relatively small. Slash removal generally has little effect on hydrologic properties of a site except at the microclimatic level, unless the slash residue removal causes significant erosion.

All four of these scenarios have approximately 50% of the slash left in the cut block, and approximately 50% piled at the roadside. Of the four harvesting scenarios BH0 is the only one in which all of the slash is left on site. Residue recovery from the roadside piles for biofibre applications is practiced for scenarios BH1, BH2 and BH3. The primary hydrological implication of leaving these slash piles on site is the potential for increased leaching of nutrients from the slash piles into the surrounding soils, and potentially to receiving waters. However, given the small percentage of the forest floor that is occupied by these slash piles, increased nutrient fluxes from these piles are not expected to have any significant impact at the watershed scale.

Timber harvesting equipment has the potential to create considerable site disturbance. The amount of disturbance can be related to soil bearing strength, soil moisture, pressure exerted by machinery, season of harvest and operator efficiency. Full-tree harvesting has been reported to cause significant disturbance to the soil during both wet and dry conditions (Pulkki 2002). Cut-to-length harvesting has been reported to cause moderate disturbance on dry ground and heavy disturbance on wet ground, while both full-tree and cut-to-length harvesting are reported to cause low disturbance on frozen ground (Pulkki 2002). Soil compaction by harvesting machinery can increase bulk density and soil moisture, which contributes to increased overland flow, higher water tables and enhanced baseflow discharge (Johnson and Beschta 1980). Compaction is likely when harvesting machinery is used on wet soils with low soil strength (Elliot 2010). Second pass scenarios, where slash removed at the tree is collected, would be expected to increase compaction and contribute to increases in the hydrological impacts. There is evidence that soil compaction caused by forest harvesting can persist for several decades after the initial disturbance (Alexander and Poff 1985, Powers et al. 2005). When harvesting for biofibre Elliot (2010) reported that there is potential for greater onsite impacts than is commonly the case with current pulp or saw log harvesting practices as machine traffic over a given area is increased when mechanically harvesting a greater number of small-diameter trees per hectare.

It is difficult to generalize about disturbances caused by harvesting methods because there is no consistency in the methodology, season of harvest, and equipment used from site to site (Pulkki 2002), and between each of the scenarios presented in Section 4.1. Cormier and Reynolds (2011) indicated that scenario BH3 will have a much higher percentage of trees harvested by full-tree harvesting. Full-tree harvesting techniques are estimated to be utilized 70% of the time in scenario BH3, 40% of the time for BH2 and BH1, and 30% of the time in BH0 (Cormier and Reynolds 2011). Not only does scenario BH3 have the highest utilization of full-tree harvesting, but it is also the scenario in which the greatest number of small-diameter trees per hectare are removed, with up to 95% of the AAC harvested (Cormier and Reynolds 2011). Scenarios BH2, BH1 and BH0 will harvest approximately 85%, 70% and 70% of the AAC, respectively (Cormier and Reynolds 2011). Therefore, scenario BH3 would have the greatest potential for onsite impacts caused by machinery

Table 1 and Table 2 summarize the hydrological implications and the associated biogeochemical fluxes caused by harvesting in the boreal forest. These tables detail the hydrological processes and biogeochemical fluxes that are expected to be altered as result of forest harvesting, and a brief explanation of why these changes are expected has been provided. Table 3 and Table 4 summarize the relative impacts that each of the harvesting scenarios may have on the hydrological processes and biogeochemical fluxes, respectively. The direction of the change that is expected is indicated by “+” for increases or “-“ for decreases. An estimate of the magnitude of change that is expected is provided by the number of “+” or “-“ symbols within the column. Given that site level differences in forest stand characteristics, soil properties, topography, climatic variables, harvesting techniques, etc., may cause a high degree of variability in some of the hydrological and biogeochemical changes, we have indicated the degree of confidence that we have in these predictions by shading the “+” or “-” symbols from black to light grey. Darker symbols indicate increased confidence in the predicted response to harvesting.

Table 1 Estimated short term (3-5 years) hydrological implications of forest harvesting in the boreal forests in the Atikokan region

Hydrological Process	Changes caused by harvesting	Details
Interception	Reduction	Canopy removal increases the amount of rainfall and snowfall that reaches the forest floor.
Transpiration	Reduction	Removal of trees decreases the amount of moisture transpired back to the atmosphere.
Evaporation from soil	Increase	Canopy removal increases shortwave radiation at the soil surface and evaporates water from the soil surface.
Infiltration	Variable	Dependent on management practices.
Annual Flow	Increase	Exceptions do occur due to site’s physical/geological characteristics.
Baseflow	Increase	Exceptions do occur due to site’s physical/geological characteristics.
Peakflow	Variable	Dependent on magnitude of rainfall events and site specific factors such as elevation and soil types.
Snow accumulation	Increase	Due to decreased interception (see above).
Snow melt	Increase	Canopy removal increases shortwave energy inputs and turbulent energy fluxes to the snowpack.
Soil moisture	Increase	Increased precipitation inputs and decreased transpiration losses result in wetter soils.
Water table elevation	Increase	Increased precipitation inputs and decreased transpiration losses result in wetter soils and greater groundwater recharge.

Table 2 Estimated short term (3-5 years) biogeochemical implications of forest harvesting in the boreal forests in the Atikokan region

Biogeochemistry	**Changes caused by harvesting**	**Details**
DOC concentrations in soil and streamwater	Increase	Increased decomposition of organic debris coupled with higher water tables and associated near surface hydrological flowpaths can increase DOC production and export to receiving waters.
Nitrogen concentrations in soil and streamwater	Increase	Increased soil temperatures, soil moisture, and organic debris decomposition can increase NO_3^- production which is highly mobile and often transported to receiving waters; however, exceptions do occur due to site specific conditions.
Phosphorus concentrations in soil and streamwater	Increase	Increases in soil moisture and soil temperatures combined with increases in DOC and mineral sediment export can result in increased exports of P; however, exceptions do occur due to site specific conditions.
Mercury concentrations in soil and streamwater	Increase	Increases in soil moisture, soil temperature and DOC exports can result in increased production and export of MeHg

Table 3 Relative hydrological impacts of forest harvesting scenarios BH0, BH1, BH2 and BH3

Hydrological Process	**Scenario BH0**	**Scenario BH1**	**Scenario BH2**	**Scenario BH3**
Interception	**-**	**-**	**--**	**---**
Transpiration	**-**	**-**	**--**	**---**
Evaporation	**+**	**+**	**++**	**+++**
Infiltration	+	+	+	+
Annual flow	+	+	+	+
Baseflow	+	+	+	+
Peakflow	+	+	+	+
Snow accumulation	+	+	++	++
Snow melt	+	+	++	+++
Soil moisture	+	+	++	+++
Water table elevation	**+**	**+**	**++**	**++**
Site Disturbance	+	+	++	+++

+ = increase.   -= decrease. Number of "+" or "-" signs indicates relative magnitude of change
Shading indicates our confidence in the prediction, with bold indicating we are very confident

Table 4 Relative biogeochemical impacts of forest harvesting scenarios BH0, BH1, BH2 and BH3.

Biogeochemical Flux	Scenario BH0	Scenario BH1	Scenario BH2	Scenario BH3
DOC	**++**	**++**	**++**	**++**
Nitrogen	++	++	++	++
Phosphorus	+	+	+	+
Mercury	+	+	++	+++

+ = increase. -= decrease. Number of "+" or "-" signs indicates relative magnitude of change
Shading indicates our confidence in the prediction, with bold indicating we are very confident

6. Knowledge gaps in our understanding of the impacts of biofibre harvesting for bioenergy production on hydrology and biogeochemistry in general and in the specific context of the Atikokan region.

We have identified three major knowledge gaps through our review that need to be addressed through further research:

i. How will forest harvesting affect the hydrology of the Atikokan region? We can say with a reasonable degree of certainty what the general hydrologic effects of forest harvesting will be. However, we cannot say with any certainty what the effects will be in a specific region. The forest hydrology literature has repeatedly demonstrated that these effects depend to a considerable extent on such local conditions as climate, geology, topography, vegetation, basin scale and management practices
ii. What is the hydrologic significance of slash removal vs. slash retention, both in general and in the specific case of the Atikokan region?
iii. If and how will slash removal alter key soil hydrologic properties (e.g. porosity, pore size distribution, hydraulic conductivity)?

In order to address these knowledge gaps, specific studies are required to examine these questions, including:

i. Acquisition of data on precipitation, streamflow and stream chemistry at relatively small basin scales (i.e. less than the scale of basins currently gauged by the Water Survey of Canada in the Atikokan region) that can be used to assess the effects of harvesting on streamflow in the Atikokan area. Alternatively, well-validated hydrological and biogeochemical models are needed to predict how streamflow and stream biogeochemistry will respond to forest harvesting (both in terms of location and intensity of harvesting).
ii. Obtaining the results of experiments (from elsewhere if necessary but preferably for tree species and soils similar to those in the Atikokan region) that examine how slash retention/removal at levels proposed for the Atikokan region will affect hydrologic and biogeochemical fluxes and stores.
iii. As in (ii), obtaining the results of experiments (from elsewhere if necessary but preferably for tree species and soils similar to those in the Atikokan

region) that examine how slash retention/removal at levels proposed for the Atikokan region will affect key soil hydrologic properties.

These studies should be related to site-specific conditions. Use should be made of existing soil information for the Atikokan region, supplemented by site-specific soil surveys.

7. Principles, Criteria, Indicators and Verifiers relevant to the impacts of bioenergy production on water quantity and quality

Many agencies (with regional, national or international mandates) have argued that sustainable forest management, whether for the general use of forest resources or for the specific management of forests for bioenergy production, should be based on a clear elucidation of management principles, criteria, indicators and verifiers. These represent components of a hierarchical system of standards and monitoring mechanisms (Lattimore et al. in review) that can be used in the planning phases of forest management as well as assessing the sustainability of bioenergy production systems (Lattimore et al. 2009). A *Principle* can be defined as “a fundamental truth or law as the basis of reasoning or action” (CIFOR 1999), whereas *Criteria* are used to enhance the meaning and operability of principles (Lattimore et al. in review). *Indicators* provide measurable information about a criterion, while *Verifiers* add detail to Indicators and provide the highest level of quantitative specificity (Lattimore et al. in review). Simply put, Principles and Criteria provide goals and standards, while Indicators and Verifiers are tools for measuring progress. This section of our review will concentrate on Criteria (*C*), Indicators (*I*) and Verifiers (*V*) that are relevant to the general hydrologic and biogeochemical effects of forest harvesting, and bioenergy production in particular.

7.1. General aspects of and reservations regarding the use of *C*, *I* and *V* in terms of the water resources aspects of bioenergy production.

Neary (2002) discussed the issue of assessing the sustainability of water resources in the context of forest harvesting for biofibre for energy production. He made special reference to the Montreal Process, a Canadian initiative to develop management guidelines and criteria for ensuring conservation and sustainable management of forests. Criterion 4 of the Montreal Process concerned the conservation of soil and water resources and protective and productive functions of forests. Neary (2002) identified four *I* that pertain to Criterion 4 and that specifically relate to hydrologic impacts of harvesting:

- No. 19: area and percent of forest managed primarily for protective functions (e.g. watershed, flood protection, avalanche protection, riparian zones);
- No. 20: percent of stream kilometres in forested catchments in which stream flow and timing has significantly deviated from the historic range of variation;

- No. 23: percent of water bodies in forest areas with significant variance of biological diversity from the historic range of variability; and
- No. 24: percent of water bodies in forest areas with significant variation from the historic range of variability in pH, dissolved oxygen, levels of chemicals, sedimentation, or temperature change.

Since ***I*** 23 deals with biological aspects of forest harvesting that are beyond the scope of this report, we will not deal further with it.

Neary (2002) expressed some reservations regarding the applicability of these ***I*** to biofibre harvesting. In the case of ***I*** 19, there is an assumption that protective management guarantees sustainability. However, a temporary or long-term decline in sustainability can also be caused by natural disturbance (e.g. drought, fire, insect infestation). Neary contended that rather than serve as a guarantor of forest sustainability, this ***I*** is instead more of a measure of society's attitudes to protection, of the degree to which Best Management Practices (BMPs) are employed, and of appropriate management. In the case of ***I*** 20 and ***I*** 24, our hydroclimatic and biogeochemical records are relatively short and are often insufficient to define adequately the "historic range of variation" (Bishop et al. 2009). Hydrologic and biogeochemical metrics such as annual water yields, magnitude and timing of peak and low flows, suspended sediment concentrations, water temperature, etc., are only useful ***I*** if they are related to changes in land management or to natural disturbances that could affect ecosystem sustainability. Neary stated that we need to ask two key questions: (1) has harvesting changed the hydrologic regime from a naturally dynamic state to a temporarily or permanently disturbed state?; and (2) is there any relationship between deviation from the historic range of variation and ecosystem sustainability under the current management system? If there are no linkages and change is only temporary, Neary contended that this ***I*** is not useful as a measure of the potential of biofibre harvesting to threaten the sustainability of the forest ecosystem. He argued instead for a focus on BMPs that aim to ensure forest and water sustainability as well and the economic sustainability of forestry operations. These BMPs include the exclusion of harvesting from areas with saturated or readily-compacted soils, appropriate design of stream crossings to minimize disruption to water courses, adequate cross-drainage on forest roads, and the retention of buffer zones along streams and around the margins of lakes and wetlands to minimize the transfer of water, sediment, nutrients and contaminants from harvested areas to receiving waters (Norris 1993, but see Buttle (2002) for a discussion of the hydrologic effectiveness of these buffer zones). Shepard (2006) reviewed the US system of forestry BMPs, and argued that forestry BMPs in the US (and by extension in Canada) should generally be applicable to bioenergy production. Nevertheless, these BMPs may need to be revised to reflect the accelerated production cycle in areas experiencing more frequent harvesting activity for biofibre.

7.2. P, C, I and V relevant to the hydrologic and biogeochemical effects of forest harvesting and bioenergy production

Despite the reservations raised by Neary (2002), we recognize that the specification and use of *P*, *C*, *I* and *V* are fundamental to sustainable forest management in Canada and many other parts of the world (demonstrated by Lattimore's (2011) biofibre harvesting standards database). As Heuvelmans et al. (2005) noted, multiple *I* and *V* should and are be used wherever possible for more direct representation of the complexity of environmental systems.

Lattimore et al. (2009) presented a set of *P*, *C*, *I* and *V* of sustainable forest management in the context of biofibre harvesting for energy production. Table 5 summarizes the ecosystem attributes that may be affected by biofibre harvesting, specific issues related to these attributes, the forest management activities that may contribute to them, and the operational techniques for mitigating ecological damage that Lattimore et al. (2009) felt were relevant to hydrology.

Table 5 Potential environmental impacts of biofibre production systems on hydrology, and examples of operational techniques to mitigate ecological damage arising from these impacts (after Lattimore et al. 2009).

Attribute: Ecosystem hydrologic flux (infiltration, groundwater recharge, interception and transpiration)
Issues: • Compaction creating impermeable soils and waterlogged depressions • Decreased leaf and slash surface area after harvesting → decreased interception and transpiration • Increased leaf area from biofibre plantations → increased interception → decreased infiltration to water table • Changes to water tables
Contributing activities: • Removal of slash and resultant loss of protective roadbed for extraction machinery • Removal of vegetation and alteration of soil properties • Whole-tree harvesting, especially with clearcutting • Plantation establishment • Irrigation of short-rotation woody crop plantations
Possible mitigation techniques: • Follow regional Best Management Practices for maintaining water quality, if available • Maintain buffer zones in riparian areas • Manage for healthy soils • Avoid short-rotation woody cropping systems where irrigation causes deleterious changes in groundwater levels • Apply chemicals (e.g., pesticides, herbicides, fertilizers) according to guidelines

Table 6 Principles (*P*), Criteria (*C*), Indicators (*I*) and Verifiers (*V*) related to the water quantity and quality aspects of bioenergy production (adapted from Lattimore et al. 2009).

P	The productive capacities of ecosystems and landscapes are maintained
C	Ecosystem components that determine site productivity, notably soil and water, return to pre-harvesting conditions within an acceptable time from disturbance, or are enhanced by harvesting practices
I1	Practices should ensure soil conservation and improvement (*S*)
V1.1	Road building for energy feedstock extraction is minimized through use of existing logging roads, where possible, and prompt road deactivation upon obsolescence (*F*)
V1.2	Roads are built, maintained and deactivated according to codes of good practice (*F*)
V1.3	Soil surveys are conducted and topographic information is gathered when developing management plans (*F*)
V1.4	Forest management will consider climate and weather data (*F*)
V1.5	Site-specific management plans are prepared with objectives to:
V1.5.1	Conserve nutrients and prevent pollution (*S*)
V1.5.2	Prevent soil compaction and rutting (*S*)
V1.5.3	Preserve soil organic content (*S*)
V5.4	Ensure an adequate amount and distribution of organic matter (slash, decaying wood, litterfall) remains to sustain soil function (*S*)
V5.5	Ensure a healthy chemical status to maintain or enhance plant growth and development, water quality and biodiversity (*S*)
V5.6	Prevent erosion (*S*)
I2	Soil nutrient status, temperature, structure and processes are maintained within the historic range of variability or are improved
V2.1	Nutrient budgets are estimated at the forest management unit level before a management plan is chosen (*F*)
V2.2	Periodic soil analysis to monitor:
V2.2.1	Soil chemistry (e.g. nutrients, pH) (*S*)
V2.2.2	Toxic compounds (e.g. heavy metals, pesticides) (*S*)
V2.2.3	Soil physical properties (*S*)
V2.2.4	Soil biological properties (*S*)
V2.2.5	Soil erosion (*S*)
I3	Practices should ensure water conservation and improvement
V3.1	Utilization of best management practices (*F*)
V3.2	Landscape-level estimates of management impacts on watersheds (*F*)
V3.3	Road networks and stream crossings are designed to minimize impacts (*F*)
V3.4	Design and employment of streamside management zones (SMZs) is adequate to protect streamwater quality and biota (*S*)
I4	The quality and quantity of surface and groundwater is maintained within the historic range of variability, or improved
V4.1	Periodic hydrologic analysis to monitor:
V4.1.1	Hydrologic regime (e.g. water yield, peak and low flows, evapotranspiration) (*F*)
V4.1.2	Water physical properties (e.g. turbidity, temperature) (*S*)
V4.1.3	Water chemistry, including toxic compounds (*S*)
V4.1.4	Water biological properties, including diversity and population sizes of aquatic organisms (*S*)

(*F*) indicates that *C*, *I* or *V* are applicable at the forest management unit level,
(*S*) indicates that *C*, *I* or *V* are applicable at the site level.

Lattimore et al. (2009) built on information such as that presented in Table 5 to outline the *P*, *C*, *I* and *V* that could be used for developing and maintaining sustainable bioenergy production systems. We have focused on those *P*, *C*, *I* and *V* most relevant to water quantity and quality (Table 6). Many of these *I* and *V* specifically relate to the maintenance of soil physical, chemical and biological properties; however, maintaining these properties would also lead to the maintenance of key water quantity and biogeochemical properties. Note that *F* in Table 6 indicates that *C*, *I* or *V* are applicable at the forest management unit level, while *S* indicates that they are applicable at the site level.

In order to update and expand on the *P*, *C*, *I* and *V* presented in Lattimore et al. (2009), we have examined those *C*, *I* and *V* relevant to hydrology and water quality given in Lattimore's (2011) biofibre harvesting standards database. Among the common aspects of these management components at the international level are:

1. *V* based on the use of forest managers' knowledge of best operating procedures in a particular region;
2. *C* that specify the need to base forest management on environmental planning prior to the initiation of harvesting operations, and use of documented evidence characterizing the soils in the forest management unit as a key *I*; and
3. *C* that require the adoption of conservation, monitoring and maintenance practices and such associated *I* as evidence of the adoption of such soil conservation techniques as the monitoring of the qualitative and quantitative parameters of the relevant water and soil resources and evidence that the road network does not promote soil erosion.

The water-related *C* and *I* specified by the Canadian Standards Association were particularly useful in expanding on the material given in Table 6 and providing greater specificity. We focussed on three particular *C* and their related *I*:

1. Criterion 3. Conservation of Soil and Water Resources.
   Indicator: The proportion of sites considered as excellent or good in relation to this criterion (selection of harvest sites, minimum amount of biomass left in final harvest areas and water protection measures) shall be at least 90 % of the total harvest area based on the results from the quality control of nature management;
   Indicator: Peatlands that are in their natural state have not been drained for energy wood cultivations.
2. Criterion 17. All operations taking place close to watercourses and small water bodies shall safeguard water protection.
   Indicator: Soil scarification for regeneration, fertilization, stump removal, clearing of shrub layer vegetation, or use of chemical pesticides or herbicides shall not take place on buffer-zones. Canopy biomass is removed from buffer-zones if possible.
3. Criterion 19: The quality of groundwater shall be safeguarded in forestry operations.

> Indicator: Chemical pesticides or herbicides shall not be used in groundwater areas that are important (Class 1) or suitable (Class 2) sources of water supply. Fertilizers shall not be used in groundwater areas that are important (Class 1) sources of water supply. Stumps shall not be removed in Class I groundwater areas.

Heuvelmans et al. (2005) provided a valuable elaboration of aspects of Lattimore et al.'s (2009) *V4.1.1*: the regional hydrologic regime [or what Heuvelmans et al. (2005) term the regional water balance]. The main environmental burdens associated with the water balance are potential for flooding and drought, and the average amount of water available for downstream uses. They went on to discuss the benefits and limitations of two contrasting attribution approaches when assessing the environmental consequences of forest harvesting on the regional water balance: static attribution and dynamic attribution. Static attribution ignores temporal variability in indicators of regional water balance response to harvesting (which are discussed in greater detail in Section 8.2) and instead compares several harvesting scenarios in terms of one global score (e.g. total average streamflow) per scenario. Dynamic attribution is based on the recognition that multiple values exist for every variable of the indicator set, which are gathered through long-term monitoring or modelling. Time series of such hydrological and biogeochemical variables such as water table level, streamflow or DOC concentrations must be aggregated into one or a few indicators that reflect environmental burdens posed by harvesting (e.g. flow percentiles derived from flow duration curves).

7.3. Using I and V to assess the effects of bioenergy production on water quantity and quality

Heuvelmans et al. (2005) have argued for consideration of harvesting impacts on the regional water balance, and have described specific hydrologic indicators associated with the water balance that should be considered when assessing the environmental consequences of bioenergy production. They present two alternatives to constructing indicators of harvesting impacts on the regional water balance that have been normalized to a reference system, which they assume to be the potential natural vegetation in the region of interest. For average downstream water availability and drought risk:

$$Ind_B = \frac{Ind_{B_{ref}} - Ind_{B_{act}}}{Ind_{B_{ref}}}$$

where Ind_B = normalized indicator of average downstream water availability and drought risk, Ind_{Bref} = non-normalized indicator for the reference system and Ind_{Bact} = non-normalized indicator for the system under study.
For flood risk:

$$Ind_C = \frac{Ind_{C_{act}} - Ind_{C_{ref}}}{Ind_{C_{ref}}}$$

where Ind_C = normalized indicator of flood risk, Ind_{Cref} = non-normalized indicator for the reference system and Ind_{Cact} = non-normalized indicator for the system under study. The flood risk indicator has the same meaning as the drought risk and downstream water availability indicators: positive scores indicate unwanted impacts and negative scores indicate desired effects. These normalized indicators can simply be averaged to get the overall score of the impact of harvesting for bioenergy production on the regional water balance. Although Heuvelmans et al. (2005) focussed their attention on indicators related to water quantity, normalized forms of other indicators outlined in Table 6 that address the biogeochemical aspects of bioenergy production could also be derived (e.g. DOC concentrations in the system under study relative to DOC levels in unharvested streams in the region).

8. Life Cycle Assessment and harvesting for bioenergy production

8.1. Introduction

Life Cycle Assessment (LCA) can be defined as “a systematic set of procedures for compiling and examining the inputs and outputs of materials and energy and the associated environmental impacts directly attributable to the functioning of a product or service system throughout its life cycle” (US EPA 2010). These potential environmental aspects of a service or product can be assessed by:

1. Compiling an inventory of relevant inputs and outputs of energy and matter;
2. Evaluating potential impacts associated with identified inputs and releases; and
3. Interpreting the inventory and impact phase findings in relation to the study objectives (US EPA 2010)

With respect to (1), the focus of this review is on the output of matter (water and associated dissolved and particulate constituents) from forest areas harvested for bioenergy production. This review has already examined the potential impacts of these outputs at various scales ranging from the stand to the watershed. This section reviews previous work related to LCA in the context of water and of forest harvesting (whether for wood products in general or specifically for bioenergy production), and outlines approaches that have been suggested for assessing the potential impacts of land use change in the context of LCA. It then evaluates the relative impacts of forest harvesting for bioenergy production in terms of water quantity and quality (discussed earlier in the report) in the context of LCA. A subsequent section then describes the knowledge gaps that need to be addressed in order to use this approach to conduct a complete LCA of the impacts of bioenergy production in the Atikokan region on water quantity and quality. This builds on the previous identification of knowledge gaps associated with how harvesting associated with bioenergy production may impact on various aspects of the hydrology and biogeochemistry of the Atikokan area (Section 6).

8.2. LCA, water and forest harvesting

Heuvelmans et al. (2005) identified two impact related categories that are relevant to water quantity: extraction of abiotic resources and land use. They proposed that because the environmental impacts of such land use activities as forestry can fluctuate with time (e.g. impact on water table elevations over the course of the growth of a forest plantation on previously agricultural land), the comparison of different forest harvesting scenarios should be done for a complete harvest rotation. In a LCA context, land use impact consists of two types of intervention (Maes et al. 2009):

1. land use *Occupation* impact (the impact associated with the use of an area at a given time for a given purpose); and
2. land use *Transformation* impact (impact of human-induced change in land use for a given area).

Following Maes et al. (2009), Occupation impact is calculated as A*T*I, where A = area occupied, T = time of occupation, and I = environmental impact of the land. Transformation impact is calculated as $A^*\Delta I$, where ΔI = change in environmental impact following transformation. Koellner and Scholz (2007) extended this to include the amelioration of any impacts that occurs during the land *Restoration* phase. They suggested using the current regional status to assess whether a specific land use type is better or worse than the regional average land use mix. They then quantifed ecosystem damages arising from land transformation and occupation in terms of the *Ecosystem Damage Potential* (*EDP*). Figure 1 plots the change in *EDP* during the sequence of land Transformation, Occupation and Restoration.

Positive values of *EDP* indicate ecosystem degradation, while negative values indicate an improvement in ecosystem properties relative to conditions preceding the land use change. The integral of the change in *EDP* over time and area is the total transformational impact of that land use change. It is important to note that Figure 1 is the simplest of examples presented by Koellner and Scholz (2007). In this case, the ecosystem returns to the original conditions after restoration, such that there is no irreversible damage or net ecosystem improvement. As in Koellner and Scholz's (2007) original analysis, we have assumed linear temporal trends in *EDP*. Figure 2 is a modification of Figure 1 that is more relevant to consideration of the hydrologic and biogeochemical effects of harvesting for bioenergy production.

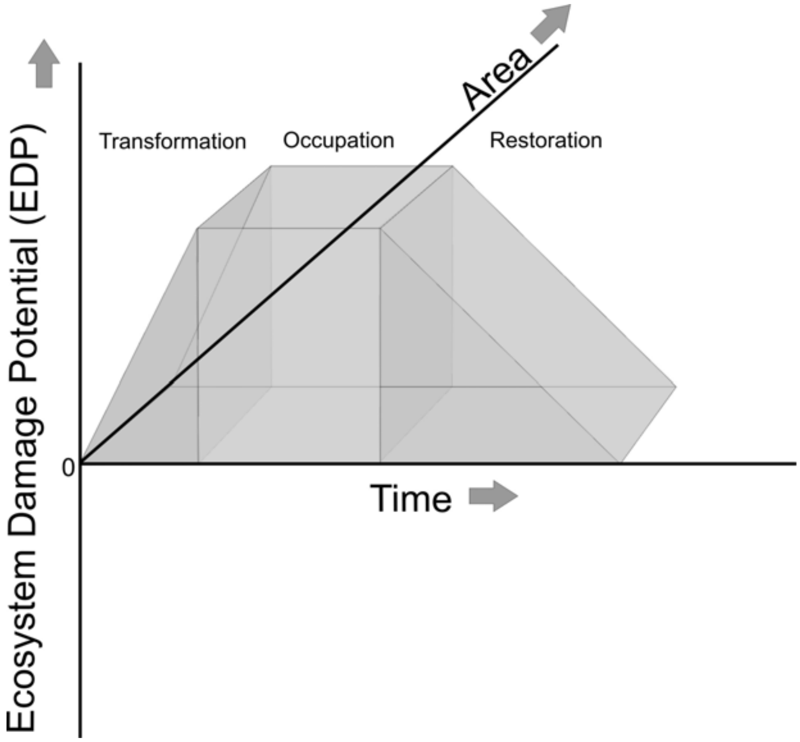

Figure 1 Change in Ecosystem Damage Potential (EDP) with time and area for a given land use activity. The upper surface of the grey volume is the damage function, while the grey volume represents the total damage of a land use activity (modified from Koellner and Scholz 2007).

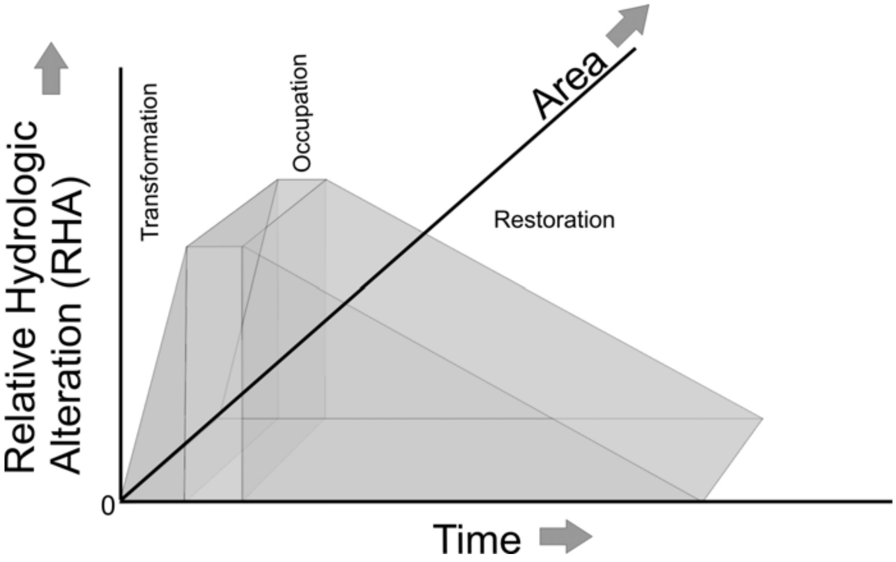

Figure 2 Change in Relative Hydrologic Alteration (RHA) with area and time.

We are now considering the relative change in hydrologic (or biogeochemical) conditions compared to the non-harvested condition [*Relative Hydrologic Alteration* (*RHA*) or *Relative Biogeochemical Alteration* (*RBA*)]. Note that there is a very short (often less than 1 year) period of Transformation and Occupation compared to the duration of the Restoration period (often several years or decades depending on the hydrologic or biogeochemical property being considered). Koellner and Scholz (2007) provided preliminary estimates of the number of years to transform an initial land intensity into a final one. They estimated that it would take 25 years to go from a current forest plantation condition to a semi-natural forest, and 10 years to go from a current semi-natural forest to a forest plantation. These values are similar in magnitude to the time lengths required for hydrologic recovery of various hydrologic properties noted earlier in this review (e.g. Thomas 1990, Buttle et al. 2005). Thus, this approach is suitable for examining forest rotation systems, where the use of a given area might periodically alter between being in an intensive state of site preparation and harvesting and an extensive state of recovery (Koellner and Scholz 2007). As Koellner and Scholz (2007) noted, the damage of land transformation is greatest for land use types which are difficult to restore and need very long time periods to develop (e.g. primary forest). They also stressed that a major challenge of this approach is the development of reliable generic characterization factors which can express the *EDP* (and by extension the *RHA* or *RBA*) of specific land use types.

Returning to the land use impact category noted earlier, Heuvelmans et al. (2005) suggested that the ‘function’ of land use with respect to water flows can be conceived as the way a land use system affects output related impacts (i.e. hydrologically-relevant indicators such as average water availability, flood and drought risks). This can be distinguished from an examination of the environmental mechanisms that explain how the site properties have been altered during land use change such that the hydrological behaviour of the land has been altered. Heuvelmans et al. (2005) argued that the temporal changes in land quality produced by these mechanisms are internal to the harvesting process (in LCA terminology, the product system) and do not need to be evaluated in the land use impact category of a LCA. Instead, they suggested that any change in land quality is evaluated as a change in water outputs from a given area after one rotation compared to the situation at the start of the rotation. Table 7 presents their suggested approach for assessing the impacts of forest harvesting on several aspects of water quantity.

Table 7 Scheme of a LCA methodology for assessing impacts on water quantity (from Heuvelmans et al. 2005).

Impact category	Indicator	Environmental threat
Input related		
Abiotic resource depletion	Water dynamic reserve life	Future freshwater reserves
Land use	Change in surface runoff	Flood mitigating capacity
	Change in (infiltration minus evapotranspiration)	Drought mitigating capacity
	Change in precipitation surplus	Control on water flows
Output related		
Regional water balance	Daily streamflow with exceedance probability of 5%	Flooding of human properties, disturbance of ecosystems by floods
	Monthly streamflow with exceedance probability of 50%	Average water availability for other ecosystem processes and human activities, e.g. hydropower generation
	Monthly streamflow with exceedance probability of 95%	Drought risk, drying of wetlands

For both the land use and regional water balance impact categories, indicators are defined at a smaller scale in order to account for spatial variability of water reserves and flows. While the approach given in Table 7 represents one of the few LCA-related studies that explicitly consider the potential impacts of forest harvesting on water, we feel that there would be important insights that can be obtained by considering how such impacts may change during the course of a harvesting rotation. Therefore, following from the previous discussion of Maes et al. (2009) and Koellner and Scholz (2007), the methodology in Table 7 could be expanded to consider how these indicators (and others noted in Section 7.2) of each impact category change during the Transformation, Occupation and Restoration phases associated with bioenergy production.

8.3. Relative impacts of bioenergy production on water quantity and quality in the context of LCA

In this section we use the modified approach of Koellner and Scholz (2007) to suggest how the temporal trajectories of *RHA* and *RBA* for a complete harvest rotation might differ between the different bioenergy harvesting scenarios addressed in this review. This is based on our assessment of the relative changes in water quantity and quality that would accompany these harvesting scenarios. Nevertheless, we have not provided examples for each of the hydrologic and biogeochemical properties that were discussed in Section3. Our goal instead is to illustrate the value of the approach in the context of examining how the harvesting scenarios might affect some aspects of water quantity and quality, to highlight key differences in the response of particular hydrologic and biochemical properties to these scenarios, and to suggest what future work is needed to provide the information needed to incorporate this approach into a LCA of bioenergy production in the Atikokan region.

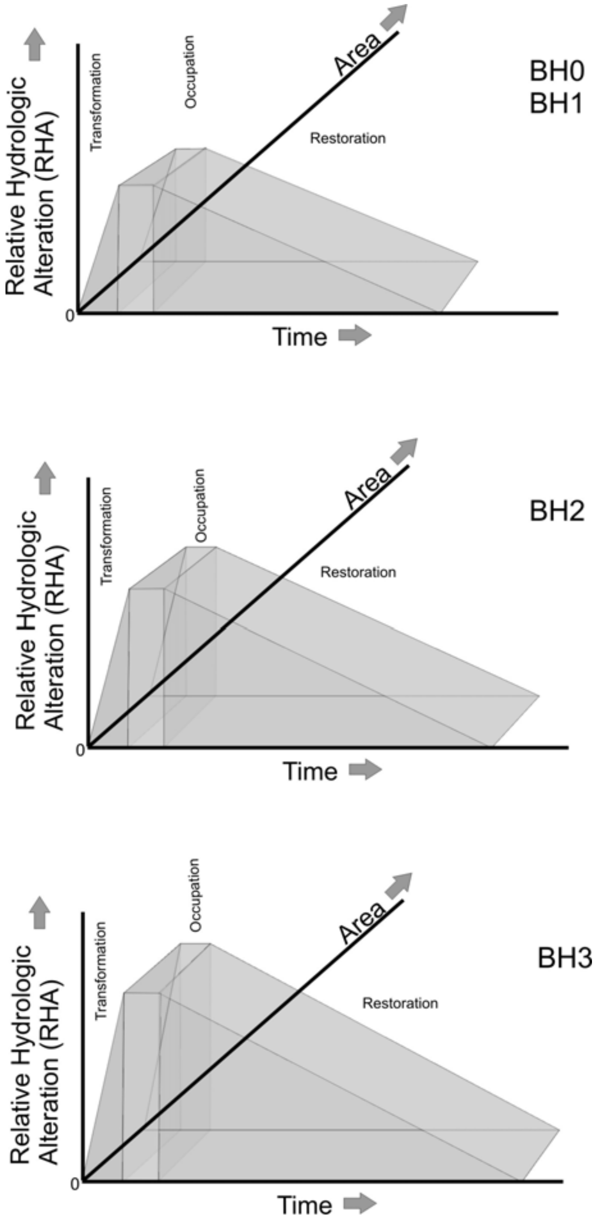

Figure 3 Relative change in rainfall interception with area and time for the different harvesting scenarios.

Figure 3 shows how rainfall interception might change under all four harvesting scenarios. In all cases, harvesting would increase *RHA* (decreased interception) during the Transformation and Occupation phases. The temporal trajectory of *RHA* for BH0 and BH1 in this and subsequent Figures is essentially the same, since the only difference between the two scenarios is the removal of 75% of the slash pile left at the roadside for pellet production. We feel that this would have an insignificant impact on the properties examined. *RHA* would increase from BH0/BH1 through to BH3 due to increased hardwood harvesting. This would be accompanied by an increase in the length of the Restoration period.

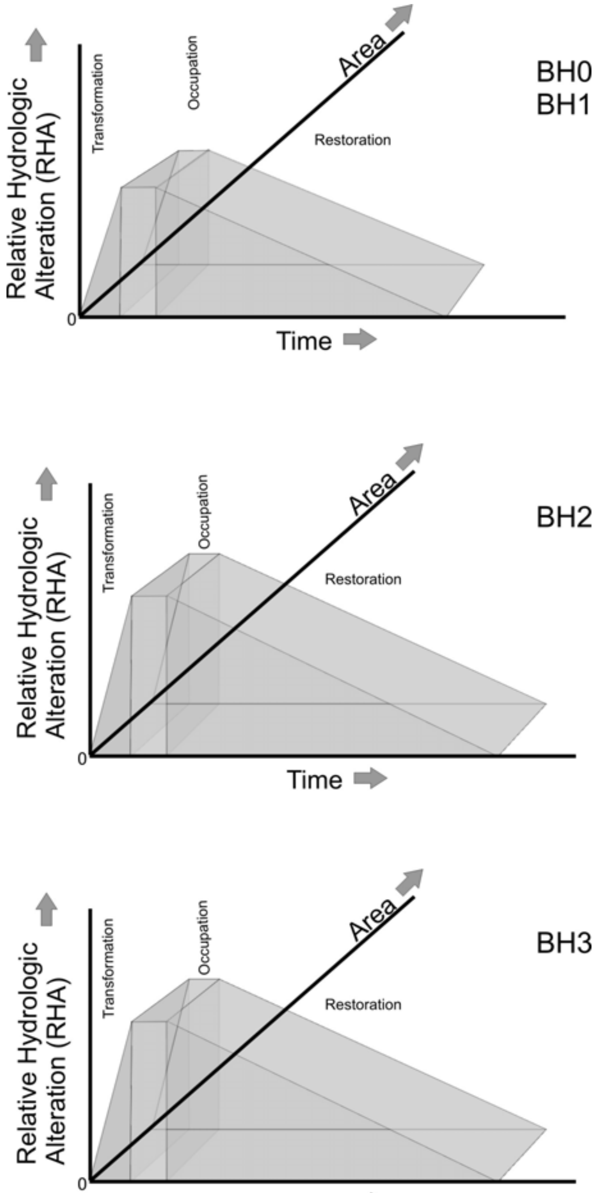

Figure 4 Relative change in snowfall interception with area and time for the different harvesting scenarios.

As with rainfall, there would be decreased interception of snowfall during the Transformation and Occupation phases, following by an almost immediate initiation of recovery during regeneration (Figure 4). We anticipate a slightly greater reduction in interception (larger *RHA*) from BH0/BH1 to BH2 due to increased softwood harvesting under the latter scenario. There would be a minor increase in *RHA* from BH2 to BH3 due to a slight increase in softwood harvesting; however, we suspect that this would be difficult to detect using standard hydrological approaches.

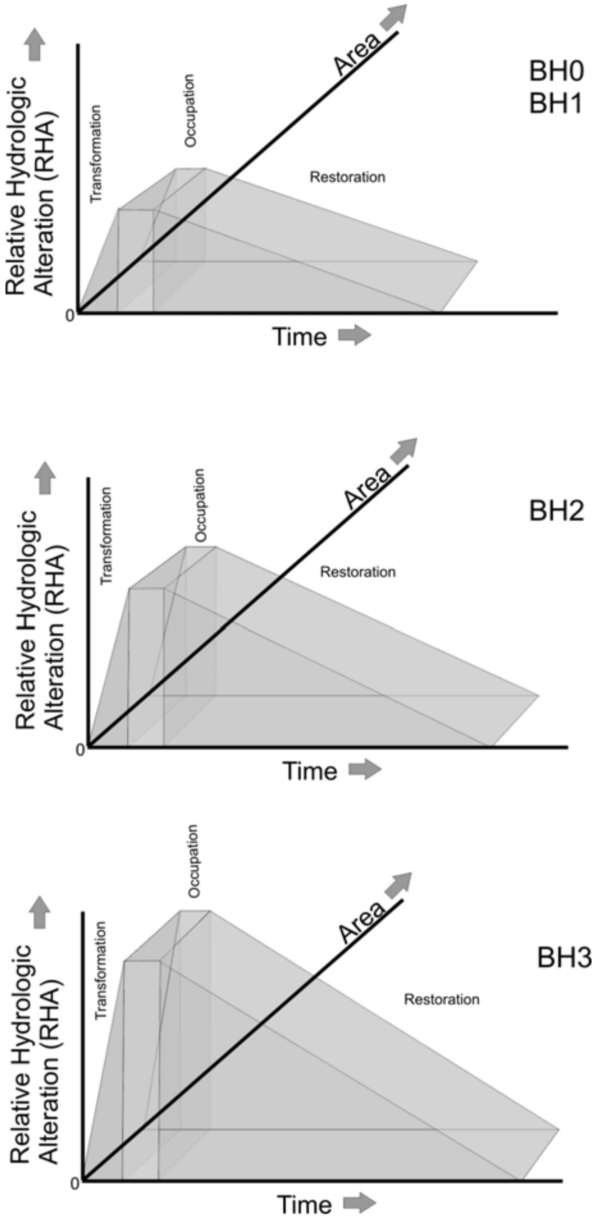

Figure 5 Relative change in forest floor evaporation with area and time for the different harvesting scenarios.

There would be a general increase in evaporation from the forest floor under all four harvesting scenarios (Figure 5). The increase in forest floor evaporation under BH0/BH1 would be relatively minor as a result of partial removal of the forest canopy and associated increases in net radiation reaching the forest floor and greater windspeed and turbulent energy fluxes over the surface. Forest floor evaporation would progressively increase with the greater harvesting associated with BH2 and BH3, as would the duration of the Restoration time.

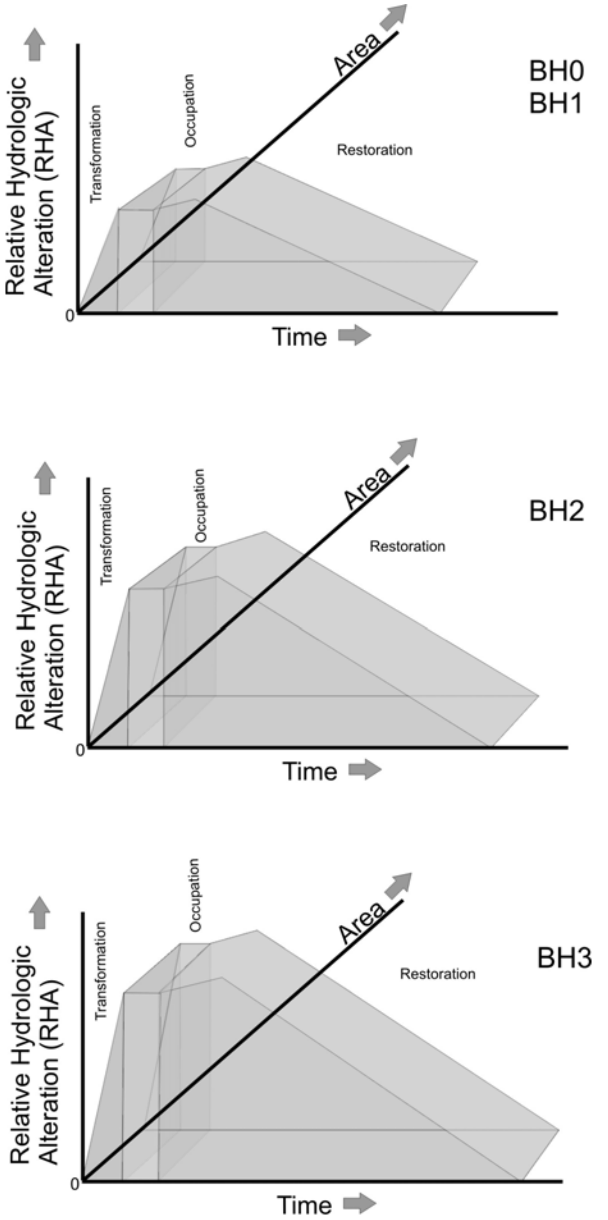

Figure 6 Relative change in snowmelt rate with area and time for the different harvesting scenarios.

There will likely be a general increase in snowmelt rates under all four harvesting scenarios (Figure 6). This increase in *RHA* would result from the removal of the forest canopy and greater exposure of the snowpack to shortwave energy inputs and turbulent energy fluxes. Snowmelt rates would increase from BH0/BH1 through to BH3 due to more removal of softwoods. These have a greater potential to shade the snowpack than do hardwoods, such that their harvesting leads to a proportionately greater increase in shortwave energy receipt at the snowpack surface. We suggest that the snowmelt rate may increase slightly during the initial Restoration period for all scenarios. This is attributed to the increase in surface roughness and turbulent energy fluxes as regenerating vegetation begins to protrude above the snowpack surface, as well as increased longwave energy fluxes to the snowpack from the regenerating vegetation. This is followed by a reduction in turbulent fluxes and greater shading of the snowpack surface (and reduced shortwave energy inputs) as regeneration continues (Buttle et al. 2005).

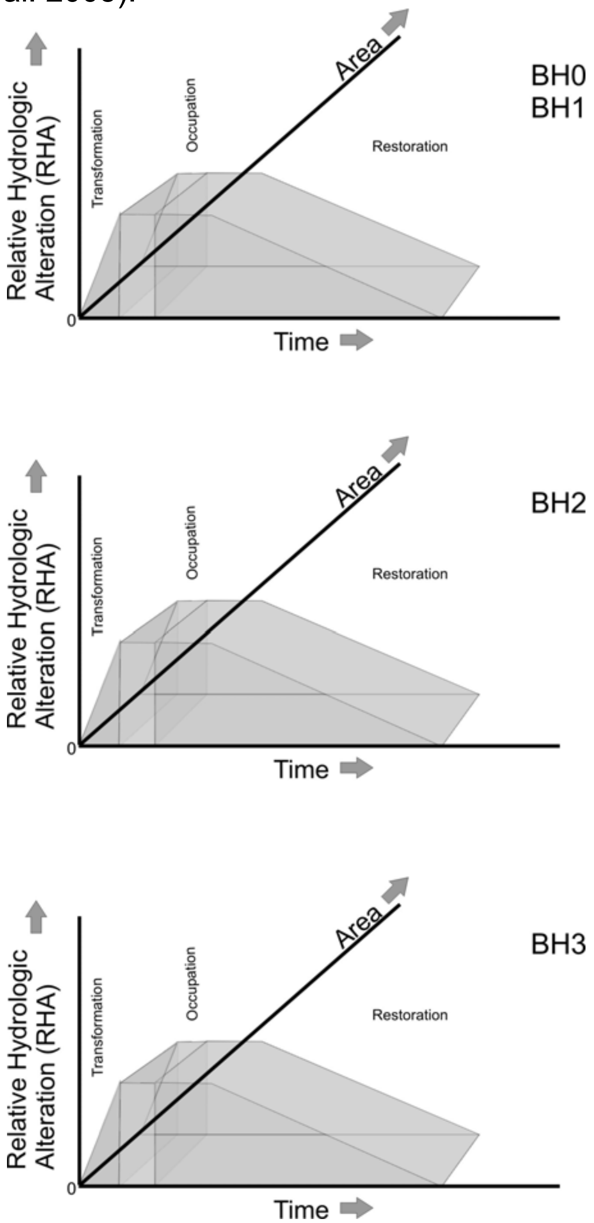

Figure 7 Relative change in water yield with area and time for the different harvesting scenarios.

Water yield is the term used to represent the total depth of annual runoff from a drainage basin, and there is strong evidence from the literature to suggest a general increase in water yield under all four scenarios (Figure 7) as a result of removal of the forest canopy and corresponding decreases in interception and evapotranspiration and increases in soil water and groundwater recharge.While we anticipate an increase in water yield under BH0/BH1 relative to the unharvested condition, we do not feel that the increase in harvested area under BH2 and BH3 would be sufficient to lead to a demonstrable increase in water yield beyond that for BH0/BH1. For all scenarios, we anticipate that increased water yield may persist for several years following Occupation before a decline is observed during the Restoration period. This is in contrast to the trends in *RHA* for the other hydrologic properties examined above, where we expect that *RHA* would begin to diminish shortly after Occupation had ended.

The issue of the potential impacts of forest harvesting on peak flows is a particularly contentious one in the hydrological literature, as noted earlier in this review. Figure 8 suggests that there would be a general increase in small to moderately sized peak flows under all four harvesting scenarios. We feel that such increases would largely be in the form of enhanced peak flows generated by snowmelt and rain-on-snow, as a result of removal of the forest canopy and corresponding increases in snow accumulation and melt, combined with generally wetter soils and greater extents of saturated areas that may generate surface runoff. Peak flows generated by rainfall would increase but to a lesser extent, since snowmelt and rain-on-snow inputs are generally responsible for annual maximum peak flow generation in forest landscapes in Ontario (Buttle and Metcalfe 2000, Buttle and Eimers 2009). It is important to emphasize that we anticipate that it will be the relatively small peakflows that may increase following harvesting, and that harvesting will not have a significant impact on extreme peak flows. This is consistent with observations from elsewhere (Buttle 2011). As in the case of water yield, we anticipate an increase in relatively small peak flow events under BH0/BH1 relative to the unharvested condition, with little additional increase under BH2 and BH3. As with water yield, we anticipate that the increase in peak flows may persist for several years following Occupation before a decline is observed during the Restoration period.

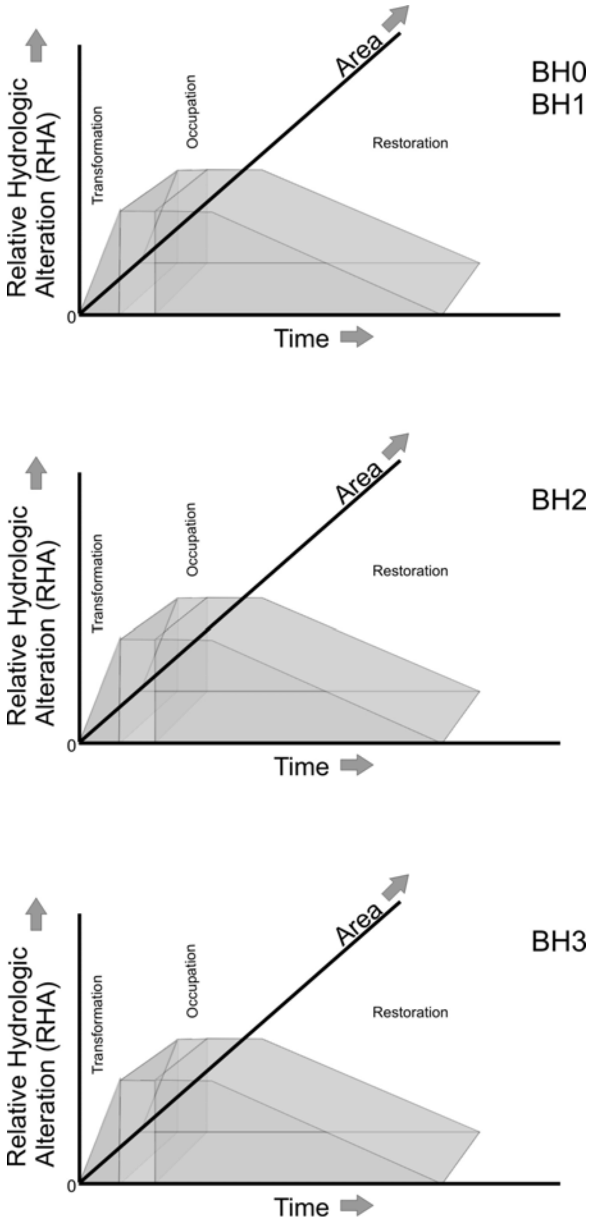

Figure 8 Relative change in peak flows with area and time for the different harvesting scenarios.

We have selected DOC concentrations in streamwater as an example of how a biogeochemical property might respond during the Occupation, Transformation and Restoration phases of a harvesting rotation (Figure 9).

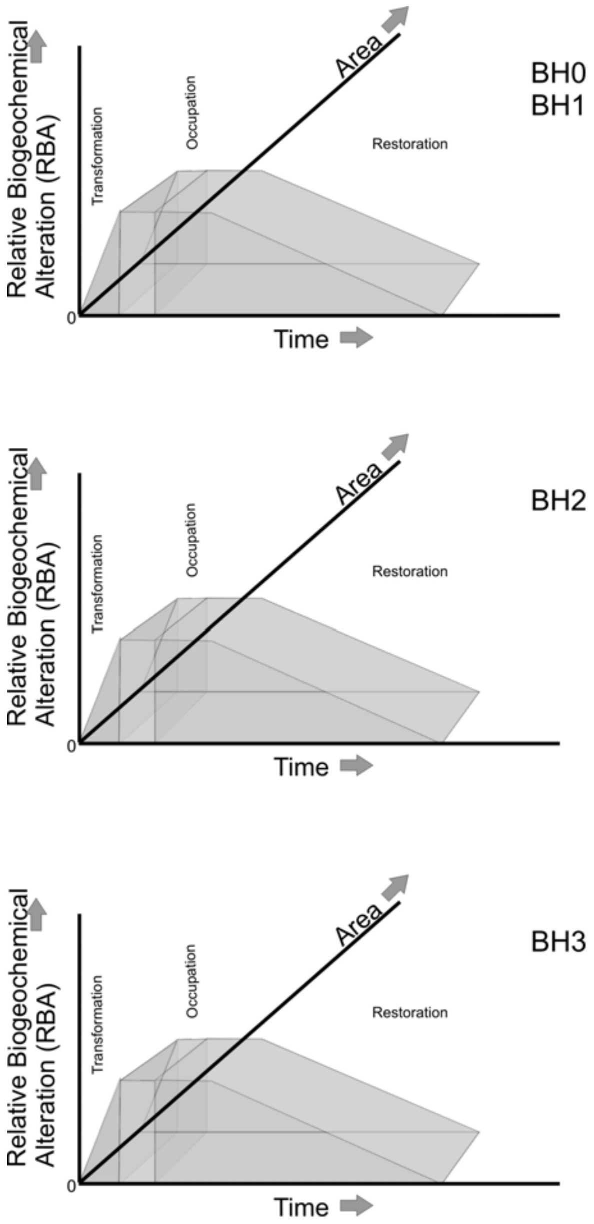

Figure 9 Relative change in DOC concentrations in streamflow with area and time for the different harvesting scenarios.

Harvesting under all scenarios is expected to increase DOC concentrations in receiving waters as a result of increased supply of organic residues (slash) to the forest floor combined with enhanced rates of decomposition. Increased concentrations are expected to persist for several years following harvesting (during the initial portion of the Restoration phase), followed by a decrease in concentrations during regeneration. We could find no conclusive evidence from the literature showing that the increase in DOC concentrations following harvesting is related to the intensity of harvesting. Therefore, we anticipate no significant differences in the temporal trajectory of *RBA* between the harvesting scenarios.

8.4. Knowledge gaps that must be addressed to incorporate this approach in LCA

There are several key knowledge gaps that require study before the comparative approach given in the previous section can be incorporated in a LCA of bioenergy production:

1. Determination of the absolute values of hydrologic and biogeochemical alteration under the various scenarios. Maes et al. (2009) presented an approach to assessing the impact of land use changes on the data on the amount of evapotranspiration from a given area, and this could be extended to other aspects of the hydrological and biogeochemical cycle in forest landscapes.
2. Testing of the validity of our suggested relative differences in response between scenarios for various hydrologic and biogeochemical properties. As noted in our discussion of knowledge gaps related to the hydrological and biogeochemical characteristics of the Atikokan region, there is a pressing need for empirical studies that examine how forest harvesting will affect water quantity and quality in this area. These studies would greatly help in testing our hypothesized changes in *RHA* and *RBA*; nevertheless, initial tests could be model based, using current hydrological models such as HBV (Lindström et al. 1997) and biogeochemical models such as INCA for carbon (Futter et al. 2007), nitrogen (Wade et al. 2006) and phosphorus and mercury (Wade et al. 2002). As Creed et al. (2011) note, such coupled monitoring – modelling approaches provide the best way to pose and answer “what if” questions regarding the consequences of forest management activities for water quantity and quality.
3. Characterization of how these properties behave during the Restoration phase of the *RHA* and *RBA* temporal trajectories. In particular, we require answers to the following questions: what is the total duration of the Restoration period for a given property? Does that duration increase with the magnitude of land transformation impact (Koellner and Scholz 2007)? What is the form of the trajectory of that change?

9. Summary and Conclusions

This report has reviewed the key hydrologic and biogeochemical impacts of forest harvesting, and specific impacts related to the four forest management scenarios for bioenergy production that we were provided. The potential effects of harvesting for bioenergy production on water quantity and quality appear to be similar in type and magnitude to those posed by conventional forest harvesting. Our confidence in predicting the relative impacts of this harvesting for the four harvesting scenarios is greater for aspects of water quantity than for biogeochemistry. Nevertheless, we caution that these predictions are based on experimental and monitoring results from forest landscapes that may differ significantly from that in the Atikokan region. Between-site differences in such aspects as climate, vegetation, geology and topography, as well as forest management practices such as season of harvest and equipment utilized, mean that we cannot predict absolute effects on hydrologic and biogeochemical properties for specific locations within the Atikokan landscape with confidence. The study results that form the basis of our review also have often been obtained at much smaller spatial scales than those that are used operationally in forest management. The potential for changes in the detectability and magnitude of hydrologic and biogeochemical impacts of harvesting on receiving waters needs to be borne in mind when attempting to predict the effects at a specific location or across a given area in the Atikokan region.

We have suggested a number of knowledge gaps that need to be addressed in order to increase our understanding of the hydrological and biogeochemical characteristics of the Atikokan region and their potential response to forest harvesting. Information on the role of these key processes and properties in controlling water quantity and quality in the Atikokan area is critical to the sustainable management of the region's forest and water resources. We have also suggested a number of indicators and verifiers that could be used to assess the environmental impacts of the harvesting scenarios in the Atikokan region and have argued for a land use approach to a Life Cycle Assessment of bioenergy production. This approach considers the temporal trajectory of the hydrologic and biogeochemical alteration of the landscape through the Transformation → Occupation → Restoration phases of a complete harvest rotation. It is important to note that the results of the "thought-experiments" we present in the context of these trajectories indicate that the increased intensity of harvesting that occurs moving from scenario BH0 to BH3 does not always result in an increase in the relative alteration of a site's hydrologic or biogeochemical properties. The magnitude of response to harvesting for various aspects of the region's water quantity and quality can differ dramatically, and this differential response needs to be considered explicitly when assessing the environmental consequences of bioenergy production in the Atikokan region. The hydrologic and biogeochemical studies that we feel are needed in order to address the knowledge gaps related to water quantity and quality in the Atikokan region will greatly assist both the prediction of the absolute magnitude of the impacts of bioenergy production and the testing of our hypothesized hydrologic and biogeochemical responses to the harvesting scenarios. Nevertheless, we feel that these studies should be conducted in concert with model-based predictions of ecosystem response to harvesting.

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