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Forest harvesting and hydrology in boreal Forests: Under an increased and cumulative disturbance context

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ABSTRACT

Boreal forests cover about one-third of the global forested area and are under rapid alteration due to increased natural and human-induced forest disturbance, which have important impacts on forest carbon cycling, hydrology, biodiversity, and many other ecological characteristics, processes, and functions. In this review, we focus on how forest harvesting affects hydrological processes in boreal forests within the context of increased and cumulative forest disturbance across various spatial scales. At the stand level, harvesting affects snow processes (i.e., snow interception, snow water equivalent, ablation, and snowmelt), decreases evapotranspiration (ET) and water use efficiency (WUE), and has negative impacts on soil dynamics (i.e., infiltration and soil moisture). These hydrological changes at the stand level can be counteractive or additive, cumulatively leading to more varied effects at larger spatial scales. In small watersheds, spring freshets (or high flows) are consistently increased following harvesting, while annual streamflow is often increased but some contradictory results are found in Siberia, Russia. These varied responses are likely dependent upon differences in energy budgets, climate, post-disturbance vegetation trajectories, and their dynamic interactions over space and time. For larger watersheds and regions, cumulative forest disturbance interacts with climate, leading to more complicated and varied hydrological responses. Forest management implications and future research topics are also suggested.

1. Introduction

The boreal forest, also known as the taiga, covers about one-third of the global forested area (Frelich and Kuuluvainen, 2021). Boreal forests are generally located in Canada, China, Finland, Norway, Russia, Sweden, and the United States, approximately between the latitudes of 50° to 65° N. Boreal ecosystems are dominated by vast forests, wetlands, and lakes with a broad circumpolar distribution (Kayes and Mallik, 2020). The climate of the boreal ecosystem is characterized by short summers and long, cold winters with most of the annual precipitation falling as snow. Dominant tree species are cold-tolerant and fire-adapted conifers, which can store carbon (Walker et al., 2019), purify air and water (Saarikoski et al., 2015), buffer flow extremes (Paavilainen and Päivänen, 1995), and regulate the climate (Ellison et al., 2017). Boreal forests also support local communities in terms of economic benefits and cultural values. For example, in Canada, boreal forests create jobs, offer tourism and recreational opportunities, and are culturally and economically significant to Indigenous people (Burton et al., 2006).

Boreal forests are sensitive to climate change and human activities. Climate warming has promoted tree disease and insect outbreaks, increased the likelihood of wildfire, and shifted evergreen trees toward deciduous trees (Bonan, 2008; Chapin et al., 2010), resulting in losses of boreal forest biomass. According to climate predictions, the boreal zone will have a rapid and considerable temperature increase from 4 to 11 °C by the end of 21st century (Gauthier et al., 2015), which can alter fire regimes and other natural forest disturbances (e.g., insect-attack,

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drought-related tree die-off) (Weber and Flannigan, 1997). These increased disturbances, along with human activities such as forest harvesting, road construction, and land conversion pose growing pressures on boreal forests. It is commonly understood that in large landscapes or watersheds, different types of forest disturbance accumulate and interact over space and time (Wei and Zhang, 2010; Scherer, 2011). This highlights that studying and managing the effects of forest harvesting in boreal forested watersheds must be conducted in the context of increased and cumulative forest disturbance, particularly when large landscapes or watersheds are included.

Changes in boreal forests (e.g., harvesting, wildfire) can lead to significant hydrological responses. Among all biomes, forest change in boreal zones has the considerable biogeophysical, hydrological, and ecological effects (Bonan, 2008). A global study conducted by Wei et al. (2017) suggested that 1% of forest change in boreal zones has a larger impact on annual streamflow (a 0.77% increment in annual streamflow) than in other biomes with an average increase of 0.66%. However, research findings on forest change and hydrological responses (e.g., response direction) in boreal regions are not consistent. For example, some studies (e.g., Goodbrand et al., 2022; Ide et al., 2013; Macdonald et al., 2003) showed that forest harvesting or disturbance in boreal regions can cause increased annual streamflow, while Hou et al. (2022) detected the opposite response. A recent review on forest change and hydrology in snow dominant regions (covering both boreal and temperate forests) by Goeking and Tarboton (2020) also concluded that there are large variations and even contrasted hydrological responses to forest disturbance. These inconsistent findings might be due to the differences in climate, disturbance severity, and spatial scale. With climate change and growing disturbance in boreal forests, it is important to summarize what we have learned to date so that we can design management strategies to minimize hydrological impacts and sustain healthy water.

Based on our knowledge, we are unaware of any published comprehensive reviews on forest harvesting and hydrology specifically focused on boreal forests and believe such a review is critically needed because: i) boreal forests cover a large area (14% of Earth’s land and 33% of Earth’s forested area) and have significant benefits, ii) forest production is important in boreal forests and forestry activities are increasing in boreal forests coupled with considerable natural (e.g., wildfire and insect infestation) and cumulative disturbances which likely affect hydrological processes (e.g., snow processes, groundwater recharge, infiltration, streamflow), and iii) the effects of forest harvesting and other disturbances on hydrological processes remain unclear in this biome despite of growing literature. The main aim of this review is to summarize what we have learned on forest harvesting and hydrological impacts in a disturbance context across various spatial scales (forest stands, small watersheds, and large watersheds or regions) and recommend practical management strategies and research needs for the protection of hydrological functions.

2. Forest disturbance: harvesting, natural, and cumulative disturbance

Natural forest ecosystems are continuously cycled by forest disturbance and post-disturbance recovery through successional processes. In boreal forests, harvesting, wildfire, and insect attack are three common disturbance types. At the stand level, harvesting and severe wildfires are considered as stand-replacing disturbances, removing the majority of tree stands. In contrast, insect attacks or drought-related die-offs are typically non-stand-replacing with the survival of non-target or understory vegetation, creating more diverse structures and layers. Non-stand-replacing disturbance causes a delayed or non-linear impact on hydrological processes as there is a lag between insect attack, tree death, needle fall, and the toppling of trees (McEwen et al., 2020). These three types of forest disturbance have different effects on forest stand structures and soil properties, and consequently various hydrological impacts (Zhang and Wei, 2012).

In large, boreal watersheds or landscapes, there are multiple types of forest disturbance (e.g., harvesting, wildfire, insect attack) occurring at different locations, severities, and times (Wei and Zhang, 2010). They cumulatively affect hydrological processes through the diverse combinations of forest age, species, stand structure, and recovery that they create across a landscape (Kuuluvainen et al., 2021; Sturtevant and Fortin, 2021). For example, the mortality caused by droughts or mountain pine beetle (MPB) infestation increases fuel loads, and consequently, leads to an increased likelihood of wildfire and altered wildfire behaviour (Dieleman et al., 2020; Kane et al., 2017). Thus, understanding how cumulative forest disturbance affects hydrology is critical at large watershed and regional scales. It also highlights that a broad disturbance context is needed for studying and managing the hydrological impacts of harvesting.

3. Forest harvesting and hydrology at the stand scale

3.1. Harvesting and snow processes

The forest canopy plays a major role in snow processes (e.g., snow accumulation and snowmelt) due to its influence on precipitation interception, radiation, and wind speed (Davis et al., 1997; Schelker et al., 2013). Precipitation interception refers to precipitation (rainfall or snowfall) that does not reach the ground (Gerrits et al., 2009; Levia et al., 2011) and evaporates or sublimates back to the atmosphere. Snowfall interception in boreal forests is particularly important for regional hydrological cycling because the streamflow regime is dominated by the spring freshet, which is driven by snowmelt (Buttle and Metcalfe, 2000). Up to 60% of cumulative snowfall can be intercepted by boreal forests and over 30% of annual snowfall can return to the atmosphere via sublimation (Pomeroy and Schmidt, 1993). As a result, removal of forests or changes in forest canopy can considerably reduce snow interception, and consequently alter snow dynamics.

Forest harvesting not only reduces snow interception, but also increases snow accumulation in boreal zones, often expressed as snow water equivalent (SWE). For example, Schelker et al. (2013) found that SWE increased by 27% on average in harvested sites following clear-cutting in Northern Sweden. Variations in SWE between harvested and undisturbed sites are dependent on the amount of annual snowfall (Talbot et al., 2006), the intensity and frequency of snowfall events (Strasser et al., 2011), canopy characteristics (Davis et al., 1997), and the severity and type of disturbance (Varhola et al., 2010; Goeking and Tarboton, 2020). In a comparison of SWE between harvested plots, grey-phase pine beetle attack plots, and undisturbed plots, Varhola et al. (2010) showed that clear-cut plots had the greatest peak SWE, followed by the grey-phase stands and then undisturbed plots.

Conversely, field observations in Russia indicated that SWE could decrease after harvesting. According to Onuchin (2015) and Onuchin et al. (2018), the influence of clear-cutting on the amount of snow depends on geographical location and the spatial alternation of harvested and undisturbed sites. In regions with a severely continental climate, strong wind causes blizzards on vast clear-cuts in the first few years after harvesting. These blizzards increase snow moisture evaporation and reduce SWE (Onuchin et al., 2021). Varhola et al. (2010) also found that wind is the main factor affecting snow redistribution since it can redistribute snow scoured from the centre of clear-cuts into the forest and deplete clear-cut snowpack via enhanced sublimation.

Forest disturbance increases snow ablation and snowmelt volume by changing the surface energy balance (Musselman et al., 2015). In disturbed sites, forest harvesting increases the amount of shortwave radiation reaching the surface of the snow and reduces the amount of longwave radiation (Woo and Giesbrecht, 2000). At the same time, canopy removal exposes the snow surface to greater solar radiation and higher wind speed, leading to increased sensible and latent heat exchange and altered snow ablation rates (Davis et al., 1997; Talbot et al., 2006). In addition, snow surfaces with organic debris (e.g., needles, barks, branches) have a lower albedo than debris-free snowpacks, and thus absorb more radiation and melt or sublimate faster (Gleason et al., 2013). Nevertheless, it is commonly expected that burned and clear-cut stands have higher ablation rates and snowmelt volume, while undisturbed stands have lower ablation rates and snowmelt volume (Ketcheson et al., 2012). For example, Ketcheson et al. (2012) found that clear-cut stands had a higher snow ablation rate (13 mm SWE/day) than forested stands (9 mm SWE/day) in the Bic-Saint-Fabien, Québec.

3.2. Harvesting and its effects on evapotranspiration and water-carbon coupling

3.2.1. Evapotranspiration

Evapotranspiration (ET) encompasses the movement of water to the atmosphere from the processes of evaporation (including sublimation) and transpiration. ET is driven by both climatic factors (e.g., temperature, solar radiation, humidity, vapor pressure deficit, and wind) and forest characteristics (e.g., tree species, tree ages, canopy density, and interception capacity). Transpiration accounts for $\sim 65\% \pm 18$ of total ET in boreal forest regions (Schlesinger and Jasechko, 2014). As forest disturbance changes the capability of vegetation to transpire and the physical characteristics of the site, it follows that forest disturbance could have a large effect on ET.

Studies have consistently found a net reduction in ET (25–40%) after harvesting in boreal regions (Liu et al., 2005; Mkhabela et al., 2009; Petrone et al., 2014; Rannik et al., 2002). Removal of the forest canopy results in higher soil evaporation and sublimation rates while also reducing evaporation of canopy intercepted precipitation (Amiro et al., 2006; Liu et al., 2005). However, the substantial drop in transpiration due to tree removal is usually large enough to offset any increased evaporative losses, leading to a net decrease in ET. ET reductions vary by tree species and disturbance types in boreal forests. A comparison in 50-year post-logging boreal sites found that transpiration rates in young birch and aspen stands were twice higher than in young fir stands (Burenina et al., 2012). Mkhabela et al. (2009) postulated that more diverse vegetation explained a consistently higher ET in burned (192 to 313 mm) compared to harvested boreal forest sites (117 to 194 mm).

Studies on less severe disturbances (e.g., non-stand replacing insect attacks, low-intensity wildfire, or partial cutting) show less consistent impacts on ET. The net effect on ET is variable and depends not only on the characteristics of the disturbance itself, but also on the characteristics of remaining forests (e.g., understory, productivity), as well as site and climatic conditions. Eddy covariance studies in partial cut and MPB attacked stands have found both a net decrease (e.g., 62% reduction in Meyer et al., 2017) or no change in ET (Brown et al., 2014; Mathys et al., 2013). In some cases, post-disturbance understory transpiration and soil fluxes have largely increased after non-stand replacing disturbances due to competitive release (Goeking and Tarboton, 2020), which could offset overstory ET losses.

3.2.2. Water-carbon coupling

During photosynthesis, CO_2 uptake and water loss occur simultaneously, linking terrestrial water and energy cycles through vegetation. This carbon and water coupling is often described by water use efficiency (WUE) as in Equation (1) (Niu et al., 2011).

$$\mathrm{WUE} = \frac{\mathrm{GPP\ or\ NPP\ or\ NEP}}{\mathrm{ET}} \tag{1}$$

where, WUE is water use efficiency, GPP is gross primary production, NPP is net primary production, NEP is net ecosystem production, and ET is evapotranspiration.

Research approaches used to study WUE at the stand level include isotopic analysis, eddy covariance, and modelling. Because eddy covariance measures carbon and water fluxes simultaneously, it has been commonly and widely used (Liu et al., 2017), providing important direct measurements to calibrate scaling-up methods (Xiao et al., 2008).

At the stand level in boreal forests, most studies show a reduction in WUE after forest harvesting, likely because significant levels of evaporation are maintained relative to a larger drop in growth (Mkhabela et al., 2009; Petrone et al., 2014; Volik et al., 2021). After harvesting, both GPP and ET are reduced significantly, with GPP close to zero immediately after harvesting as there is commonly little actively photosynthesizing vegetation left on the site. Although ET is also reduced, it is not reduced as much, partly because of the increased importance of evaporation from litter and soil in disturbed stands. This asynchronous response leads to lower WUE in young stands after harvesting at the stand level (Mkhabela et al., 2009; Petrone et al., 2014; Volik et al., 2021). Mkhabela et al. (2009) reported WUE values between 0.62 and 1.51 g C kg^{-1} water in harvested sites compared to 2.0–2.6 g C kg^{-1} water in undisturbed sites.

In contrast to harvesting, the limited number of studies of WUE following non-stand replacing disturbances such as insect defoliation or partial stand mortality in boreal forests find either a temporary reduction in WUE (Meyer et al., 2017), or no reduction at all (Brown et al., 2012). This is likely due to differences in both carbon and water dynamics as there generally is not the same increase in soil exposure and impact to understory or non-target vegetation, leaving more residual vegetation on the site.

Forest harvesting can alter the transport of carbon (e.g., dissolved organic carbon, DOC) in aquatic systems. In boreal Europe, the impacts of harvesting on DOC have caused very important environmental issues for downstream communities. For example, in Sweden, forestry activities considerably increase DOC with a 92% increment caused by clear-cutting and a 195% increment from site preparation (Schelker et al., 2012). Similar increases have been found in Finland that forestry operations promote DOC release (Kaila et al., 2016). The effects of harvesting on water quality are beyond the scope of this review, but it is a separate review in this special issue (Shah et al., 2022).

3.3. Harvesting and soil dynamics

Forest harvesting can considerably affect soil infiltration and thus soil moisture. Timber harvesting today is highly mechanised in boreal regions. A major consequence of machinery is soil compaction. The degree of compaction depends on ground pressure, vehicle vibration, soil parent material (soil type), stoniness, root mass and texture, soil water content, and the season in which harvesting occurs (Cambi et al., 2015; Toivio et al., 2017). Soil compaction results in reduced infiltration capacity and soil moisture, and an increase in the potential of surface erosion (Sutherland, 2003). In-suit measurements in boreal forests in Alberta, Canada found that soil compaction due to harvesting decreased hydraulic conductivity and infiltration rates during the first three skidding cycles (Startsev and McNabb, 2000). These negative impacts can be extrapolated to the watershed scale, subsequently impacting annual and seasonal streamflow.

Severe wildfires tend to volatilize waxes and oils from litter, which may condense soil particles, producing hydrophobic (water repellent) conditions in soil surfaces which in turn, reduce infiltration, and increase surface runoff and soil erosion (Kettridge et al., 2014). In addition, losses of forest canopy and floor materials after severe wildfires can promote more energy for increasing soil evaporation. This, along with limited soil infiltration and soil water recharge due to hydrophobicity of soils can cause lower soil moisture (Holloway et al., 2020).

4. Forest harvesting and hydrology in small watersheds

4.1. Effects of forest harvesting on streamflow

Changes in hydrological processes at the stand level can be counteractive and additive, producing varied effects on streamflow at larger spatial scales. In small watersheds, paired watershed experiments (PWEs) have long been used to assess the streamflow responses to forest harvesting. Relative to PWEs in temperate and tropical forests (Bosch and Hewlett, 1982; Brown et al., 2005; Stednick, 1996; Zhang et al., 2017a), fewer studies using PWEs have been conducted in boreal forests, and they are mainly in Sweden (Löfgren et al., 2009; Rosén et al., 1996), Finland (Ide et al., 2013), and Canada (Goodbrand et al., 2022; Macdonald et al., 2003; Monteith et al., 2006; Swanson et al., 1986; Swanson and Hillman, 1977). The summarized results below are based on PWEs and the studies of long-term monitoring or observations. Modelling-based research on the relationship between forest harvesting and streamflow is not included in this review.

The results from PWEs in both Canada and Sweden consistently reported increased annual streamflow and spring freshets (peak flows or high flows) after forest harvesting (Macdonald et al., 2003; Monteith et al., 2006; Sørensen et al., 2009). The increased solar radiation and ablation in the harvested sites would lead to more rapid and earlier melt processes, and thus higher peak flows are expected. For example, following forest harvesting in the Baptiste Creek, Canada (approximately 55% of tree removal in two treatment watersheds), a 59–61% increase in spring flows (peak snowmelt and total freshet discharge) and a 5–14 day advancement in peak flows were detected in the B5 stream (Macdonald et al., 2003). Similar results on streamflow increments after harvesting were also found in the Tri-Creeks experimental watershed, Canada (21–60% in peak flows and 3–18% in annual streamflow; Goodbrand et al., 2022) and Balsjö catchment in Sweden (54–68% in peak flows and 34–36% in annual streamflow; Sørensen et al. 2009) with >50% and 30% of the watersheds disturbed, respectively.

In Canadian boreal forests, much of the research has been done by the Global Energy and Water Cycle Experiment (GEWEX) and the Boreal Ecosystem-Atmosphere Study (BOREAS). These field observations aim to investigate the impacts of forest harvesting or regeneration on soil erosion, snowmelt rate and timing, evapotranspiration, sublimation, snow accumulation, and streamflow (Buttle et al., 2009), and fields are mainly established in Alberta (Granger and Pomeroy, 1997), Saskatchewan (Stewart et al., 1998), Yukon (Rasouli et al., 2019), Northwest Territories (Spence and Hedstrom, 2021), and Ontario (Webster et al., 2021). In addition to GEWEX and BOREAS, some work has also been conducted in the boreal forests in Quebec (Tremblay et al., 2008; Plamondon and Ouellet, 1980). By comparing hydrological processes in clear-cut, regeneration, and openings, it is found that harvesting consistently increases peak flows and annual streamflow (Buttle et al., 2009; Guillemette et al., 2005), which is consistent with PWE findings.

In Russia, researchers found some contradicting responses of annual streamflow to harvesting based on their observations. For example, the studies conducted in the dark-needled conifer forest of the West Sayan Mountains in Siberia show that 50% logging increased annual streamflow more than twice in the first year following harvesting (Burenina et al., 2012). However, in watersheds with severely cold winters, forest harvesting results in increasing snowstorms and snow evaporation, and consequently decreases annual streamflow (Onuchin et al., 2021).

4.2. Effects of forest harvesting on groundwater-surface water interactions

Understanding groundwater-surface water (GW-SW) interactions in boreal forested watersheds can greatly improve our knowledge of flow regimes, flow pathways, water retention, and biological or ecological implications for fish, stream water chemistry, algae productivity, or invertebrate assemblages (Caschetto et al., 2014; Hayashi and Rosenberry, 2002; Larocque and Broda, 2016; Williams, 1993). Currently, researchers rely on indirect relationships or related hydrological processes (e.g., decreased interception, decreased transpiration, and changes in infiltration rates and groundwater recharge) to determine how forest harvesting may affect GW-SW interactions in boreal regions. Some studies in boreal forests and peatlands have shown that forest harvesting can increase the water table (Carrera-Hernández et al., 2011; Finnegan et al., 2014; Henriksen and Kirkhusmo, 2000; Marcotte et al., 2008; Jutras et al., 2006), which has the potential to change GW-SW interactions. However, results depend on landscape positions, soil type and texture, soil and till depth, and current and previous climatic conditions (wet vs dry periods) (Devito et al., 2012; Ferone and Devito, 2004; Thompson et al., 2018). For instance, Thompson et al. (2018) showed that aspen harvesting in Alberta's boreal forest did not significantly increase GW levels due to dry conditions and deep glacial till with a large moisture storage capacity. Conversely, simulations of aspen harvesting in the same region during wet conditions could result in 1.0–3.5 m of water table rise and a lag in water table response of 1–5 years (Carrera-Hernández et al., 2011).

Changes in hydrological regimes following forest harvesting, such as increased or decreased low flows, increased peak flows, and possible shifting of seasonal flows (Guillemette et al., 2005; Moore et al., 2020; Schelker et al., 2013; Sørensen et al., 2009) could be an indication of increased or decreased GW-SW interactions. Further, changes in streamflow could, in turn, directly impact GW-SW interactions due to the influence of stream discharge on hyporheic exchange (Mojarrad et al., 2019). Forest harvesting could also influence GW-SW interactions indirectly through changes in the stream morphology (e.g., aggradation of the stream channel), increased sediment erosion, increased fine sediment, clogged pore spaces, decreased large wood recruitment, and increased nutrients and biological activity (Conant et al., 2019; Harvey and Bencala, 1993; Moore and Wondzell, 2005; Wondzell and Swanson, 1999).

Forestry roads have the potential to impact GW-SW interactions through the interception of precipitation on the road surface or the interception of subsurface flow pathways (Moore et al., 2020; Moore and Wondzell, 2005; Smerdon et al., 2009; Wemple and Jones, 2003). Forest roads are generally more compact than the surrounding soils, which could result in overland flow of precipitation and the redirection of runoff to ditches, culverts, and streams rather than the infiltration and recharge of precipitation. Groundwater has the potential to become surface water if subsurface flow pathways are intercepted by forestry roads, and once again get redirected into the stream. However, it is also possible that ditch water may be redirected into forest soils rather than directly into streams, which would allow that water to infiltrate back into the subsurface (Moore et al., 2020; Moore and Wondzell, 2005; Smerdon et al., 2009; Wemple and Jones, 2003). While most studies on forestry roads have been conducted in steep mountainous regions, it is possible that roads could impact subsurface flow in boreal regions with less relief, although this would largely depend on the location of the road with respect to groundwater flow pathways, local topography, and local geology (Smerdon et al., 2009).

4.3. The role of watershed properties

Understanding the role of watershed properties (e.g., watershed size, topography, geology, soil) in regulating hydrological processes is an important but challenging task in hydrological science (Jencso and McGlynn, 2011; Julian and Gardner, 2014; Kirchner, 2003; Li et al., 2018; Tetzlaff et al., 2015). In boreal regions, some studies have reported how watershed properties control low flows. For instance, Karlsen et al. (2016) showed that specific discharge during the summer low-flow period increased with catchment area and the fraction of area characterized by deeper sediment deposits in the Krycklan basin in Sweden. The significant role of watershed properties in low flows is understandable as low flows are mainly associated with soil infiltration and groundwater recharge where soil properties, topography, and geology often play an important role. In addition to low flows, Devito et al. (2017) found that the poor surface-drainage networks and greater regional slope of the fine-textured glacial deposit led to small long-term runoff coefficients in a boreal plain catchment in Alberta, Canada.

Watershed properties can also affect the forest-streamflow relationship. In two recent global reviews on the effects of forest cover change on annual streamflow, Zhang et al. (2017a) and Li et al. (2017) demonstrated that larger watersheds are more resilient to hydrological changes caused by forest disturbance as larger watersheds often include diverse land uses and landforms. Similarly, using the Budyko framework and the global datasets, Zhou et al. (2015) found that watershed size, slope, and forest cover play a significant role in the forest-runoff relationship. Thus, understanding the roles of watershed properties can enhance our knowledge in explaining the effects of forest change on hydrology. However, the role of watershed properties in forest changes and hydrological responses is poorly understood in boreal forests, with limited research.

5. Cumulative forest disturbance and hydrology at large watersheds or regional scales

5.1. *Cumulative forest disturbance and streamflow*

In large, boreal watersheds, the effects of cumulative forest disturbance on annual streamflow can be positive, negative, or insignificant. For example, Zhang and Wei (2014) compared annual streamflow responses to cumulative forest disturbance (>25%) in the Willow and Bowron watersheds in sub-boreal region, Canada, and found that Bowron did not show any statistically significant relationships between annual streamflow and cumulative forest disturbance, while cumulative forest disturbance significantly and positively correlated to annual streamflow in Willow. Recently, Hou et al. (2022) detected significant reductions in annual streamflow (42–44 mm) caused by cumulative forest disturbance in two boreal forested watersheds in northern British Columbia, Canada. These reductions might be due to increased ET as a result of the cumulative replacement of fast-growing pioneering species following MPB infestation.

Cumulative forest disturbance can also increase high flows (spring freshets), while the impacts on low flows are inconsistent in large, boreal forested watersheds. For example, in Canada, cumulative forest disturbance significantly increased high flows in the Moffat, Baker (154%), and Willow (65%) watersheds (Zhang, 2013). However, low flows were significantly increased in the Baker (163%) watershed, while insignificant changes were observed in the Moffat and Willow watersheds (Zhang, 2013) as well as in some watersheds in Ontario (Buttle and Metcalfe, 2000). Recent reviews have also confirmed that high flows consistently increased after forest disturbance (Goeking and Tarboton, 2020), while positive, negative, and insignificant effects on low flows have been reported (Moore et al., 2020).

Cumulative forest disturbance in larger watersheds often occurs gradually with a mix of disturbance types and desynchronized recovery processes, which is likely to produce a complex hydrological response (Zhang et al., 2017b). The buffering effect of diverse topography, forest types, and climate may also contribute to the more muted effects on annual streamflow (Li et al., 2018; Giles-Hansen and Wei, 2022). Forest disturbance at higher elevations can synchronize the timing of snowmelt between low and higher elevations, thus resulting in more pronounced impacts on high flows (Zhang, 2013).

5.2. *Cumulative forest disturbance and carbon–water coupling*

In large boreal forested watersheds, WUE estimates are mainly based on modelling and remote sensing. Understanding the effects of cumulative disturbance and recovery on GPP, NPP, and ET is essential for accurate predictions of carbon storage and water yield in large boreal forested watersheds or regions (Clark et al., 2014). For large watersheds and regions, MODIS-based models of GPP, NPP, and ET have been widely utilized to investigate regional spatial and temporal changes in WUE (Sun et al., 2016).

In comparison to the stand level, where WUE is normally reduced after harvesting, WUE at large scales does not show such a consistent response, highlighting that landscape-level dynamics may not mirror those at a finer scale (Giles-Hansen, 2021).

WUE is affected by both biological and environmental factors, and so it follows that the change in WUE also depends on the type of climate in which it occurs (Tian et al., 2010). In boreal forests, there is an emerging recognition that the effects of forest disturbance on WUE are variable, depending on disturbance type, climate and site conditions, and dynamics of vegetation recovery. For example, Beaulne et al. (2021) found paludification reduced black spruce growth but did not alter WUE in the south of James Bay in Eastern Canada. At the regional scale, there may also be variable responses, reflecting landscape diversity in these influencing factors. A recent study (Giles-Hansen, 2021) in the central interior of British Columbia (about 400,000 km^2, sub-boreal region) showed large differences in the change in WUE from cumulative disturbance across regional climatic gradients. In drier climates, WUE decreased, driven by a higher sensitivity of NPP to forest disturbance than ET (−20%). However, in moderately wet climates, a higher sensitivity of ET to forest disturbance causes WUE to increase with cumulative forest disturbance (+12%). Very wet climates did not show a significant change in WUE with cumulative forest disturbance.

5.3. *The interactive roles of climate variability and cumulative forest disturbance in annual streamflow*

5.3.1. *Case studies in British Columbia, Canada*

Climate variability and cumulative forest disturbance are two major drivers that affect hydrological processes in large, boreal forested watersheds (De Niel and Willems, 2019; Wei et al., 2017). Researchers have often separated their relative contributions to annual streamflow to quantify their individual roles as well as their combined effects in large watersheds. For example, Hou et al. (2022) found that cumulative forest disturbance played a considerably greater role in annual streamflow variations with the average of 77.3% than climate variability (22.7%) in the Osilinka and Mesilinka watersheds situated in the northern British Columbia (boreal region). However, in some watersheds (Baker, Moffat, and Willow) located the central interior of British Columbia (sub-boreal region), Zhang (2013) found that relative contributions of cumulative forest disturbance and climate variability were quite similar, with the average value of 50.8% and 49.2%, respectively. These results demonstrated large variations in hydrological responses to cumulative forest disturbance and climate variability in boreal or sub-boreal regions.

It is important to highlight that cumulative forest disturbance and climate variability can produce offsetting or amplifying effects on hydrology due to the difference in their impact directions. For example, several studies in boreal forested watersheds have identified offsetting effects of these two drivers on annual streamflow (Wei and Zhang, 2010; Zhang and Wei, 2012; Zhang et al., 2017b). The offsetting effects on streamflow can stabilize water resources and maintain water supply downstream (Khoi and Suetsugi, 2014). Amplifying impacts on annual streamflow have also been detected. For example, both climate variability and cumulative forest disturbance simultaneously decreased annual streamflow in the Osilinka and Mesilinka watersheds (Hou et al., 2022). This amplifying effect can likely lead to increased drought severity and frequency.

Despite limited studies, these case studies from British Columbia, Canada clearly suggest that forest and watershed managers need to consider the individual strengths of these two major drivers (climate variability and cumulative forest disturbance) as well as their combined effects in terms of both magnitude and direction.

5.3.2. *Case studies from Siberian region, Russia*

In the taiga zone of Siberia, the main forest disturbance type is large-scale clear-cutting (Onuchin and Burenina, 2000). A modelling study on the dynamics of streamflow of nine rivers of Central Siberia whose catchments are located in three natural zones (forest tundra, northern and middle taiga) showed that at high latitudes, increased forest cover increased streamflow, whereas in the down south it had the opposite effect (Onuchin et al., 2017). This suggests that the influence of logging areas on streamflow varies between Siberian landscapes and climate.

Since forest recovery changes vegetation structurally following clear-cutting, hydrological responses are determined not only by climatic changes, but also by vegetation succession trajectories. This implies a wide range of possibilities as to moisture redistribution between ET and streamflow in response to forest disturbance, even under homogeneous geographical conditions (Onuchin et al., 2017). For example, the research in three large watersheds within the Angara River basin (Onuchin et al., 2006) showed that streamflow decreased over the 20-year study period starting in the early 1960s due to harvesting which increased wind exposure and consequently increased snow moisture evaporation. However, since 1975, streamflow for these three rivers has tended to increase. This was due to increased areas of secondary young stands, which accumulated snow more efficiently than recent clear-cuts and coniferous stands, and thereby increased streamflow. Despite limited research, existing studies have demonstrated varied and even contrasted hydrological responses to forest disturbance in the Siberian region, based on differences in snow dynamics.

6. Management implications and research needs

Forest disturbance affects both water quantity and water quality. In this paper, we have focused on water quantity only, while the effects on water quality are reviewed in Shah et al. (2022) (this special issue). A visual summary of the key processes and results of this review is provided in Fig. 1. Stand-level research often helps us understand the processes and associated mechanisms, while studies at the larger spatial scales (e.g., large watersheds or regions) address cumulative effects. As shown in Fig. 1, more consistency in hydrological responses to forest harvesting or disturbance has been found at the stand level. As the scale of study increases, there is less consistency with larger differences and even contrasted responses likely due to more interactions or interplays of various contributing factors (e.g., watershed properties, climate, different forest dynamics across landscapes).

6.1. *Management implications*

Forest harvesting in boreal regions can significantly affect hydrology through the change in soil processes (e.g., infiltration rates) and GW-SW interactions due to soil compaction. At the operational level (forest stands and small watersheds), logging machines with broader wheels or tracks and using brush mats (the remaining woody debris from harvested trees) can help reduce the ground pressure and thereby reduce the risk for soil compactions (Ilintsev et al., 2021; Ring et al., 2021). Other solutions involve digital planning tools to optimise terrain transport. For example, the planning tool BestWay integrates depth-to-water (DTW) maps, slopes, standing tree volume, transport distance, and the number of possible landings (Flisberg et al., 2020). Such tools based on LiDAR scanning and digital terrain models are used to identify sensitive areas to be avoided during forest operations and thereby reduce the risk of damages (Hoffmann et al., 2022). Further development of these tools includes locating biogeochemical hotspots, as well as landscape heterogeneity and structures for biodiversity.

This review shows that forest disturbance and post-disturbance vegetation trajectories play an important role in stand-level snow dynamics and snowmelt, and consequently streamflow in the watershed scale. However, these connections are dependent on local site conditions and climate. Although forest disturbance can commonly increase SWE and snowmelt, local climatic conditions (e.g., blizzards caused by strong wind) may reverse the impacts. As snow hydrology is a dominant component of the water budget in boreal landscapes, a careful design of forest dynamics and landscape patterns according to local sites and climate conditions would allow a good regulation and management of energy budget and snow dynamics for desired hydrological processes and functions.

The design of forest management strategies for sustaining water supply and minimizing hydrological risks (typically with large watersheds and landscapes) must consider cumulative forest disturbance and their post-disturbance vegetation recovery dynamics. In addition, this review clearly demonstrates that it is essential to consider the interactive roles of forest disturbance and climate over a long period of time for managing and protecting water resources and functions in boreal forested watersheds. Forest and watershed managers need to consider

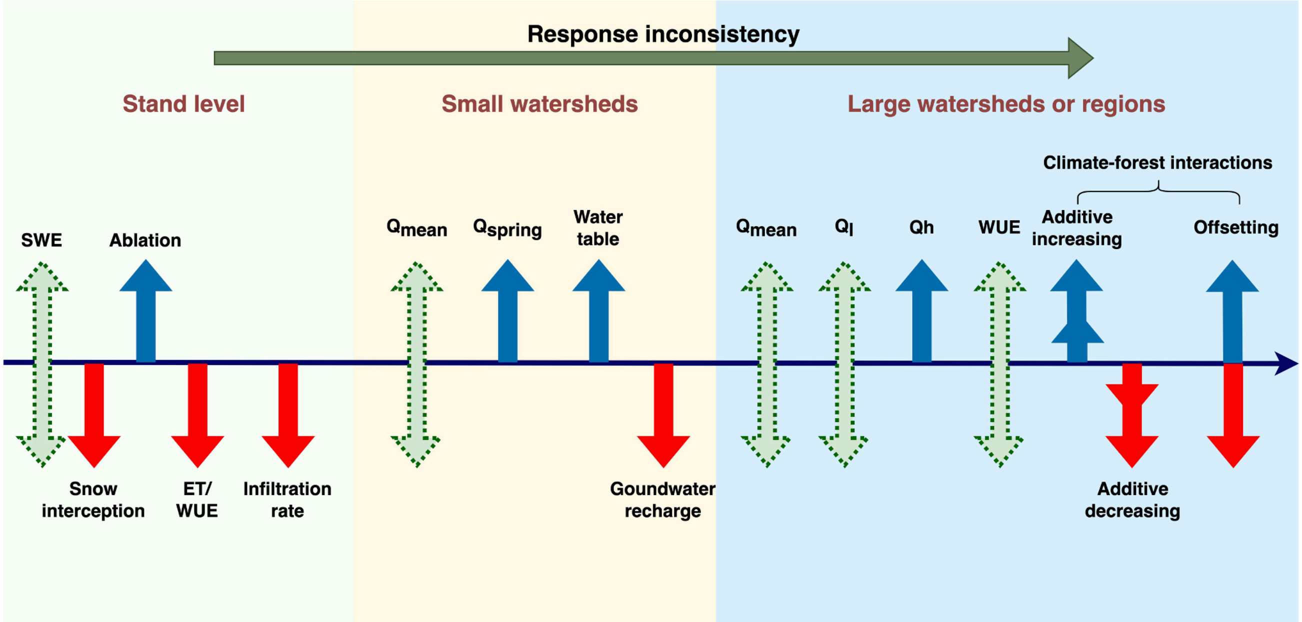

Fig. 1. A visual summary on effects of forest harvesting (or cumulative forest disturbances) on hydrological processes at stand level, small watersheds, and large watersheds or regions ($>$1000 km^2) in boreal forests. Note: WUE, ET, and SWE refer to water use efficiency, evapotranspiration, and snow water equivalent, respectively; Q_{mean}, Q_{spring}, Q_{l}, and Q_{h} denote annual mean flow, spring flow, low flow, and high flow, respectively.

these two major drivers as well as how their interactions may affect hydrological processes in terms of both magnitude and direction over time to ensure satisfactory hydrological functions and services in boreal forests.

Results on cumulative forest disturbance and WUE can be used to guide regional-level strategies that need to consider the potential trade-off between gain in forest productivity and conservation of water resources (Gao et al., 2014). To date, there are few studies examining the effects of long-term cumulative forest disturbance on WUE at the landscape level, and more studies are needed at the appropriate temporal and spatial scales to inform ecosystem and water management. In addition, trade-off analyses should also be implemented to consider different responses of hydrological variables as shown in Fig. 1.

6.2. *Research needs and future priorities*

This review also identified the following significant research gaps and future research needs are required.

Snow hydrology is central to our understanding of the forest-water nexus in boreal regions. Despite extensive research at the stand level, our review shows that there are large variations or even contradictory conclusions in forest changes and snow processes at small, large, and regional scales. The large variations are likely associated with differences in disturbance type, climate, and spatial scale. More research is needed on snow hydrology (e.g., SWE, snowmelt) with consideration of interplays of various contributing factors across different spatial scales. More research is needed to explain contradicting findings in Russia.

Although boreal forests have a relatively uniform and flat topography, research has shown that some watershed properties such as watershed size, slope, and aspect in upland watersheds or some sub-boreal regions can play an important role in the forest-streamflow relationship. This is mainly due to their effects on the distribution of radiation energy and consequently sublimation and snowmelt process. Thus, further understanding of how watershed properties influence hydrology at different spatial scales can enhance our knowledge in explaining the effects of forest change on hydrology in boreal forested watersheds.

The difference in scale between forest harvesting across the local reach and watershed scale GW-SW interactions, heterogeneity of soils and geology, unknowns about aquifer-surface water connectivity, and other complexities make it difficult to develop generalizations for forest practitioners. Questions remain regarding dynamic changes in GW-SW interactions, flow pathways, and residence time which can be evaluated by geochemical tracing, isotopes, and modelling. Direct studies on the effects of forest harvesting on GW-SW interactions are needed globally across boreal forests under a variety of geologic and climatic conditions before generalizations can be made for forest management. These studies will be critical for understanding future water supply and potential risks of droughts under future climate change and increased forest disturbance.

While the effects of cumulative forest disturbance on flow magnitudes (i.e., annual mean, high, and low flows) have been discussed in this review (Section 5.1), its impacts on other flow regime components (i.e., return period, duration, timing, and variability) have been rarely studied. Cumulative forest disturbance can significantly affect not only flow magnitudes but also various other flow regime components, which may produce negative consequences for aquatic function and ecosystem services. A comprehensive understanding of flow regime alterations due to cumulative forest disturbance is essential for watershed management decisions in boreal forests. Such understanding helps design sustainable management strategies with respect to water and protecting aquatic ecosystem functions.

Changes in ET from forest disturbance are important considerations of forest management, where the associated potential impacts such as flooding, altered water supply, or increased risk of environmental damage are a concern. At relatively large scales, it can also affect precipitation recycling (Ellison et al., 2012) and thus local and down-wind directional moisture inputs (Creed et al., 2019). Further analysis of seasonal ET and how ET changes in boreal forests affect precipitation recycling will help to identify mechanisms, explain inconsistent findings, and solidify a theoretical description of how forest disturbance and climate interact to affect hydrology in boreal forests.

7. Conclusions

Due to the large land base and growing forest disturbance, understanding and sustainably managing boreal forests can greatly support our ability to meet the UN Sustainable Development Goals (SDG) by 2030 and carbon neutrality commitments by 2050. This review highlights that studying and managing harvesting effects in boreal forests must be placed in the context of increased and cumulative forest disturbance. It also demonstrates that with increasing spatial scales (from stands to large landscapes), there are larger inconsistencies in hydrological responses to harvesting or cumulative forest disturbance. Design of forest management programs such as harvesting or climate change mitigation and adaptation must therefore consider historic forest disturbance and recovery trajectories, watershed properties, local climate conditions, and their interactions. As different forest operations and long-term management programs lead to different combinations of influences, optimization of forest management to address these many different outcomes are difficult. A better understanding of specific influences, such as the hydrological influences reviewed and recommended in this review, is a step along the way to ensure healthy and functional boreal forests under future climate change.

CRediT authorship contribution statement

Xiaohua Wei: Conceptualization, Writing – original draft. **Krysta Giles-Hansen:** . **Sheena A. Spencer:** Writing – original draft, Writing – review & editing. **Xiaowen Ge:** Writing – original draft, Writing – review & editing. **Alexander Onuchin:** Writing – original draft, Writing – review & editing. **Qiang Li:** Writing – original draft, Writing – review & editing. **Tamara Burenina:** Writing – original draft, Writing – review & editing. **Aleksey Ilintsev:** Writing – original draft, Writing – review & editing. **Yiping Hou:** Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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