



OPEN Windthrow in riparian buffers affects the water quality of freshwater ecosystems in the eastern Canadian boreal forest

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Despite the wide application of riparian buffers in the managed boreal forest, their long-term effectiveness as freshwater protection tools remains unknown. Here, we evaluate windthrow incidence in riparian buffers in the eastern Canadian boreal forest and determine the effect of windthrow on the water quality index of the adjacent freshwater ecosystems. We studied 40 sites—20 riparian buffers, aged 10 to 20 years after harvesting and 20 control sites within intact riparian environments—distributed among clay and sandy (esker) soils and black spruce (*Picea mariana*) and jack pine (*Pinus banksiana*) stands. We observed more windthrow in the harvested stands (36%) relative to the control sites (16%), regardless of substrate and species. We determined that the most important factors explaining windthrow were exposition, harvesting, aquatic environment size, and stand characteristics. These factors drive wind exposure, speed, and force, which determine post-harvest windthrow risk. Furthermore, windthrow negatively affected the water quality index of the adjacent aquatic systems, i.e., greater windthrow decreased the protective effect of the riparian buffer. We recommend increasing the use of partial harvest near riparian environments and adapting riparian buffers to site conditions to ensure the long-term protection of adjacent freshwater ecosystems.

Keywords Boreal forest, Ecological interactions, Natural disturbances, Sustainable forest management, Silviculture, Water quality

The boreal biome represents one-third of the Earth's forested area^{1,2} and also contains the greatest proportion of freshwater in the world^{3,4}. The boreal forest provides a major sustainable source of timber and energy^{5,6}, and two-thirds of boreal forest area is managed, inducing anthropic pressure on forest and aquatic landscapes^{1,3,7,8}.

Using mechanized equipment for forest harvest can negatively affects freshwater ecosystems by disturbing the surrounding watershed's substrate and plant coverage^{5,9,10}. Ruts and compacted soils are common in post-harvested areas, diminish the water retention capacity of the soil, and increase rainfall overflow into freshwater ecosystems^{11–13}. The resulting erosion and leaching of the soils lead to greater sedimentation and nutrient input into freshwater bodies, negatively affecting water quality^{9,14–17}. However, other studies have also shown neutral or no significant impacts^{18,19}. These negative effects can be mitigated by riparian buffers, strips of preserved forest of a defined width that surround water bodies in areas subjected to forest harvesting^{20,21}. This freshwater preservation tool attempts to provide a forested buffer between a harvested area and an aquatic environment, thus ensuring soil retention in the riparian ecotone^{12,22}. However, riparian buffers are subject to increased windthrow risk, especially those as narrow strips (i.e., 15 m or less); this disturbance is a major challenge for ensuring the long-term preservation of aquatic ecosystems^{21,23,24}.

Windthrow vulnerability is a complex phenomenon, involving climatic^{25,26}, topographic^{27–31}, silvicultural^{26,32–34}, substrate^{35–37} and stand factors at multiple scales^{26,28,38,39}. Climate and topography influence windthrow risk by affecting wind speed^{27,28,40}. A greater topographic exposition leads to higher wind speeds and

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an increased applied force on the tree stems, favoring windthrow^{27,39,41–44}. Harvesting practices modify windthrow dynamics, as a larger harvested zone favors higher wind speeds produced by the downdraft effect in open areas^{27,29,30,34,45}. A lower post-harvest stand density limits the protection and support effect of neighboring trees (edge effect) and decreases the wind dispersion capability in the riparian buffer^{34,39,46,47}. Substrate characteristics also affect windthrow risk by influencing root anchorage and roots' growth rates^{36,37,48,49}. Trees are less sturdy when they have shallower and less extensive root systems and, thus, are more prone to windthrow. Finally, stand characteristics, such as stand species, age, and slenderness, influence windthrow risk. For example, black spruce (*Picea mariana*) is vulnerable to windthrow because of its superficial root system and a higher height/diameter at breast height (DBH—which represents the diameter of the tree at a height of 1.3 m) (slenderness) ratio^{32,38}. In contrast, jack pine (*Pinus banksiana*) has deep taproots that improve root anchorage, leading to relatively less windthrow^{36,38}. Slenderness is an important variable in windthrow management, as it informs on the surface area of the stem (height) relative to its structural sturdiness (DBH). For example, high slenderness stands have a greater energy transfer between the wind and stem, and the trees have a lower structural strength; the result is increased windthrow and breakage^{32,41}.

Windthrow negatively affects freshwater ecosystems by increasing the amount of large woody debris in the riparian zone, compared to the natural rate of dead wood found in forest without anthropogenic intervention^{21,50–52}. This new addition of large woody debris leaches carbon and nutrients into the water at an increased rate, thus causing negative effects^{21,50,53}. Furthermore, windthrow diminishes the number of roots and the extent of root anchoring in the riparian buffer, thus reducing its water and soil retention capacity^{40,53}. Lower soil retention allows terrestrial nutrients and carbon to be washed into adjacent water bodies. This material is then decomposed, which consumes the available oxygen in the water, thus negatively affecting water quality for fishes, amphibians, and aquatic insects⁵⁴.

Here, we evaluate windthrow in riparian buffers of the eastern Canadian boreal forest and assess its impact on boreal freshwater quality 10 to 20 years after a clearcut. Specifically, we aim to (1) determine the effect of tree species and substrate on windthrow in riparian buffers; (2) evaluate environmental, silvicultural, topographic, and climatic factors affecting windthrow in riparian buffers; and (3) analyze the relationship between windthrow and water quality in freshwater ecosystems.

Results

Mortality and windthrow in riparian buffers

Riparian stands, regardless of treatment, had a mean mortality (standing dead trees and windthrows combined) of 28%. Mean windthrow doubled in riparian buffers (36%) and was significantly higher ($p < 0.001$) than in the controls (16%). Windthrow accounted for 76% of on-site mortality; the remaining portion was standing dead. Substrate and species also significantly affected windthrow ($p < 0.001$, Fig. 1). Esker sites (regardless of treatment and stand species) experienced significantly higher mean windthrow occurrence (35%) than clay sites (28%). We also observed a significantly higher windthrow occurrence in jack pine stands (36%) than in black spruce stands (28%). From 3480 tree observations, the GLM analysis confirmed that species, substrate, forest harvesting (treatment), and the interaction between them all had a significant relationship with windthrow ($p < 0.05$, Fig. 1);

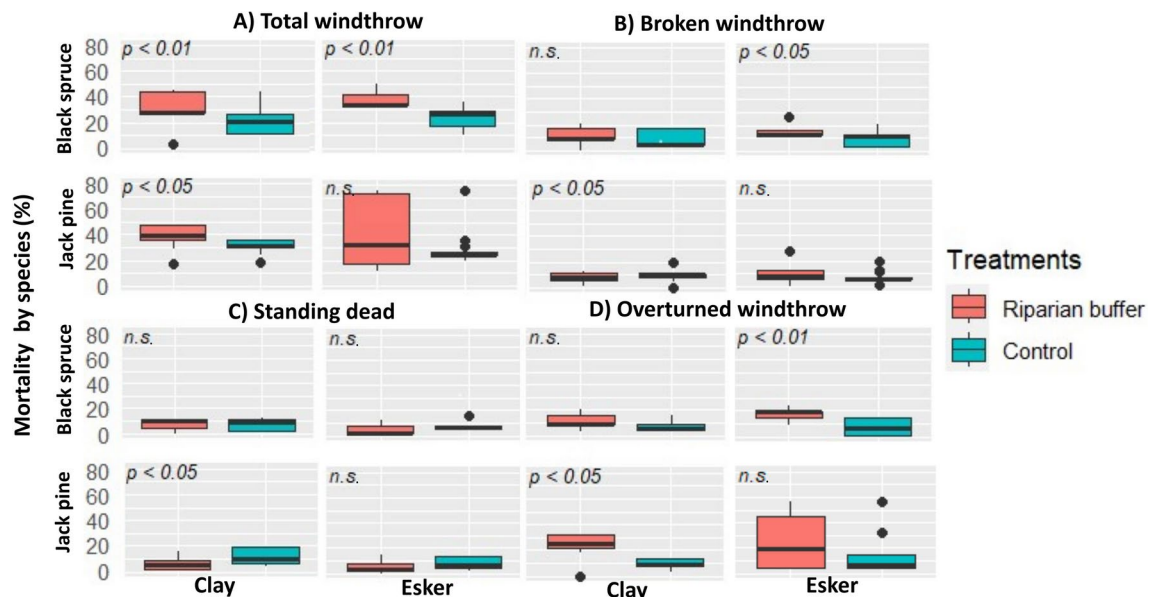


Fig. 1. Mortality by species (%) in riparian buffers in response to substrate and silvicultural treatment 10–20 years after clearcutting. **A** Total windthrow (includes broken and overturned windthrow); **B** broken windthrow (%); **C** standing dead (%); and **D** overturned windthrow (%). Significant differences between the control sites and treatment (sorted by stand species and substrates) are shown directly on the graph; all other relationships showed no significant difference.

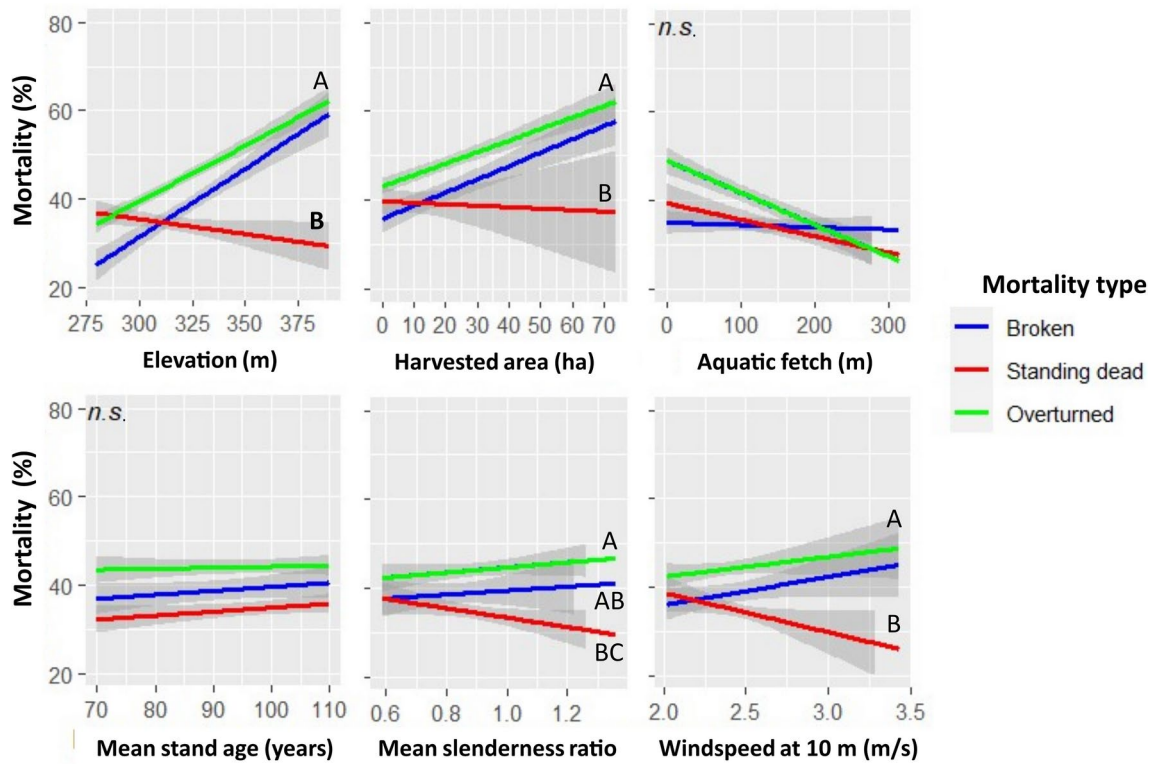


Fig. 3. Relationship between the mortality (%) and various stand, geographical, and climate variables, as determined by binomial logistic regression. Statistical differences are shown by letters.

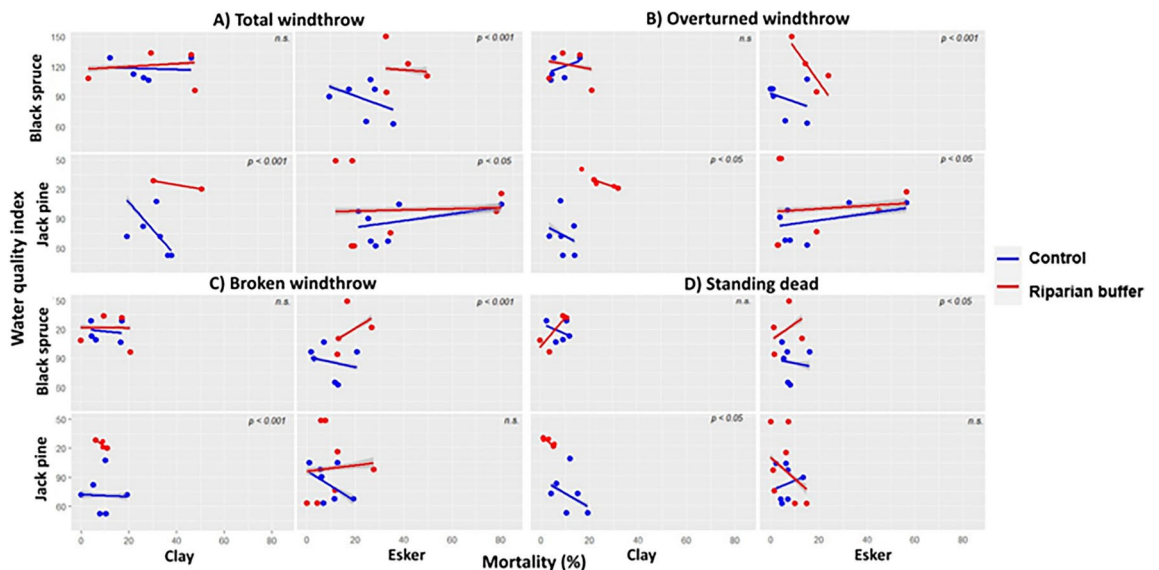


Fig. 4. Relationship between water quality and mortality (%). **A** Total windthrow (%); **B** broken windthrow (%); **C** overturned windthrow (%); and **D** standing dead (%). Significant differences between analyzed parameters are shown directly on the graph; all other graphs showed no significant difference. Higher values for the water quality index reflect a lower water quality.

in water quality, but this effect was variable from site to site. Broken windthrow also impacted water quality, with a significant difference between species, substrate, and treatment for black spruce on eskers and jack pine on clay. Generally, broken windthrow was more common in harvested stands (19%) and reduced water quality by 12%. Standing dead trees were not significantly more present on harvested stands and had no significant effect on water quality.

Discussion

Our study fills a knowledge gap by linking the increased windthrow severity in riparian buffers to a decreased freshwater quality in riparian buffers 10 to 20 years post-harvesting. Moreover, we identified stand and substrate characteristics favoring increased windthrow and how the loss of trees through windthrow reduced the protective effect of the riparian buffer over time.

Windthrow in riparian buffers after clearcut systems

Windthrow in riparian buffers affected 28% of residual trees^{26,33,38,55} and 80% of post-cutting mortality related to windthrow, which is consistent with previous studies on edge environments (e.g., riparian buffers and partial harvests,^{47,51,56}). Edge environments are known for their elevated susceptibility to windthrow because of their high wind exposure and low stand density^{57–59}. Harvested sites had significantly more windthrow than our control sites (windthrow rate of 36% vs. 16% respectively) because residual trees left in the riparian buffers face an increased risk of mortality when stand density is reduced^{28,60}. Overturning was the most frequent windthrow type in our sites (54% of windthrow), followed by breakage. Overturning and breakage were directly associated with the treatment.

Black spruce is considered more vulnerable to windthrow than jack pine because of its shallow rooting³⁸. Black spruce also had a higher overall breakage than jack pine. In black spruce stands, smaller diameter trees are more vulnerable to breakage, whereas trees having low slenderness ratios tend to be more resistant^{33,38,42}. The increased presence of overturning in jack pine stands was therefore counterintuitive and likely explained by the interaction between their root anchorage and substrate. Jack pine has deep taproots that are adapted to xeric environments, which leads to slower root development in compact and humid substrates, i.e., clay³⁶. Thus, we observed more overturning in jack pine stands on clay soils^{36,37} than in xeric environments. Furthermore, these clay sites had the highest recorded mortality in our study (72%). However, if we exclude the data of jack pine on clay, jack pine had a lower overall windthrow incidence than black spruce, as observed in earlier studies^{37,38,59}.

Although species and substrate are the main driving factors of windthrow risk^{35,38,61}, there are numerous other factors not included in our study which are involved in this ecological process⁵⁹. Conifers are susceptible to windthrow because of a lower mechanical resistance threshold to wind pressure relative to hardwoods^{23,40}. However, the risk of breakage stems from multiple factors, including the stature of the trees, the aerodynamic properties of the stand, the general and local incidence of winds, and soil conditions⁴². Thus, more work is needed to better understand this phenomenon in the riparian buffer after silvicultural treatments, as our own study couldn't answer these questions^{28,62,63}. Standing dead mortality class was the least frequent and had the weakest interaction with treatment³². Trees can die standing through a stand self-thinning process, senescence, insects, or pathogen attack, factors not included in our study^{64–66}. Further research on standing dead trees in the riparian buffer should be explored to explain this complex phenomenon^{67,68}.

Interaction between the analyzed factors and windthrow type

We determined that elevation, harvesting area, aquatic fetch, mean stand age, tree slenderness, and wind speed at 10 m all influenced windthrow abundance in the riparian buffer. The three most important factors were exposure with elevation^{40,69,70}, harvested area^{40,43,71} and aquatic fetch. Contrary to our initial hypothesis, we observed greater windthrow incidence on esker sites, caused mainly by their high natural elevation^{27,37,69}. This trend could also be explained by the increased wind exposure along the riparian edge, which increases the mechanical force applied to these edge trees^{23,41,68}. With higher wind speeds in harvested zones^{26,28}, trees located along the edges of the riparian buffer are more exposed and vulnerable to overturning than trees located toward the interior of the buffer^{23,26,32,60}. In our study, old and dominant trees were also more vulnerable to windthrow via overturning, as observed in previous studies^{32,47,60}. This may be explained by older trees having higher slenderness ratios (smaller stems relative to their height), which increases the surface area of the tree exposed to the wind^{26,32,33,38,42,72}.

The importance of aquatic fetch in our results reinforces the importance of considering the aquatic environment during clearcut^{14,17,54,73}. We found that aquatic fetch has a negative correlation with windthrow (Fig. 4); therefore, riparian buffers around small lakes and rivers are more susceptible to windthrow. Forest stands near small rivers and lakes have smaller aquatic fetch and are thus less naturally affected by the wind, leading to stands having shallower roots^{27,38}, rendering these trees more susceptible to windthrow^{23,59}. Existing mechanistic and hybrid-mechanistic models^{28,41} can estimate the increased risk of windthrow after harvesting, but these models are lacking for riparian buffers. Moreover, most models neglect the freshwater ecosystem (e.g., lake and river area and perimeter, fetch) when interpreting windthrow risk, which reduces the predicted accuracy and the effect of windthrow on water quality⁴¹. The inclusion of known predictors derived from the literature^{28,32} and a large data set containing freshwater ecosystem data contributed to the strong performance of our analysis. Unexplained variation can be attributed to the randomness of wind factors and other tree-level factors that we did not consider in this study, such as decay, disease, and insects.

Interaction between windthrow severity and water quality

We found a direct and negative correlation between mortality agents such as (insects, fires and pathogens), windthrow severity and water quality. (Fig. 5). In general, the negative correlation was more pronounced in the jack pine stands and esker pine environment because they had a higher mean windthrow percentage (Figs. 2 and 5). This effect can be explained by lower riparian stability and vegetation post-windthrow, which reduces the filtration and retention capability of the soils, leading to reduced water quality from the greater nutrient and sediment input^{17,62}. Overturned windthrow exposes the ground and reduces the extent of roots in the buffer, which plays a key role in retaining water and soil^{12,16}. Clearcut systems are the most commonly used harvesting method in eastern Canada (710 332 ha in 2020⁷⁴) and is known to affect the watersheds of freshwater

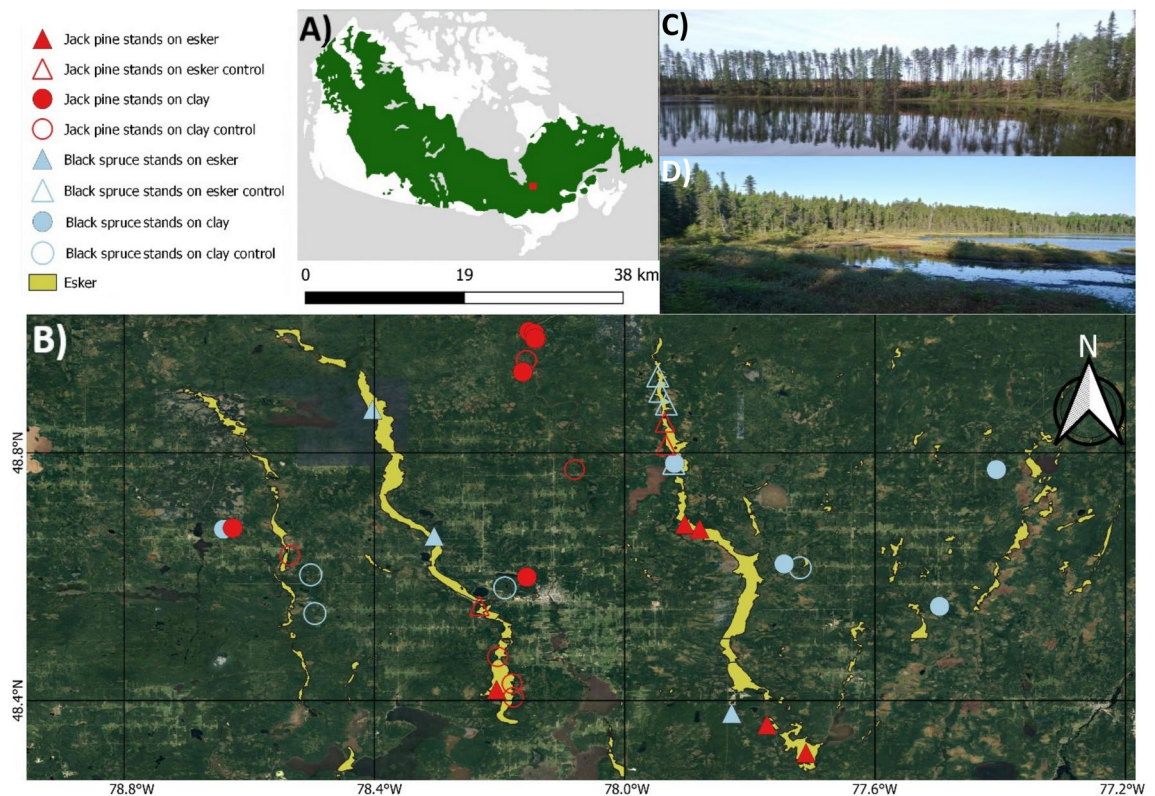


Fig. 5. **A** Study area in the Canadian boreal forest (green region); **B** Distribution of study sites in the Abitibi region of Quebec, Canada; sites are classified according to (i) their dominant stand species of either jack pine (red) or black spruce (blue), (ii) soil being either sandy/gravel (triangle) or clay (circle), and (ii) treatment either as riparian buffer (solid symbol) or control (empty symbol); **C** post-harvest riparian buffer on an esker soil; and **D** control riparian stand on a clay soil. The satellite imagery was created with the open source software QGIS, version 3.34.8 (<https://qgis.org/en/site/forusers/download.html>), with open source data available from the Quebec ministry of natural resources and forest ([Forêt ouverte \(gouv.qc.ca\)](http://Forêt_ouverte(gouv.qc.ca))).

ecosystems⁷⁵. Riparian buffers are mandatory in all Canadian provinces (since 1977 in Quebec)^{14,76} and are often used in many other countries to reduce the impacts of clearcut systems on freshwater ecosystems²⁴. Despite this extensive application, very few studies have analyzed the short- and long-term interactions between post-harvesting windthrow and water quality in boreal riparian buffers⁶². Georgiev et al. (2021)⁷⁷ in Germany found increased nitrate and reduced dissolved oxygen (DO) in water bodies ten years post-harvest, mainly caused by the greater amount (and leaching) of coarse woody debris from the initial harvesting and subsequent windthrow events. However, contrary to our findings, they did not note a significant difference in long-term water quality between the harvested and naturally perturbed stands (e.g., windthrow, insects, and mortality). This difference may be explained by the water quality monitoring of the Georgiev et al. study being conducted at the watershed outlet, which greatly reduces the relative impact of forest management practices and natural forest disturbances (such as wildfire, insects and pathogens) on the lake itself¹⁵.

Esker ecosystems are sensitive to the negative effects of windthrow because they naturally have a higher water quality, low nutrient content, and less interaction with their watershed^{4,77}. A massive increase in nutrient leaching and sedimentation post-windthrow creates an imbalance in the esker freshwater ecosystem and a reduced capacity to absorb the effects of a disturbance^{73,78}. Overturning was greater on esker sites, which in turn disturbs the soil and reduces plant coverage in the riparian zone and thus reducing water quality overtime^{15,36}. Compacted soils and ruts were present in all harvested sites; these features compound the negative effects of rainfall¹⁴. Increased dissolved organic carbon (DOC) and nitrate concentrations and decreased DO were the primary physicochemical modifications of these perturbations. The altered water quality can also be explained by the post-harvest increase in large woody debris in the water bodies and the subsequent leaching of this material into the freshwater ecosystem^{21,51}.

Implications for forest management in riparian buffers

Silvicultural prescriptions for riparian buffers are often generic and rigid for stands in the boreal biome in terms of implementing measures to protect water courses. However, sustainable clearcut systems must be adapted to local factors and must consider the factors involved in these ecological processes, such as the intensity and extent of management activities and the specific watershed characteristics, e.g., vegetation, substrate, geology, topography, and climate^{5,79}. Furthermore, riparian buffers in Canadian forests tend to have smaller widths than

the recommended value to adequately protect the terrestrial and semi-terrestrial fauna communities in the riparian environment^{80–82}. However, an exception can be seen in the New-Brunswick province, where riparian buffer widths are modulated by the harvesting method and tree species⁸³. Indeed, clearcut systems in conifer stands have larger riparian buffers, while deciduous stands, which are less susceptible to windthrow (such as maple and birch), have smaller riparian buffers, similar to those in the Quebec province⁸⁴. They also close the forest roads after harvesting, which significantly reduces sedimentation and erosion risks in the environment^{9,83}.

Our study demonstrated that the current width of riparian buffers in eastern Canada (20 m) is insufficient to protect water quality in the boreal ecosystem under many conditions. However, our results do not allow us to recommend a minimum width for riparian buffers. Thus, we recommend re-evaluating the silvicultural prescription applied to riparian buffer width in windthrow-sensitive areas, such as esker environments, in jack pine stands, and around small rivers and lakes, to prevent and minimize the negative effects of windthrow on freshwater ecosystems^{15,21}. Esker environments are vulnerable to the pressures of anthropic activities, such as gravel extraction, forest harvesting, tourism, and mining⁴, which also negatively affect the quality of surface and subsurface freshwater. Esker water is essential for large communities in northern Canada, as it serves as the primary water source for human consumption and has the benefit of having a low operational cost for its extraction and treatment². Therefore, riparian buffers should be adapted on esker sites to preserve high freshwater quality and reduce windthrow. Riparian buffer width should also be revised in higher-elevation areas and account for the slope on site to prevent windthrow and minimize soil erosion and the resulting sedimentation and nutrient leaching into lakes and rivers^{23,27,43,69}. Given the effects of clearcutting in a watershed, forest managers must consider freshwater ecosystems when selecting silvicultural treatments and harvesting methods^{15,24,54,85}. We therefore suggest increased use of partial harvest rather than clearcut systems, because clearcuts aren't effective tools for preserving water, terrestrial biodiversity, and to preserve water quality, as seen in our study. However, edge feathering in clear-cuts could also be an opportunity to explore, as it reduces the edge effect in the environment, thereby also decreasing the windthrow risks⁵. We also recommend further research on partial harvesting in the boreal forest and near riparian environment, to bridge the current gap in the literature on this topic^{33,64,67}. Partial harvesting (such as shelterwood systems) promotes tree growth and regeneration and reduces post-harvest windthrow^{32,64,86–88}, for species as black spruce (mid shadow) and jack pine (full light)^{30,62,84–86}, providing a long-term solution for reducing anthropic impacts on freshwater ecosystems⁵⁴. Furthermore, sustainable clearcut systems must integrate aquatic and terrestrial interactions to promote the effective long-term protection of freshwater ecosystems. To help this endeavor, we argue that further research should explore riparian buffers in other regions and at various scales (local, watershed, and regional) and improve modelling tools for predicting windthrow, especially under climate change, given the expected increase in the frequency and severity of forest disturbances in boreal forests^{2,30,31,89}. We also suggest the inclusion of further and more in-depth research on freshwater quality and windthrow in boreal riparian buffers, because this study only highlights general trends on this front.

Conclusion

This study highlights the knowledge gap in clearcut system and their interaction with freshwater ecosystems. An increase in windthrow incidence reduced freshwater quality even 10–20 years in the future. This new information demonstrated that the width of riparian buffers in eastern Canada must be revised and research to improve the long-term protection of water quality in freshwater ecosystems. We also recommend the application of partial harvest over-time instead of clearcut systems in higher-risk environments, such as eskers, high-elevation stands, and near small lakes and rivers. Finally, we recommend including freshwater ecosystems in forest and landscape management to ensure their long-term protection.

Materials and methods

Study area

The study was conducted in the Abitibi Regional County Municipality (MRC), Québec, Canada (Fig. 5) in the balsam fir (*Abies balsamea*)–white birch (*Betula papyrifera* Marsh) and eastern spruce–feathermoss bioclimatic zones⁹⁰. The study area covers 7 948 km² and contains 393 boreal lakes (≥ 6 ha) that cover 3% of the MRC Abitibi region. The lake and river bottoms are clay or sandy substrate^{91,92}. Regional climate is subhumid subpolar, and mean annual temperatures range between –2 and 2.5 °C, with an annual precipitation of 800–900 mm⁹² and a mean annual wind speed of 2.8 m/s⁹². Because of this dry climate, fire is the main natural disturbance in the area with a relatively short fire-return cycle of 150 to 250 years⁹³. Forest harvesting has removed 20% of the regional forest over the last 20 years (71 237 ha/year, mainly via clearcutting)⁹⁴. During the Wisconsin glacial period, the Laurentide ice sheet covered most of eastern Canada⁹⁵. The ice sheet retreat shaped a flat regional landscape (mean elevation 310 m⁹⁶) and left behind surficial glaciation-related features. These forms include eskers, a sand and gravel deposit from glacial meltwaters, and clay glaciolacustrine deposits from the proglacial Lake Ojibway–Barlow. Eskers provide well-drained sandy and xeric soils and also act as a natural filter as water passes through the porous sediments to become high-quality groundwater^{4,71}.

Experimental design

For this study, we selected 40 riparian sites next to lakes (22) or rivers (18), representing a series of 20 sites in riparian buffers—a preserved 20 m wide forest stand between a water body and an area harvested by clearcutting 10 to 20 years ago (harvested 2001–2010)—and 20 sites in unharvested stands (control) (one point in time). We applied three criteria for selecting our sites: (1) dominant tree species, (2) time since time since clearcut, and (3) substrate (soil) (Supplementary information S1). Furthermore, we selected half of our sites near rivers with similar Strahler orders, and the other half near lakes with similar surface areas. All selected sites were covered,

i.e., more than 75% of the basal area in each site, by either pure black spruce or pure jack pine forest. We used these two species as they are the dominant trees in the regional forest landscapes and the most harvested. The selected sites were mature stands aged 70 to 90 years old, as this age represents when most stands are harvested in eastern Canadian boreal forests. All selected sites were found on either clay or sand (esker sites) substrate, as these two soils are the most abundant substrate types in the study area. We used open access data sets from the Ministère des Ressources naturelles et des Forêts (MRNF) ([Forêt ouverte \(gouv.qc.ca\)](http://Forêt_ouverte(gouv.qc.ca))) to determine the soil type at potential sites. Within each group (stand species, substrate, and treatment), we established 5 replicates for a total of 40 study sites (5 replicates \times 2 substrates \times 2 tree species \times 2 treatments; Supplementary information S1).

Sampling plan

Stand characterization and windthrow

We conducted field surveys to characterize the stands and windthrow in summer 2021. All surveys took place within a 400 m² square plot (20 \times 20 m) adjacent to the aquatic environment, and distances were measured from the edge of the freshwater body⁵⁷. To consider the effect of spatial position at each site, we established three zones: (1) a 5 \times 20 m zone near the aquatic edge; (2) a 10 \times 20 m intermediate zone in the plot center; and (3) a 5 \times 20 m harvested edge (Supplementary information S2). For all commercial trees (DBH > 9 cm) in the plot, we noted the species, the breast height diameter (DBH), the spatial position (within one of the three above-listed zones), and wound severity (category 1 (< 25%), 2 (25%–50%), 3 (50%–75%), and 4 (> 75%) by analyzing the wound presence caused by harvesting on the stem, following the MSCR method⁹⁷). We classified each tree as either alive, standing dead (standing dead trees, which can have a broken crown), broken (standing dead tree with a broken stem under the crown), or overturned (fallen with exposed roots and soil). Total windthrow (Table 1) was obtained by adding together the categories broken and overturned trees. To estimate stand age, for each site we recovered 10 to 15 tree cores from randomly selected trees. Cores were collected at the root collar. In the laboratory, the cores were air-dried, mounted on wood boards, sanded, and analyzed to determine the tree and mean stand age, following standard dendroecological protocols⁹⁸. We calculated the slenderness ratio using tree height divided by its DBH to gather information on the structural resistance of the stem to windthrow³². For each plot, we measured the average slope and basal area at the center of the plot (with a factor 2 prism) and measured the average stand height on 10 to 20 randomly selected trees, using a Vertex laser geo at the base and crown of the trees.

Water quality sampling

In the summer of 2022, we measured the physiochemical parameters of the water bodies adjacent to the forest sites. Two samples were collected the same day (at least 7 days after heavy rainfall), 5 m from the shore and averaged. Water temperature (°C), pH, specific conductivity (μ S/cm), dissolved oxygen concentration and saturation (mg/L and %, respectively) were measured 50 cm below the surface with a Pro Quattro multiparameter sonde (YSI, Yellow Springs, USA). We collected water samples on site with a 1 L opaque Nalgene bottle connected to a 2 m long pole. Two 50 mL acid-washed transparent glass vials were filled with 40 mL of unfiltered water to analyze total nitrogen (mg/L) and total phosphorus (mg/L). Two 40 mL brown glass vials were filled completely with filtered lake water (0.45 μ m syringe filters) to be analyzed for dissolved organic and inorganic carbon concentrations. Nutrient vials were pre-washed in a 10% HCl bath for 24 h, rinsed with distilled water, and then dried in an oven at 200 °C for 4 h. Vials for dissolved organic and inorganic carbon concentrations were preheated in a furnace for 4 h at 450 °C to remove any potential trace of carbon. Water samples for nutrient and carbon concentrations were analyzed by the Interuniversity Research Group in Limnology at the University of Québec in Montreal, following the protocol of Wetzel and Likens (2000)¹⁰¹. We estimated the particulate organic carbon concentration by filtering between 500 and 1000 mL of water through a 0.7 μ m glass fiber filter. These filters were heated beforehand at 375 °C for 16 h and then weighed when empty and dry. After filtration, the filters were oven-dried (105 °C for 8 h) and weighed again to measure the organic and inorganic particulate carbon weight. Filters were then heated a second time (375 °C for 16 h) and reweighed to determine the particulate inorganic carbon and calculate the organic carbon weight¹⁰².

Topographic, climate, and anthropic factors

We compiled the main topographical variables of each study site to evaluate the role of tree and stand characteristics, topographic factors, climate, and anthropic disturbance on windthrow (Table 1). We determined regional mean annual wind speeds at 10 m above ground at a 250 m resolution⁹². To characterize our sites based on topographic and anthropic factors (see Table 1), we used the open governmental database [Forêt ouverte \(gouv.qc.ca\)](http://Forêt_ouverte(gouv.qc.ca))¹⁰³. To account for the fragmentation caused by harvesting, cutblock configuration, and the aquatic environment, we created six variables: (1–2) areas of the adjacent harvested area and aquatic environment (lakes or rivers), (3–4) distances to the adjacent harvested area and aquatic environment, and (5–6) a simple fetch index for the harvested area and aquatic environment, derived from Montoro Girona et al. (2019)³². For the harvested stands, this fetch is the ratio between the radius of the riparian patch and the mean distance to adjacent stands. For controls, we used the ratio of the riparian environment and the mean distance of the nearest road or adjacent cut. The aquatic fetch was measured as the longest traceable distance through which wind can traverse an aquatic environment without obstacles, using the ESRI GIS software suite (ArcMap)¹⁰⁰. This environmental data was then analyzed using the ESRI GIS software suite (ArcMap) and the open-source software QGIS²⁷.

Data analysis

To analyze the overall windthrow percentage at the stand level in response to harvesting, substrate, and species, we ran a generalized linear model (GLM) on the stand data set, following Mäenpää et al. (2020)²³. We used the R package lme4, applying a binomial distribution and a logit link function. Density on a site (number of trees/ha)

Category	Variable	Type	Unit	Description	Source	References
Tree and stand measurements	Management status	Categorical	–	2 categories: Managed and unmanaged stands (control)	Field survey	23,26,28,57
	Stand type		–	2 categories: black spruce or jack pine	Field survey	28,32,33
	Substrate type		–	2 categories: clay soil or sand and gravel (esker)	Field survey	4,35,38
	DBH		Cm	Diameter at breast height	Field survey	27,40,42
	Spatial position		–	3 categories: next to the harvested area, intermediate environment (middle), and near the aquatic environment	Field survey	27,38,43,69
	Windthrow rate	Numerical	%	4 categories: total windthrow, overturned, broken, and standing dead	Field survey	28,42,43,68
	Stand density		Tree/ha	Number of trees per hectare	Field survey	34,39,72,98
	Estimated height		M	Estimated mean height (10–20 trees on site)	Field survey	28,47,50
	Slenderness		–	Ratio of estimated height/DBH on site	–	26,32,38,42
	Wound severity	Categorical	–	Category from 1 (<25%) to 4 (>75%)	Field survey	32,42,60
	Basal area	Numerical	m ² /ha	Represents the cross-sectional area of the tree stem measured at DBH	Field survey	25,28,68
	Stand age		Year	Mean age of the stand	Field survey	25,28,68
Topographic factors	Slope	Categorical	%	Mean slope in 4 categories: 0–5, 5–10, 10–15, and 15–20	Field survey	27,29,43,73
	Elevation	Numerical	M	Mean elevation on site	Ministère des Ressources naturelles et des Forêts (MRNF)	25,28,29,68
Climate factors	Wind speed	Numerical	m/s	Mean wind speed at 10 m above the ground in 3 categories: riparian buffer, harvested area, and aquatic environment	Environment and climate change Canada (ECCC)	27,42,99
Anthropic factors	Riparian buffer width	Numerical	M	Mean width of riparian buffer	MRNF	21,23,26,68
	Distance to the harvested area		M	Mean distance of riparian buffer to harvested area	MRNF	26,32
	Perimeters of the harvested area		Km	Mean perimeter of adjacent harvested area	MRNF	28,33,60
	Area of the harvested area		Ha	Mean area of adjacent harvested area	MRNF	33,34
	Simple fetch index of the harvested area		–	Represent the relation between adjacent distance to harvested area and area of harvested area	–	27,43
	Distance to the aquatic environment		M	Mean distance of riparian buffer to aquatic environment	MRNF	14,17,70,73
	Perimeter of the aquatic environment		Km	Mean perimeter of adjacent aquatic environment	MRNF	14,17,70,73
	Area of the aquatic environment		Ha	Mean area of adjacent aquatic environment	MRNF	12,15,29
	Aquatic fetch	M	Represent longest traceable distance which wind can traverse an aquatic environment without obstacles	–	27,43,100	

Table 1. Description of analyzed trees and stands, topography, climate, and anthropic parameters.

was weighted to ensure its importance in the equation¹⁰⁴. The fixed effects were species, substrate, management status and the pairwise interactions. We then tested each windthrow type individually (broken, overturned, and total) and standing mortality to determine the impact of the fixed effects on the various windthrow types. The data set for each windthrow type was tested for normality and homoscedasticity when required by the test assumptions. To identify the most influential parameter (Table 1) on overall windthrow incidence, we applied a decision tree method in R using the rpart package¹⁰⁵. The selected variables were management status, species, substrate, DBH, relative position, windthrow, stand density, estimated height, slenderness, wound severity, basal area, age, slope, topex, altitude, wind speed (in riparian buffers, cuts, and aquatic environment), adjacent cut-related variables (area, distance and perimeter, simple fetch index), adjacent aquatic environment-related variables (simple fetch index, area, distance, and perimeter), and average riparian buffer width (Table 1).

To analyze the water quality in the riparian environment at each site, we created a water quality index using the Weighted Arithmetic Water Quality Index Method ($WQI = \sum QiWi / \sum Wi$)^(104, Supplementary information 3). The index used an inverse scale; thus, a lower score indicated a better water quality environment. The water quality index relied on the collected physicochemical characteristics of the sampled aquatic environment (Supplementary information 4). We then produced linear mixed effect models (lmer) for the water quality index¹⁰⁶ using the lme4 package in R. The fixed effects were species, substrate, silvicultural treatment, and the pairwise interactions. The random effects were the aquatic environment (river or lake). Finally, we analyzed water quality and windthrow using linear mixed effect models (lmer). The fixed effects were the same as for the quality index, although with overall windthrow and windthrow type (broken, standing dead, and overturned) added. The random effects were the aquatic environment (river or lake). All statistical analyses and calculations were performed using the statistical software R version 277 4.2.2 and R studio version 20,232.03.0 build 386¹⁰⁷.

Data availability

The datasets used during the current study available from the corresponding author on reasonable request.

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Author contributions

MMG, GG: conceptualization; MMG, GG and MG: experimental design and site selection; MG, MMG, GG:

fieldwork and data curation; MG, GG, and MMG: laboratory analysis; MMG, GG, and KW: methodology; MMG: project administration; MMG, GG, and KW: resources; MMG, GG, KW, and MG: result interpretation; MMG, GG and KW: supervision; MMG, GG, KW and MG: analysis validation; MG, MMG, and GG: visualization and edition; MG: writing-original draft; MMG, GG, KW, MH, MG: writing-review; MMG and GG: funding.

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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