Forest Ecology and Management 580 (2025) 122425

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

An evidence map of research assessing the effects of timber harvesting on water quality, biotic and biodiversity indicators in running waters

D.E.L. Hanna [a,*], M. Harper [a], X. Giroux-Bougard [b], J.S. Richardson [b], T. Rytwinski [a], A. Bachhuber [a], E.J. Hudgins [c], S. Karimi [a], R. Schuster [a,d], A.D. Binley [a], R. Reedman [b], J.G. Vincent [a,d], J.R. Bennett [a]

[a] Department of Biology, Carleton University, Canada
[b] Department of Forest and Conservation Sciences, University of British Columbia, Canada
[c] School of Agriculture, Food and Ecosystem Sciences, The University of Melbourne, Australia
[d] Nature Conservancy of Canada, Toronto, ON, Canada

ARTICLE INFO

Keywords:
Forestry
Streams
Rivers
Diversity
Water

ABSTRACT

Freshwater quality and biodiversity are known to be affected by surrounding timber harvesting activities. However, variable impacts across studies make it difficult to predict the implications of harvesting for freshwaters. Evidence syntheses compile existing research to assess whether robust predictions of impact can be drawn and determine where gaps lie. Yet, no synthesis that we know of describes the overall evidence landscape of research assessing the effects of forest management for wood production (hereafter: timber harvesting) on water quality and aquatic biodiversity of running waters. We address this gap by creating an evidence map specifically focused on boreal and temperate biomes - which contribute heavily to timber production. Using Web of Science Core Collections, Scopus and Google Scholar, we located 638 relevant publications from which we identified three key primary research and evidence synthesis priorities focused on prediction of impact using existing literature. Most studies took place in the United States of America (56 %, n = 358) and quantified two or more biotic or water quality indicators (range = 1–52, mean = 7, sd = 7). Water quality was more frequently assessed across studies (80 %, n = 511) than biotic indicators (39 %, n = 248), with benthic macroinvertebrates being the most commonly assessed taxon (50 % of studies that quantified biotic indicators, n = 124). Biodiversity-specific biotic indicators (e.g. richness) were assessed at a similar frequency (51 % of all biotic indicator measurements, n = 606) to other types of biotic indicators (e.g. abundance) (49 %, n = 594). The majority of studies that contained temporal information collected data about water quality and biotic indicators for no longer than five years (56 %, n = 358) and no more than five years after timber harvesting events (66 %, n = 309 studies). Although numerous studies contained no information about the types of harvesting in their study regions (19 %, n = 122), those that did mainly focused on effects of clearcutting (n = 458 studies). Most studies did not contain watershed-scale information about timber harvesting (58 %, n = 349). Together, these findings point toward three key primary research priorities which include: capturing a broader scope of effects, especially regarding biodiversity and other biotic indicators; increasing our ability to detect long-term changes related to timber harvesting; and, better accounting for watershed level processes. We provide suggestions for approaches to address each of these research priorities and examples of how evidence syntheses that utilize and build on the dataset we compiled for this map could improve understanding and prediction of the effects of timber harvesting on fresh waters.

1. Introduction

Freshwater ecosystems make numerous contributions to people's wellbeing (MA, 2005) and are home to a diversity of species (Strayer and Dudgeon, 2010). However, their integrity is threatened by a growing suite of anthropogenic stressors (Reid et al., 2019), including changes in land use and cover caused by timber harvesting and related activities. Freshwater biodiversity has been found to decline in response to

* Correspondence to: Carleton University, Department of Biology, Room Nesbitt 209, 1125 Colonel By Driver, Ottawa, ON K1S 5B6, Canada.
E-mail address: dalal.hanna@carleton.ca (D.E.L. Hanna).

https://doi.org/10.1016/j.foreco.2024.122425
Received 1 October 2024; Received in revised form 15 November 2024; Accepted 22 November 2024
Available online 8 February 2025

surrounding harvesting activities (Growns and Davis, 1994; Richardson and Béraud, 2014; Smith et al., 2009) and water quality can also be negatively affected (Davies and Nelson, 1994; Levno and Rothacher, 1967; Webb et al., 2012). Yet, in some circumstances, these same aspects of freshwater systems (i.e. biodiversity and water quality) seem to remain unaffected by surrounding harvesting (Chiwa et al., 2020; Mckie and Malmqvist, 2009). Improving understanding of the factors that drive these shifts - and explaining why they are present under some circumstances and not others - is an important step toward furthering the development of harvesting practices and policy that minimize undesirable negative impacts on freshwater ecosystems. Identifying gaps and biases in existing literature is a helpful first step toward the development of such understanding.

Decades of research have identified numerous mechanisms for why and how timber harvesting affects freshwaters, as well as variation in these effects (Gerth et al., 2022; Tebo, 1955). For example, landscape characteristics such as the topography of a watershed can affect the movement of nutrients across hydrologically connected fresh waters. As such, the impacts of harvesting on nutrient fluxes and sediment yields - which influence water quality (Kreutzweiser et al., 2008) - between two otherwise identically-harvested watersheds will likely differ based on topography. Several aspects of harvesting practices such as techniques (Davis and Clatterbuck, 2003; Eklöf et al., 2012; Mlambo et al., 2015), spatial extent and configuration (Erdozain et al., 2018; Löfgren et al., 2009), the application of best management practices (Warrington et al., 2017) are also known to alter freshwater impacts of harvesting. Although many studies exist on these drivers, discrepancies among findings due to these and other sources of variation make it difficult to predict the implications of harvesting for fresh waters with confidence (Lunn et al., 2017).

Evidence syntheses can help assess whether robust predictions of impact can be drawn from existing research and determine where gaps lie (Cook et al., 2017; Pullin et al., 2016). Recent syntheses have advanced certain key questions about the effects of harvesting on fresh waters by investigating, for example, how the application of best management practices during harvesting affects aquatic fauna (Warrington et al., 2017), how riparian zone harvesting affects biological and chemical components of streams (Richardson and Béraud, 2014), or how harvesting in the southeastern USA affects biodiversity (Petrokofsky et al., 2021). However, no synthesis that we know of describes the overall evidence landscape (i.e. creates an evidence map) of research assessing the effects of timber harvesting on water quality and biodiversity of running waters. This makes it difficult to know whether existing research can be used to uncover generalities in harvesting best practices for water quality and biodiversity outcomes, as well as where key gaps and consequent future research directions lie.

We address this gap by creating an evidence map of published research assessing the effects of forest management for wood production (hereafter, timber harvesting) on water quality, biotic and biodiversity indicators in running waters, specifically focusing on boreal and temperate biomes. We consider these biomes as they are major contributors to global timber production (Arets et al., 2011), and are the biomes our team of authors primarily live and work in. Specifically, our evidence map showcases: 1) where research has taken place, 2) the range and frequency of biotic and water quality outcomes assessed, as well as the timeframes over which these were assessed, 3) the types and spatial extents of timber harvesting assessed, and 4) the study designs that have been used. We use these findings to identify existing gaps in this field and associated key future primary research directions that, if addressed, can help advance understanding of how timber harvesting affects fresh waters. We also discuss how the novel dataset we compiled could be built upon to address some of these key research questions and inform predictions of impact that can support improved land-use planning.

2. Methods

2.1. Data collection

2.1.1. Identification of relevant publications

Building from literature review guidelines established by the Collaboration for Environmental Evidence (Collaboration for Environmental Evidence, 2022), we developed a search string to capture publications assessing the effects of timber harvesting on biodiversity and water quality of running waters in Boreal and Temperate forests (Table 1; see Appendix A for details). This string was used to search the title, abstract, and keywords of publications in Web of Science Core Collections and Scopus on November 12, 2020 using Carleton University's institutional subscriptions. We also performed searches using Google Scholar between December 8 and 16 2020 to locate additional commercially published and grey literature. Search terms were limited to English, as this is the language primarily spoken by several of the project collaborators. In addition, we manually searched the reference lists of publications identified as relevant reviews during screening for relevant publications not found using the search strategy.

The titles and abstracts of each of the 9349 unique publications retrieved via all searches were screened for relevance by nine members of the team of co-authors following a consistency check. Articles considered relevant for inclusion met the following five eligibility criteria: 1) reports qualitative or quantitative information about water quality or aquatic biodiversity, 2) self-describes as having assessed outcomes or effects of timber harvesting, or contains sufficient information to assess these effects, 3) takes place in one or several freshwater bodies of running water, 4) takes place in a boreal or temperate forest, and 5) is a primary field-based study that includes experimental manipulations or observations. If these criteria could not be assessed via the publication's title and abstract, it was moved to full text screening where the same five criteria were assessed using information from the entire publication. It is important to note that in the context of this study's screening process we defined biodiversity indicators as those that were either self-identified as indicators of biodiversity by study authors or reflect some aspect of the variety of life forms within an ecosystem (e.g. diversity, richness, dominance, evenness). However, we also retained publications that contained any information about two or more species (e.g. abundance) to capture a broader scope of biotic indicators than solely biodiversity focused-ones. See Appendix A, Section A.1 for details concerning the identification of relevant publications.

Table 1
Search string used to locate publications assessing the effects of timber harvesting on the water quality and biodiversity of running waters in Boreal and Temperate forests. Each of the shown specific search strings were combined by the boolean operator "AND".

Targeted component of publications	Specific search string used to capture relevant publications
Environment type - Identifies publications situated in forests with running waters passing through them	forest$ OR canopy "running water$" OR stream$ OR river*
Interventions - Identifies publications focused on timber harvesting	harvest* OR log* OR clearcut* OR forestry OR timber OR buffer OR "forest age" OR "riparian canopy"
Outcomes - Identifies publications that assess water quality or biodiversity	biodiversity OR richness OR diversity OR dominance OR evenness OR "community structure" OR *invertebrate$ OR fish* OR amphibian$ OR plant$ OR herptile$ OR mammal$ OR bird$ OR moss* OR algae OR fungi OR meiofauna OR "water quality* " OR "water chemistry" OR pH OR P OR Phosphorous OR N OR Nitrogen OR K OR Potassium OR conductivity OR recovery

2.1.2. Data collection from relevant publications

We collected detailed information from all relevant publications about study locations, water quality and biotic indicators assessed, the types and spatial extents of timber harvesting taking place in assessed locations, and the study designs (see the accompanying dataset metadata published on Zenodo sheet for a detailed description of all information gathered from individual studies). All data were collected by two of the study co-authors (D.E.L.H. and M.H.), who conducted a consistency check at the start of the data collection procedure to ensure their approaches to data collection were as similar as possible (see Appendix A, Section A.1 for details). Data were collected for each unique water quality and biotic indicator (i.e. individual dataset) found in each distinct study (a study consists of data collected from distinct locations used in distinct analyses; some publications include more than one study). When collecting information about the spatial extent of harvesting, we defined the term watershed as the entire hydrologically connected area located upland of any given point in a body of running water.

2.2. Data coding and mapping method

Patterns across the compiled publications were evaluated in R Studio using the R core packages in version 4.1.3 (R Core Team, 2022), dplyr (Wickham et al., 2022), googlesheets4 (Bryan, 2023), tidyr (Wickham et al., 2024c), stringr (Wickham, 2023b), purr (Wickham and Henry, 2023a), forcats (Wickham and RStudio, 2023), readr (Wickham et al., 2024b) and janitor (Firke et al., 2023). Data visualization was completed using QGIS version 3.4 (QGIS.org, 2021) and ggplot2 (Wickham et al., 2024a). Information was summarized at various levels (i.e. publication, study, individual dataset) depending on the aspects of the overall dataset being evaluated. For example, the number of unique water quality and biotic indicators for which information was gathered was summarized at the study level, as each study collected information about a specific number of indicators. In contrast, information about study design was summarized at the dataset level because specific datasets nested within a study were sometimes collected using different study designs (e.g. a given study gathered information about mercury in benthic macroinvertebrates using a control-impact design, but also used a before-after control-impact design for information about mercury in birds (Willacker et al., 2019)).

We categorized water quality and biotic indicators, as well as the types of timber harvesting assessed across studies into broader categories that would allow for streamlined analyses. For water quality and biotic indicators, broader categories were iteratively developed by first extracting a full list of the unique indicators assessed across all studies to: 1) capture redundant terms (e.g., "% shredders" and "% shredder"), and 2) identify similar terms (e.g. using a "Benthic invertebrate health indicator" as an indicator of water quality is a similar approach to using "Benthic macroinvertebrate relative abundance" as an indicator of water quality). We then iteratively developed definitions for relevant broader categories. For example, all biotic indicators that were made up of measures of the number of groupings present in a community were categorized as measures of "richness", and all water quality indicators that included biological components -such as the macroinvertebrate examples above- were considered to be "biological indicators" of water quality. Biotic indicators were then further classified as biodiversity-focused or not. Note also that biological indicators of water quality were considered to be water quality and not biodiversity or biotic indicators when authors explicitly stated they were being used as water quality indicators. A complete list of unique water quality and biotic indicators captured across the assessed literature and how they were classified is available in the dataset published alongside this manuscript, and lists and definitions of the final set of broader categories used in our analyses are found in Appendix A, Section A.2 (Tables S1 and S2). For timber harvesting, categorization was completed based on definitions of types of timber harvesting found in the US Forest Service Reforestation Glossary (USDA, 2024), with specific definitions of timber harvesting categories outlined in Table S3 (Appendix A, Section A.2).

For mapping, we used the World Food Programme's "World Administrative Boundaries - Countries and Territories" layer to outline countries (Opendatasoft, 2023). We used the World Wildlife Fund's Terrestrial Biomes layer (Olson et al., 2001; WWF, 2012) to outline the global distribution of boreal and temperate forests, which, for the purpose of this work, we considered to be nested within three biomes: 1) temperate coniferous forests, 2) temperate broadleaf and mixed forests, and 3) boreal forests/taiga.

3. Results

3.1. Dataset overview

The 9349 publications we screened were narrowed down to 581 relevant publications. Among these, 47 were considered to be "supplementary", as their data were already collected from other publications. Among the 534 resulting publications from which we collected unique data, 45 contained more than one study (i.e., the publication presented data collected from different locations that were used in distinct statistical analyses), with the number of studies in this group ranging from two to 34. Overall, we compiled data from 638 unique studies. A complete breakdown of the process of identification of relevant publications is shown in Figure S1 (Appendix B, Section B.1).

The 534 publications from which we collected unique data were mainly peer-reviewed articles (79 %, n = 422), but also included theses (7 %, n = 37), published reports (government, NGOs, consultants, etc.) (6 %, n = 32), conference proceedings (6 %, n = 32), and book chapters (2 %, n = 11). They were published between 1955 and 2021, with the highest publication rate occurring between 2000 and 2010 (Figure S2, Appendix B, Section B.2). Peer-reviewed publications were retrieved from 119 journals, with the most common journals being *Forest Ecology and Management* (13 %, n = 70 publications), *Hydrobiologia* (3 %, n = 17 publications), and *Hydrology and Earth System Sciences* (3 %, n = 15 publications).

3.2. Study locations

We collected data from studies located in 26 of the 74 countries that contain boreal or temperate forests (Fig. 1). More than half the studies from which we compiled data were conducted in the United States of America (n = 358, 56 % of studies), and nine of the countries represented in the overall dataset only had a single study within their boundaries (e.g. Russia, Poland, Iran, etc.). An additional seven countries had five studies or less within their boundaries (e.g. France, Spain, Turkey, etc.). Canada (n = 89, 14 %), the UK (n = 35, 6 %), and Australia (n = 27, 4 %) all had more than 25 studies conducted within their boundaries (Table S4). The greatest number of studies took place in temperate broadleaf and mixed forests (n = 341, 54 % of studies) followed by temperate coniferous forests (n = 250, 39 % of studies), and boreal forests/taiga (n = 47, 7 % of studies). Just over a third of studies (n = 232, 36 %) took place in a total of 78 different experimental forests.

3.3. Water quality and biotic outcomes assessed

A total of 3569 water quality indicators and 1200 biotic indicators (606 of which were biodiversity-focused) were assessed across the 638 studies from which we compiled information. Individual studies quantified anywhere between one and 52 unique water quality and/or biotic indicators (mean = 7 indicators, sd = 7 indicators), with the majority of studies (83 %) quantifying more than a single indicator. Only 19 % of studies (n = 121) assessed a combination of both water quality and biotic indicators, and water quality indicators were more frequently assessed (80 % of studies, n = 511) than biotic ones (39 % of studies, n = 248) (Fig. 2).

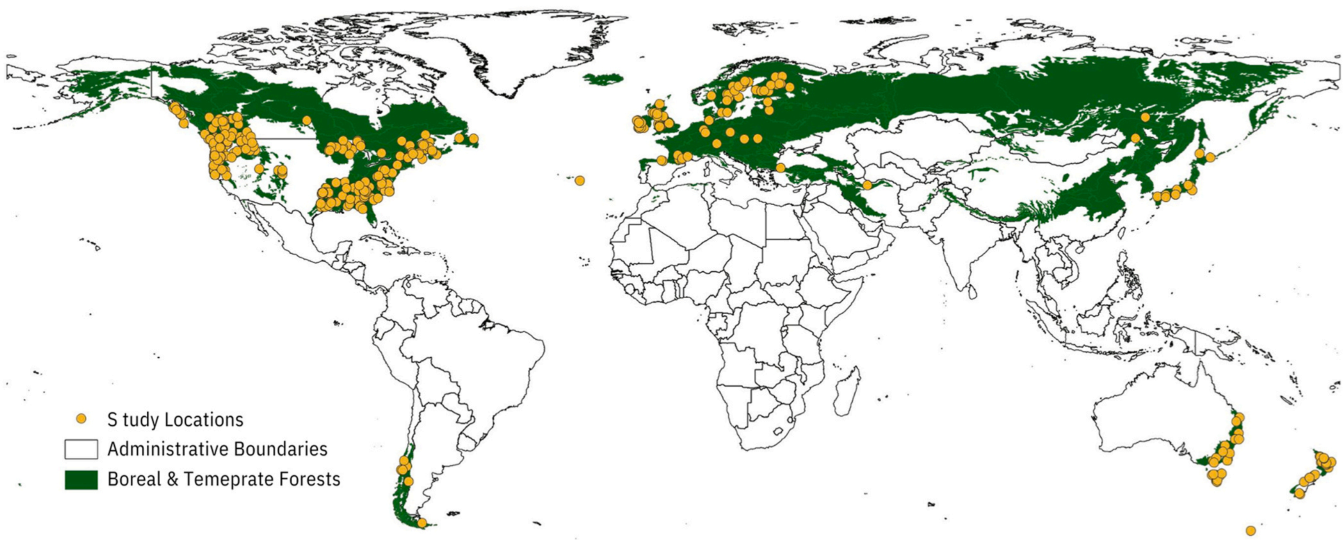

Fig. 1. Map of locations where studies assessing the effects of timber harvesting on water quality and biodiversity in running waters have taken place. Only literature published prior to November 2020 is captured by this map (n = 638 studies).

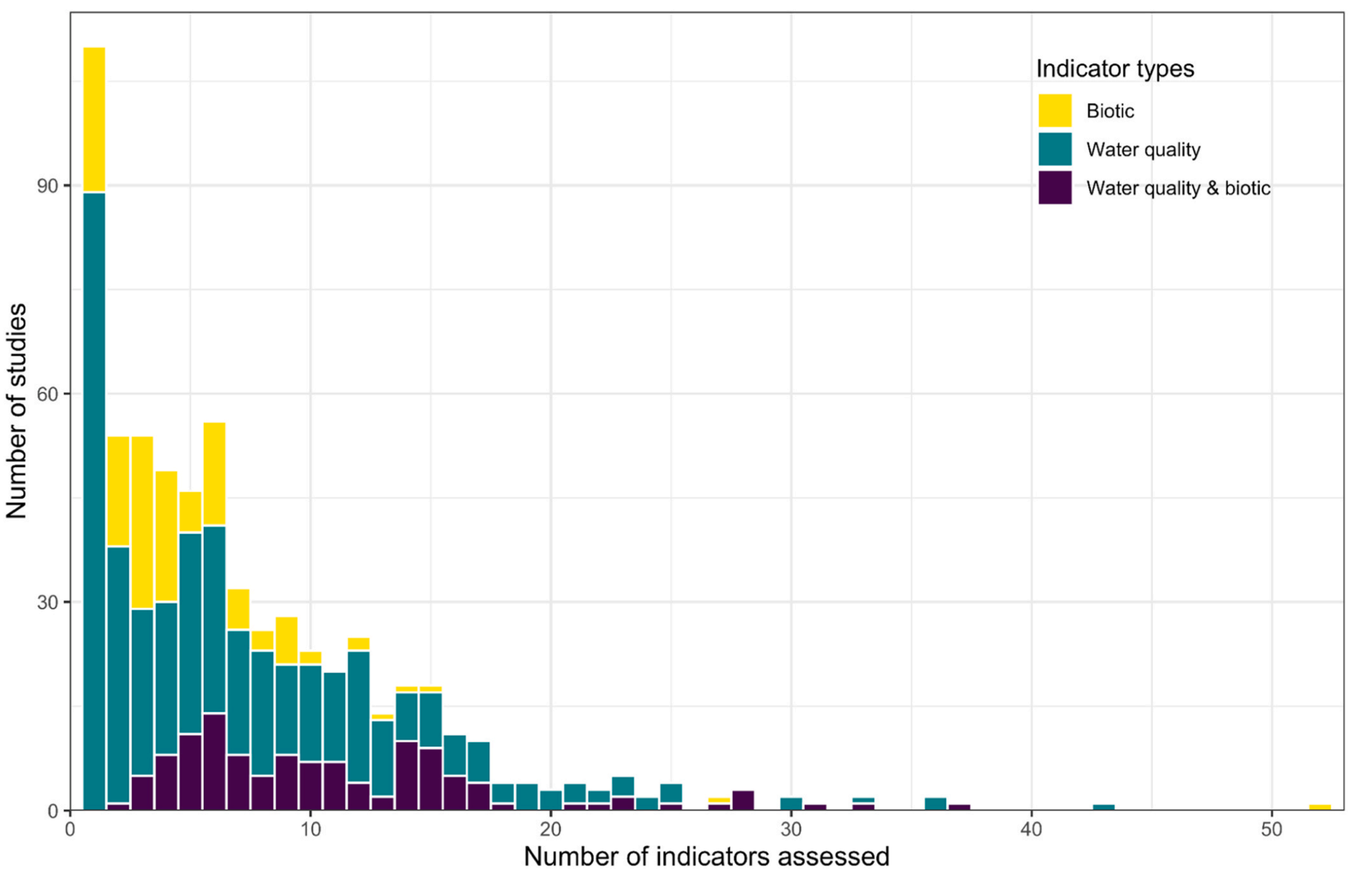

Fig. 2. The number of unique water quality and biotic indicators assessed in individual studies. Colors of the bars indicate if studies assessed biotic indicators, water quality indicators or both (n = 638 studies).

Among the 16 different types of water quality indicators assessed, nitrogen-related measures (16 %, n = 285) and measures of acidity and alkalinity (12 %, n = 223) were the most commonly assessed, with only a very small proportion of studies quantified pesticide concentrations (n = 8 studies)(Fig. 3a).

Among studies that assessed biotic indicators (39 %, n = 248), the most common taxa assessed were benthic macroinvertebrates (50 %, n = 124), followed by fish (18 %, n = 45), and amphibians (10 %, n = 25). Mosses were the least frequently assessed sub-category of taxa, with only a single study having collected data about them (Fig. 4). Studies assessed anywhere between 1 and 6 different taxa (mean = 1.48, sd = 0.79), but the majority of studies assessed species from a single taxon (66 %, n = 163). Looking at the total individual biotic indicators assessed across all studies (n = 1200) richness (17 %, n = 200) and

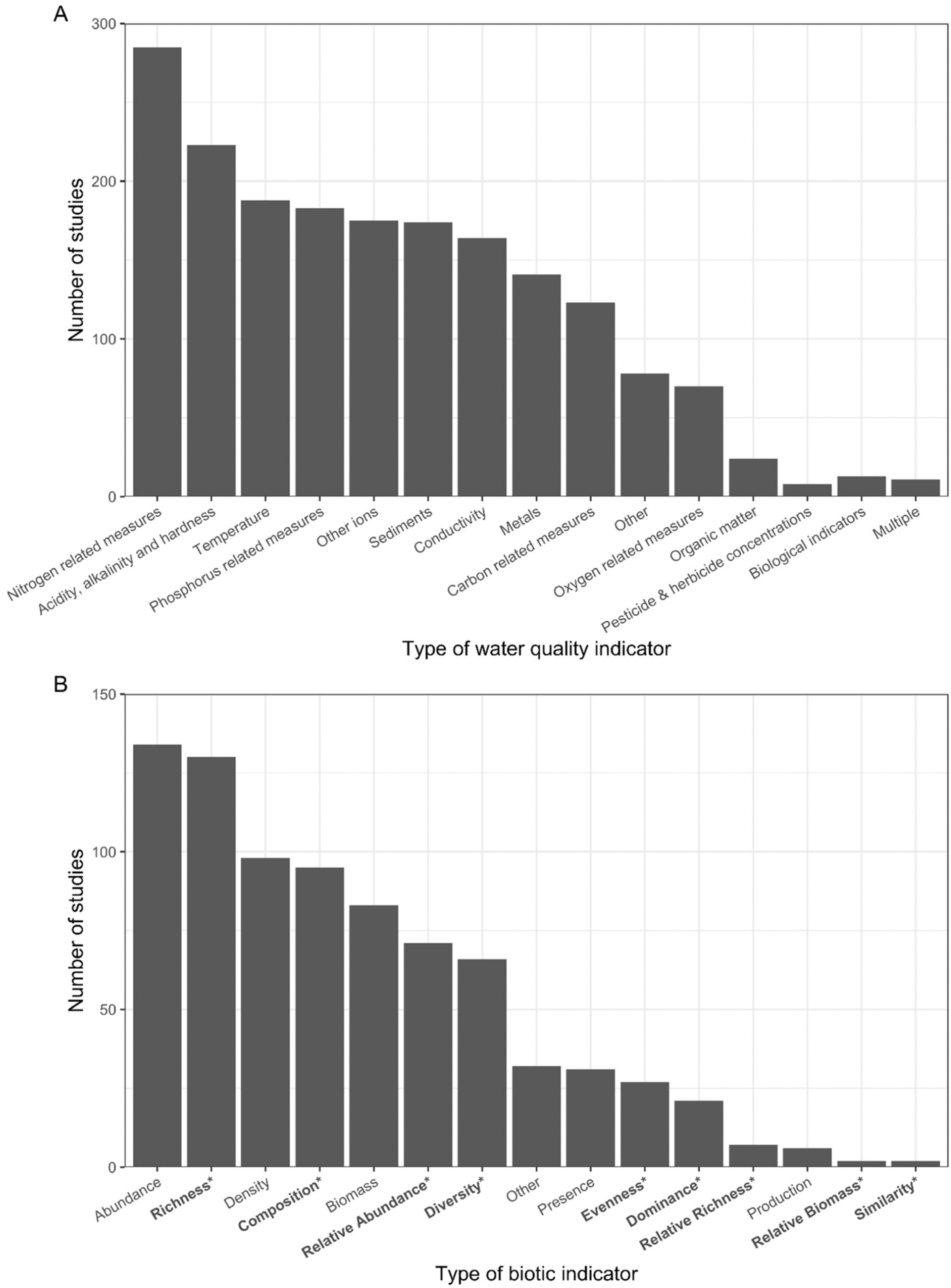

Fig. 3. The number of studies that assessed specific types of water quality and biotic indicators. Panel A: studies focused on water quality (80 %, n = 511). Panel B: studies focused on biotic indicators (39 %, n = 248), where biodiversity-focused indicators are bolded and followed by an asterisk.

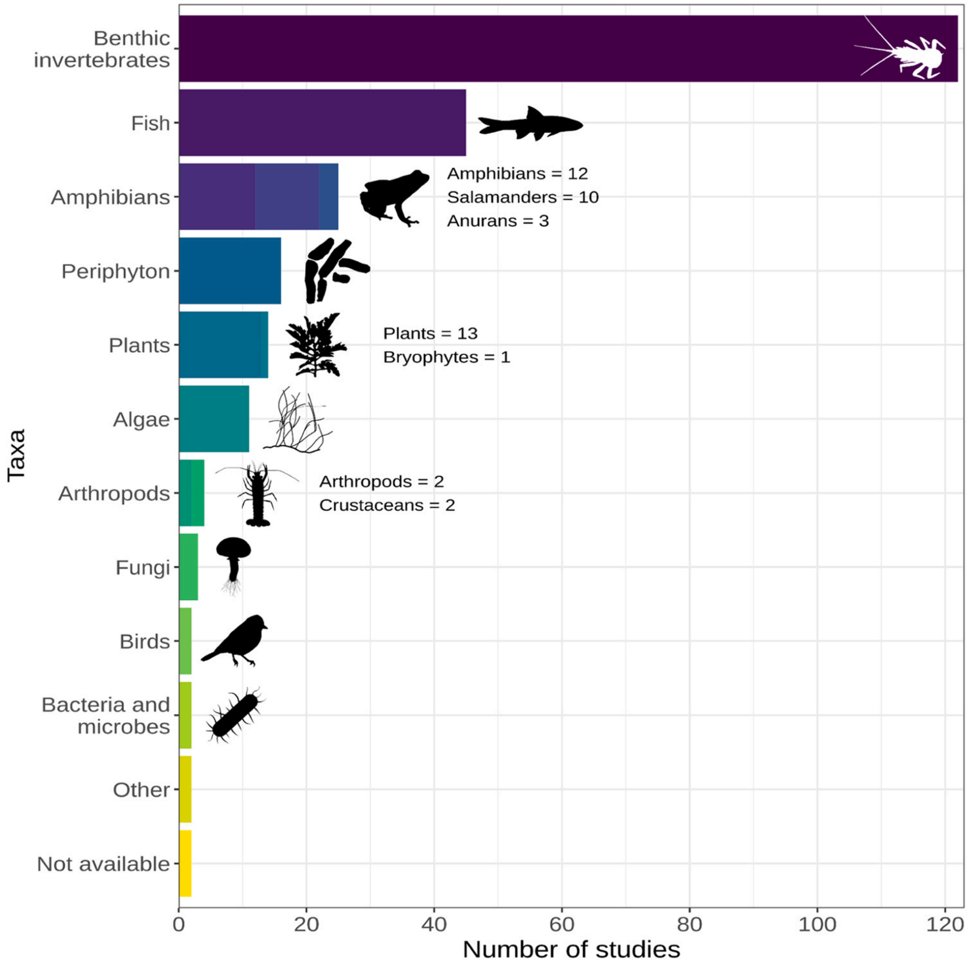

Fig. 4. Taxa assessed by studies focused on biotic indicators (39 %, n = 248). Each bar includes different colors for sub-categories which are named in writing on the left side of bars. Benthic macroinvertebrates and arthropods are separated in spite of arthropods being a type of benthic macroinvertebrate to distinguish studies that solely looked at arthropods. All included species carry out a component of their life cycle in the water (e.g. included birds breed in the water).

abundance (16 %, n = 194) were most frequently assessed, whereas measures of similarity and relative biomass were the least frequently quantified (for both: 0.2 %, n = 2). Biodiversity-focused biotic indicators (51 % of total biotic indicator assessments, n = 606) were assessed at similar frequency to non-biodiversity focused ones (49 %, n = 594) (Fig. 3b).

Among the 638 studies from which we compiled data, 11 % (i.e. 67 studies) did not have information about the timeframe over which their water quality and biotic data was collected. Among studies that did contain this temporal information, the analyzed data spanned a maximum of 60 years (mean = 7 years, sd = 8 years), but most studies (56 %, n = 358 studies) looked at data collected over a period of 5 years or less (Fig. 5a). Studies assessing biotic indicators collected data over shorter time periods (up to 45 years, mean = 3 years) than those assessing water quality (up to 60 years, mean = 7 years). Some level of information about when the timber harvesting events affecting assessed study sites had taken place was available in most studies (73 %, n = 466 studies). The range of time between harvesting and water quality or biotic data collection spanned a maximum of 150 years after harvesting (mean = 9 years, sd = 17 years), but the majority of studies that contained this temporal information (66 %, n = 309 studies) only collected data up to 5 years after harvesting (Fig. 5b). Among studies that collected information about water quality or biotic data before harvesting started (35 %, n = 225 studies), the longest time span that took place prior to harvesting was 20 years (mean = 3 years, sd = 3 years), although 40 % of these (91 studies) only collected data in the year prior to harvesting.

3.4. Harvesting types and extents

Studies took place in areas affected by between one and six different types of timber harvesting, although the majority of studies (73 %, n = 470 studies) were focused on a single type of harvesting (Figure S3, Appendix B, Section B.2). Clearcuts were the most frequently assessed type of harvesting across studies (75 %, n = 458 studies), followed by selection cuts (12 %, n = 74 studies), and thinning (10 %, n = 65 studies). Numerous studies (19 %, n = 122) did not contain information about the type(s) of harvesting that took place around the study sites they assessed, or the presence/absence of buffer zones adjacent to freshwater systems at harvested sites (46 %, n = 294 studies). Among studies that did contain information about the presence of buffer zones, the most common approach was for assessed sites to have a combination of sites with and without buffers (Fig. 6).

Most studies did not have watershed-scale information about the extent of timber harvesting that had taken place in the watersheds of the study sites from which they collected data, but 42 % (n = 289 studies) did contain this information. Among these, harvesting took place in a maximum of anywhere from 0.02 % to 100 % of the assessed watersheds (mean = 63.21 %, sd = 32.52 %). While studies with a maximum of 90–100 % of watershed-scale harvesting were most common, there were comparable amounts of studies conducted across various extents of harvesting (Figure S5a, Appendix B, Section B.2). A subset of these

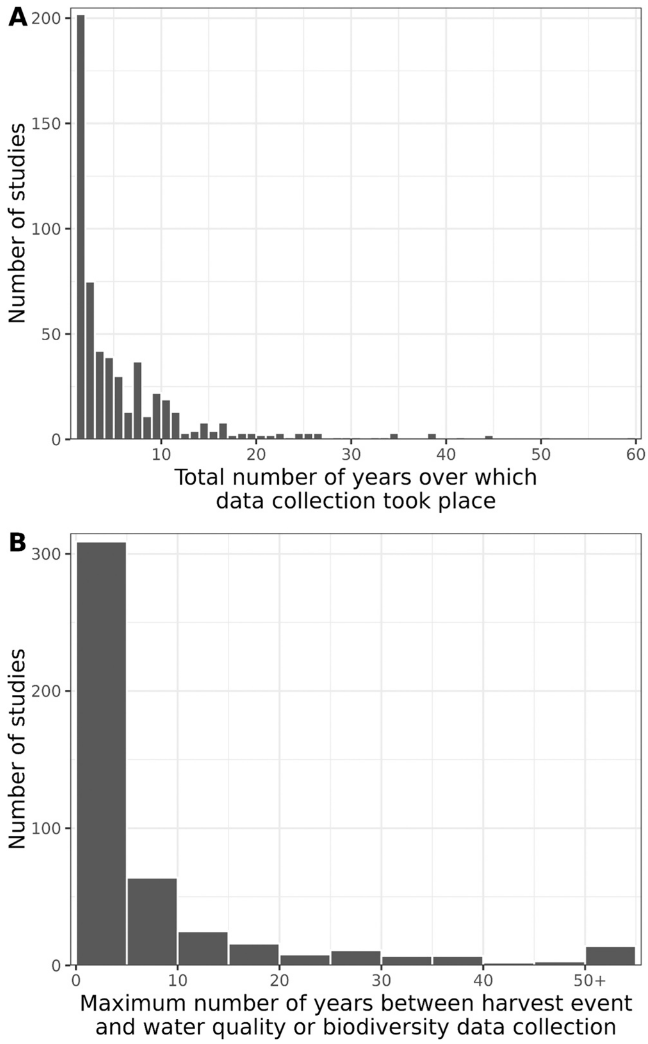

Fig. 5. Duration of studies assessing the effects of timber harvesting on water quality and biotic indicators. Panel A: total number of years over which water quality and biotic data collection took place across studies (n = 571 studies out of 638 which contained temporal information about the duration of data collection). Panel B: maximum number of years between timber harvesting and water quality and biotic data collection across studies (n = 466 studies out of 638 which contained information about when harvesting occurred relative to water quality and biotic data collection).

studies (n = 170 studies) had inter-site variability in the spatial extents of harvesting (Figure S5b, Appendix B, Section B.2).

3.5. Study designs

A small proportion of studies (2 %, n = 15) used different study designs across the various datasets they assessed. For these, we included information about each of the unique study designs they used, so the number of studies referred to in this section is higher than elsewhere throughout this publication (n = 654 vs n = 638). Before-after control-impact (BACI) was the most common design used across studies (23 %, n = 152 studies), followed by control-impact designs (17 %, n = 114 studies), control-impact designs with a gradient (28 %, n = 100 studies), BACI designs that included a gradient of impacted sites (28 %, n = 98 studies), comparisons of sites with variation in terms of different intervention modifiers (e.g. spatial extent of harvesting, time since harvesting, type of harvesting) (9 %, n = 60 studies), before-after designs (7 %, n = 44 studies). Among studies that had information about the size of the watersheds they used in their designs (i.e. area upland of the locations at which they collected information) (n = 437), the largest group of studies (40 %, n = 178) focused on watersheds between 0 and 1 km2. There were studies with sites at the outflow of larger watersheds - the largest system had a watershed of 23842 km2 - but across all studies only 84 had watersheds over 20 km2 (Figure S4). In terms of the level of replication used in study designs, 25 % of studies (n = 163 studies) did not include any form of spatial or temporal replication (i.e., respectively: replicate samples taken within sites or among different water bodies, multiple samples within or among years). However, most studies included replication, with spatial replication being the most frequent form observed across studies (28 %, n = 180 studies), closely followed by temporal replication (27 %, n = 174 studies), and studies that included both spatial and temporal replication (21 %, n = 137 studies) (Fig. 7).

Among studies that used a design that included a gradient of impacted sites (40 %, n = 258 studies) the most common type of gradient was of spatial harvesting extent (n = 106), followed by studies focused on different types of harvesting practices (n = 43), and studies assessing effects through time (n = 33). There were also studies that assessed sites distributed across several of these three gradients at once (n = 82), or focused on other types of gradients (n = 44), in variables such as land-use/land-cover or canopy cover (Figure S6). Notably, there were no BACI design studies solely focused on quantifying effects through time.

4. Discussion

Among the studies we identified, water quality was more frequently assessed than biotic data, with benthic macroinvertebrates being the most commonly assessed type of taxa. The majority of studies collected data about water quality and biotic data for no longer than five years and no more than five years after timber harvesting events. We also found that most studies did not contain watershed-scale information about timber harvesting, and that sites with small watersheds were more frequently assessed than those with larger watersheds. Together, these findings point toward three key primary research priorities to help improve understanding of the effects of timber harvesting on freshwaters. These include: 1) capturing a broader scope of effects, especially with regards to biotic data; 2) increasing our ability to detect long-term changes related to timber harvesting; and, 3) better accounting for watershed level processes. The order of these priorities does not reflect their importance, as they will all need to be addressed in tandem to inform timber harvesting policies that consistently minimize negative effects on fresh waters. We discuss each of these research priorities, provide recommendations for approaches to address them, as well as how evidence synthesis approaches that utilize and build on the dataset we compiled for this map could help contribute to addressing existing research gaps.

4.1. Capture a broader scope of effects

Our findings echo those of other work that documented a disparity between efforts to understand the effects of timber harvesting on water quality versus freshwater biodiversity (Warrington et al., 2017), with more of the existing work focused on water quality than freshwater biodiversity and biotic data. This highlights a need for increased research effort on the effects of timber harvesting on freshwater biodiversity - an especially important task as we work to bend the curve on global freshwater biodiversity loss (Tickner et al., 2020). Critical reflection is important regarding which elements of diversity are measured, their ability to effectively detect change (Baumgärtner, 2006; Santini et al., 2017), and what appropriate freshwater biodiversity conservation targets are.

Our findings also highlight a tendency for research in this field to focus on water quality or biotic data separately, as opposed to in tandem. This approach is not inherently flawed, as detailed assessments of

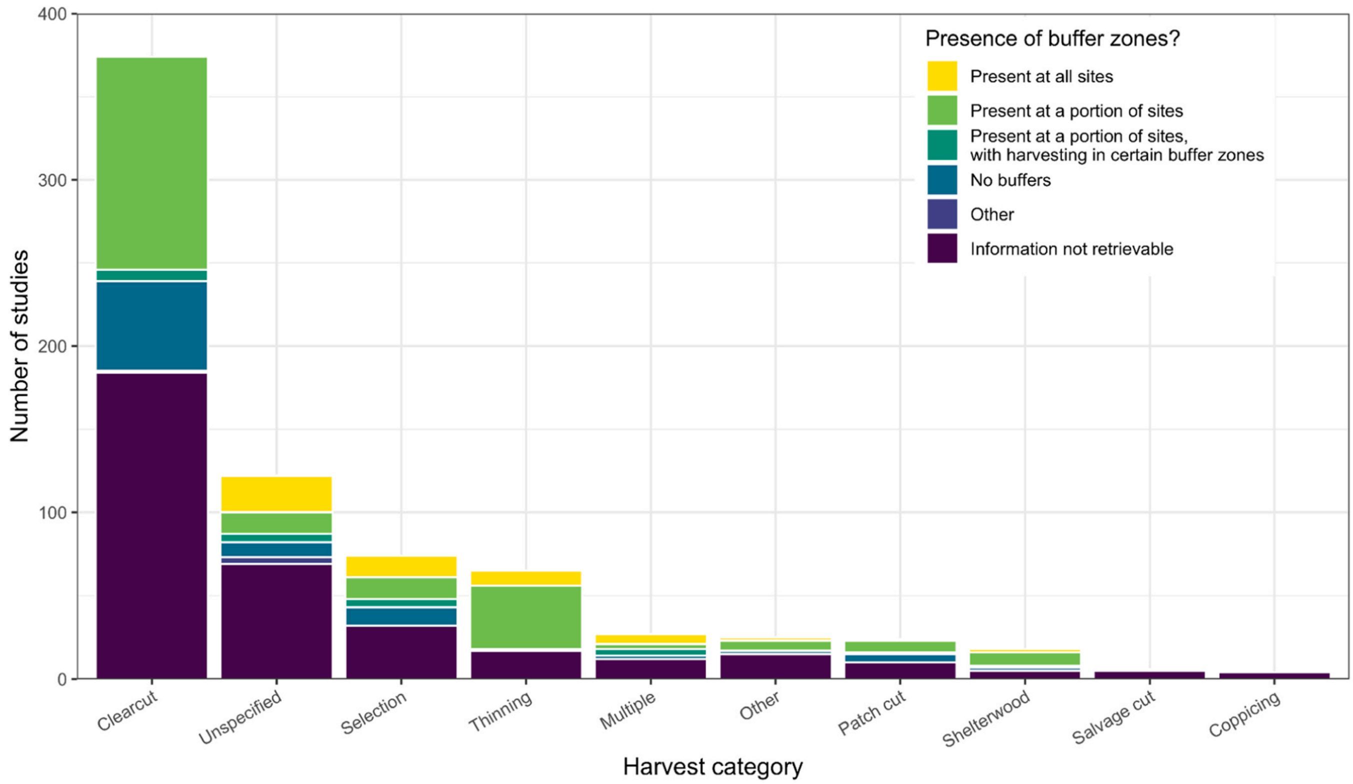

Fig. 6. Number of studies assessing different types of timber harvesting and their inclusion of riparian buffer zones. Colors of the bars indicate if studies included information about buffer zones in the harvesting treatments they explored and what types of buffers were included when this information was available (n = 638).

specific aspects of water quality or biotic data are important for advancing understanding of changes, and can shed light on the factors driving these changes. It is also understandable, given the potential logistical and cost difficulties of comprehensive biophysicochemical assessments. However, this type of approach cannot capture interactions among elements of water quality and biodiversity (or other biotic data) following harvesting, which is key to a holistic understanding of how timber harvesting affects freshwaters and the mechanisms underpinning these effects (Côté et al., 2016; Jordano, 2016; Lunn et al., 2017).

There is a specific need to increase the amount of research that investigates effects of harvesting on freshwater taxa other than benthic macroinvertebrates - a finding supported by other synthesizing work that extended beyond boreal and temperate forests (Lunn et al., 2017). Although benthic macroinvertebrates are a critical component of freshwater biodiversity that can serve as a useful indicator of the effects of harvesting on other taxa (Davies and Nelson, 1994; Kaylor and Warren, 2018), different taxonomic groups and even different individual species can respond differently to stressors such as timber harvesting (Johnson and Hering, 2009). The skew toward invertebrate research we documented thus entails risk of missing key information about the effects of harvesting on freshwater biodiversity in general, as well as other types of taxonomic groups. Using novel tools like environmental DNA to capture information about a larger breadth of freshwater biodiversity is one strategy that could help address this gap (Altermatt et al., 2023).

Although there were many studies assessing effects of timber harvesting on indicators of water quality, we found that some aspects of water quality were not well-represented by existing literature captured by our search. For example, very few studies assessed concentrations of pesticides or herbicides in water, although these are routinely applied during certain types of forestry operations (10,000 years institute, n.d.). Also, in spite of the vast diversity of water quality indicators measured across studies, not a single one of these focused on people's perceptions of water quality. Of course, including relevant additional terms our search string did not incorporate like "pesticide* " or "perception* " to specifically target literature about these other aspects of water quality would likely have broadened results. Indeed, the search terms we selected could have benefited from being more comprehensive. Still, given that our search terms did include "water quality", the fact that we did not document a wider breadth of indicators speaks to what is currently valued in scientific literature seeking to document the effects of timber harvesting on water quality. Increasing attention toward understudied aspects of water quality and the variety of voices heard in this body of literature could help generate a more holistic understanding of the effects of harvesting on water quality, as well as how people understand and relate to those effects, and in turn guide improved stewardship of waters (Leonard et al., 2023).

4.2. Increase ability to detect long-term changes

Ensuring studies take place over longer time periods than most current research will help gain insight into the full extent of the effects of timber harvesting on freshwaters. This is important because short-term research can generate trends that are misleading. For example, in Peterman et al.'s (2011) investigation of the effects of timber harvesting on salamanders they found that salamander abundance increased in areas with smaller buffers relative to those with larger buffers or no harvesting. However, they point out that this was likely due to an early response of salamanders migrating offland and into water as a result of harvesting, and that this migration is likely to in fact have lasting negative effects on the salamander population abundance. Xu and Xu's (2018) study on water quality showcases how short-term research focused on sediment delivery is susceptible to over- or under-estimating the effects of harvesting best management practices because of how suspended sediment transport is mediated by intense storms, which are usually randomly distributed through time and infrequent. Increasing the duration of studies can help control for these types of potential erroneous trends and develop a more robust understanding of the effects of harvesting through time.

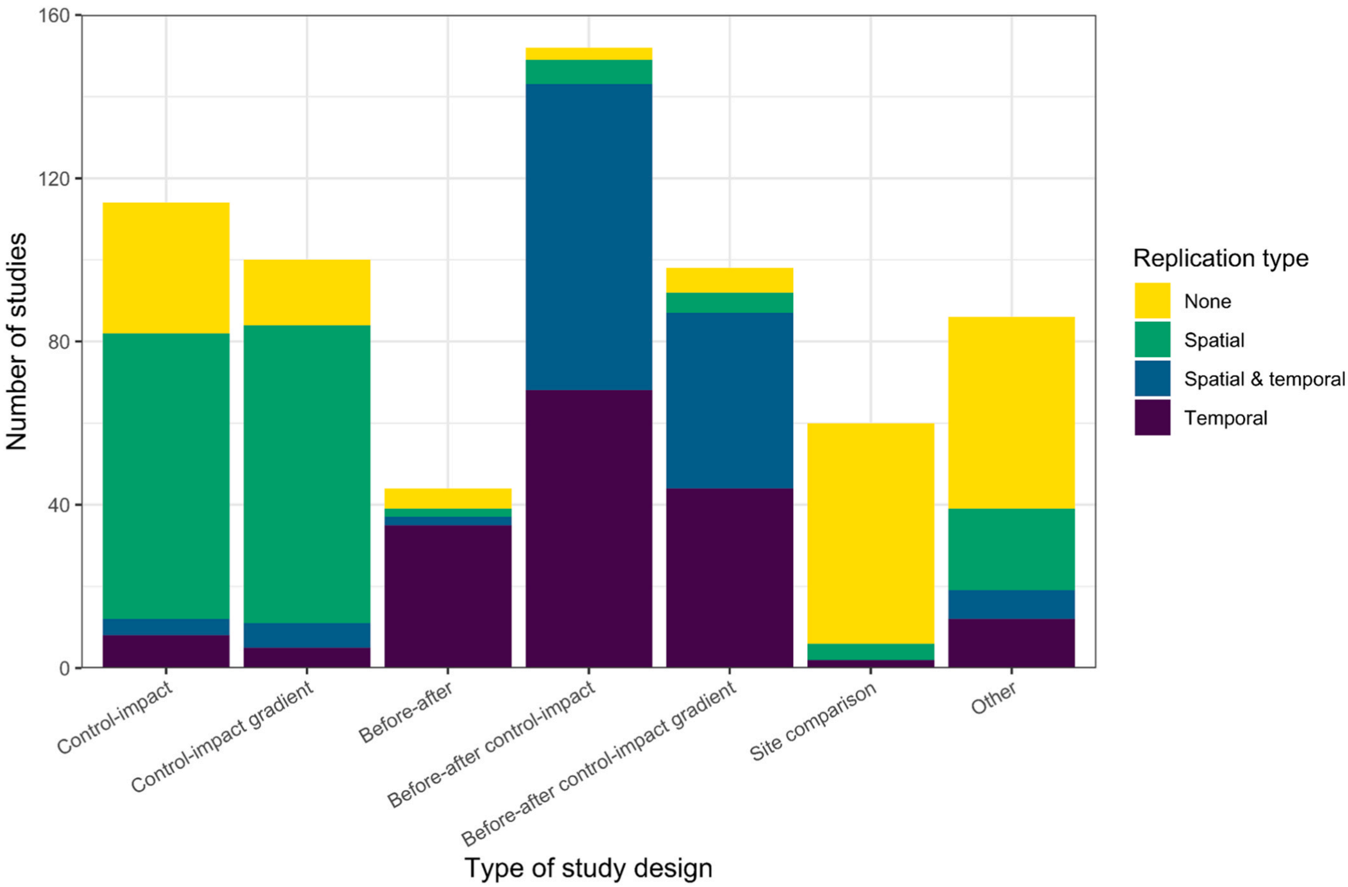

Fig. 7. Types of designs and replication used by studies. Colors of the bars indicate if studies used replication and the types of replication they included when relevant (n = 654; although only 638 unique studies are included in this analysis, 15 of these included more than one type of design).

Short-term studies also make it difficult to understand post-harvesting recovery trajectories; information that is useful when it comes to sustainable landscape-scale planning and avoiding problematic cumulative effects (Contant and Wiggins, 1991; Mansuy et al., 2020). Among studies we compiled that included temporal information, the majority quantified water quality or biodiversity no more than five years after harvesting, but research shows recovery can take longer (Davies et al., 2005; Erdozain et al., 2018; Yeung et al., 2017), and certain effects may even last for decades or showcase nonlinear recovery trajectories (Adams et al., 2014; Xu and Xu, 2018). One particularly alarming gap is the negligible amount of research assessing effects of harvesting on biotic indicators through time, especially given that the only two studies we found assessing this relationship over the course of decades documented lasting effects on certain species of fish (Helliwell et al., 2014; Martens et al., 2019). Although increasing the temporal scope of research undertaken in this field represents logistical challenges, it is an important gap that needs to be filled. Research utilizing the existing network of experimental forests - many of which have substantial prior data dating back several decades - shows promise as a means to begin addressing this gap (Elliott and Vose, 2011; Leach et al., 2020; Yeung et al., 2017).

4.3. Account for watershed level processes

Increasing the proportion of studies in this field that incorporate watershed-scale information and work at larger spatial scales could help better account for and understand the potential effects of connectivity and watershed level processes in freshwater systems. This is important because various components of a system that affect water quality (e.g., sediments, nutrients) -which can in turn influence biodiversity and individual living organisms- move through hydrologically connected landscapes. Failing to account for this can lead to biased experimental designs and analyses. For example, we documented studies that considered various sites as independent replicates, but these sites were in fact spatially non-independent because they were situated in the same watershed and had nested and hydrologically connected components (Daoust et al., 2019). Another type of design that does not account for connectivity and poses a risk of inaccurately estimating the effects of harvesting is when sites considered to be a control that is not affected by timber harvesting have in fact had timber harvesting upstream of them. Research shows that even small amounts (i.e. less than 5 %) of watershed-scale harvesting can have effects on freshwaters (Lecerf et al., 2012), so using experimental designs that account for upstream harvesting is important. This also applies to other upland factors that can influence water quality and biodiversity and individual living organisms, such land-use (other than harvesting) and land-cover (Giri and Qiu, 2016; Miller et al., 2011), point-source pollution (Wu and Chen, 2013), important climatic events (Leigh et al., 2015), and geophysical characteristics such as topography (Fukushima and Tokuchi, 2009) or watershed size (Clément et al., 2017). Existing geographic information systems-based approaches can be used to complement field-based designs and properly account for important hydrologically connected factors upstream of sampled locations in analyses (Hanna et al., 2021; Johnson and Host, 2010).

Information about watershed-scale trends could also help inform best management practices that take freshwater connectivity and watershed level processes into consideration. For example, studies containing data across sites with watersheds that have various proportions of harvesting (Fuchs et al., 2003; Kreutzweiser et al., 2005) could be used to investigate the presence of watershed-scale harvesting thresholds beyond which effects on freshwaters are deemed too high. Although previous research has highlighted how the numerous factors that influence water quality and biodiversity make generalizations about acceptable proportions of watershed-scale harvesting difficult (Picchio et al., 2021), research in the agricultural field suggests there is potential to identify watershed-scale thresholds that can inform improved management (Clément et al., 2017; Qiu and Turner, 2015). Further, there has been recent progress with regards to meaningful identification of forest disturbance thresholds and related hydrological impacts (e.g. Hou and Wei, 2024). Watershed-scale information about the configuration of harvesting may also be useful in informing best-management practices (Johnson and Host, 2010). In general, it is clear that adequately caring for freshwaters requires that hydrological connectivity and watershed level processes be considered (Abell et al., 2007), highlighting the importance of accounting for watershed level processes by including watershed-scale information in analyses documenting impacts of harvesting.

4.4. Quantify impact through more detailed synthesis

Through our evidence mapping, we discovered several promising opportunities for future evidence synthesis that could help improve understanding of the effects of timber harvesting on freshwaters. For example, we found just over 100 studies that measured both biotic and water quality indicators, had data collected over more than 10 years, and likely provided sufficient information to conduct a meta-analysis. Together, these studies represent immense potential to improve understanding of longer-term effects of harvesting on freshwaters. We also found almost 300 studies that contained watershed-scale information about proportions of timber harvesting, almost 100 of which contained data across a gradient of proportions of watershed-scale harvesting. These studies may contain sufficient information to explore water quality implications of different extents watershed-scale harvesting which could be used to identify thresholds for best management practices. Synthesizing the findings of the studies compiled in this evidence map beyond how existing reviews have already done so (see introduction) is a promising avenue of future research geared toward improved best management practices. That said, those interested in using this dataset to conduct syntheses could benefit from first updating it given that several years elapsed between data collection and publication of this evidence synthesis. Other particularly valuable ways to expand this dataset would be to include studies from tropical regions - which are also major wood producers; expand the key words used to locate publications related to water quality to include other common endpoints in forest harvesting related to water quality such as temperature, carbon, pollutants and specifically relevant metals such as mercury; expand the types of biotic indicators assessed to also include functional indicators such as primary production, respiration, decomposition, and nutrient cycling - which are an important aspect of ecosystem integrity; and, include studies that collect information about single species (as opposed to only two or more, as we did).

5. Conclusion

Our evidence map compiled information from 638 studies quantifying effects of timber harvesting on water quality or biotic indicators in waters running through boreal and temperate forests. Three future research priorities emerged through this synthesis, including the need to: 1) capture a broader scope of effects, particularly when it comes to biotic indicators (and especially biodiversity), 2) increase the ability of research to detect long-term effects of harvesting, and 3) better account for watershed level processes. The dataset published alongside this map provides an excellent starting point to work toward a global and comprehensive dataset, address some of these future research priorities through further evidence synthesis, and utilize findings to inform improved best management practices for timber harvesting that minimize effects on freshwater quality and biodiversity.

Funding

This work was supported by a Fonds de Recherche du Quebec en Nature et Technologie B3X Postdoctoral Fellowship held by D.E.L.H. [284354, 2021–2023], an ECO Canada Science Horizon Internship wage subsidy held by Meagan Harper [2022], and a Natural Sciences and Engineering Research Council (NSERC) Discovery Grant to J.R.B. (RGPIN 2016–06147).

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests

Dalal Hanna reports financial support was provided by Quebec Research Fund Nature and Technology. Joseph Bennett reports financial support was provided by Natural Sciences and Engineering Research Council of Canada. Meagan Harper reports financial support was provided by ECO Canada. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We are thankful for all the researchers who published work investigating the effects of timber harvesting on water quality and biodiversity which allowed us to compile this map.

Appendices. Supporting information

All supporting information is found in Appendix A, which contains additional information about methods, and Appendix B, which contains additional information about the dataset we assembled and results. Both these appendices are found in a single file. We also included a copy of our scoping record (Appendix C) and article screening procedure.

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.foreco.2024.122425.

Data availability

The data and R code that accompany this article are available on Zenodo (https://zenodo.org/records/14262631).

References

10,000 years institute, n.d. Pesticides & Forestry: An Overview of Potential Impacts to Fish, Wildlife and People. https://www.10000yearsinstitute.org/pesticides-in-forestry.

Abell, R., Allan, J.D., Lehner, B., 2007. Unlocking the potential of protected areas for freshwaters. Biol. Conserv. 134, 48–63. https://doi.org/10.1016/j.biocon.2006.08.017.

Adams, M.B., Knoepp, J.D., Webster, J.R., 2014. Inorganic nitrogen retention by watersheds at fernow experimental forest and coweeta hydrologic laboratory. Soil Sci. Soc. Am. J. 78. https://doi.org/10.2136/sssaj2013.11.0463nafsc.

Altermatt, F., Carraro, L., Antonetti, M., Albouy, C., Zhang, Y., Lyet, A., Zhang, X., Pellissier, L., 2023. Quantifying biodiversity using eDNA from water bodies: General principles and recommendations for sampling designs. Environ. DNA 5, 671–682. https://doi.org/10.1002/edn3.430.

Arets, E.J.M.M., van der Meer, P.J., Verwer, C.C., Hengeveld, G.M., Tolkamp, G.W., Nabuurs, G.J., van Oorschot, M., 2011. Global Wood Production Assessment of industrial round wood supply from forest management systems in different global regions (No. Alterra Report 1808 ISSN 1566-7197).

Baumgärtner, S., 2006. Measuring the diversity of what? And for what purpose? A conceptual comparison of ecological and economic biodiversity indices. SSRN Electron. J. https://doi.org/10.2139/ssrn.894782.

Bryan, J. (2023). googlesheets4: Access Google Sheets using the Sheets API V4.

Chiwa, M., Haga, H., Kasahara, T., Tateishi, M., Saito, T., Kato, H., Otsuki, K., Onda, Y., 2020. Effect of forest thinning on hydrologic nitrate exports from a N-saturated plantation. J. For. Res 31, 387–395. https://doi.org/10.1007/s11676-018-0784-5.

Clément, F., Ruiz, J., Rodríguez, M.A., Blais, D., Campeau, S., 2017. Landscape diversity and forest edge density regulate stream water quality in agricultural catchments. Ecol. Indic. 72, 627–639. https://doi.org/10.1016/j.ecolind.2016.09.001.
Collaboration for Environmental Evidence, 2022. Guidelines and Standards for Evidence Synthesis in Environmental Management. Version 5.1.
Contant, C.K., Wiggins, L.L., 1991. Defining and analyzing cumulative environmental impacts. Environ. Impact Assess. Rev. 11, 297–309. https://doi.org/10.1016/0195-9255(91)90003-3.
Cook, C.N., Nichols, S.J., Webb, J.A., Fuller, R.A., Richards, R.M., 2017. Simplifying the selection of evidence synthesis methods to inform environmental decisions: A guide for decision makers and scientists. Biol. Conserv. 213, 135–145. https://doi.org/10.1016/j.biocon.2017.07.004.
R. Core Team, 2022. R: A language and environment for statistical computing.
Côté, I.M., Darling, E.S., Brown, C.J., 2016. Interactions among ecosystem stressors and their importance in conservation. Proc. R. Soc. B Biol. Sci. 283, 20152592. https://doi.org/10.1098/rspb.2015.2592.
Daoust, K., Kreutzweiser, D.P., Guo, J., Creed, I.F., Sibley, P.K., 2019. Climate-influenced catchment hydrology overrides forest management effects on stream benthic macroinvertebrates in a northern hardwood forest. For. Ecol. Manag. 452, 117540. https://doi.org/10.1016/j.foreco.2019.117540.
Davies, P.E., Cook, L.S.J., McIntosh, P.D., Munks, S.A., 2005. Changes in stream biota along a gradient of logging disturbance, 15 years after logging at Ben Nevis, Tasmania. For. Ecol. Manag. 219, 132–148. https://doi.org/10.1016/j.foreco.2005.09.006.
Davies, P., Nelson, M., 1994. Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. Mar. Freshw. Res. 45, 1289. https://doi.org/10.1071/MF9941289.
Davis, C.T., Clatterbuck, W.K., 2003. Role of the Tennessee master logger program in implementation of best management practices on non-industrial private forests. South. J. Appl. For. 27, 36–40. https://doi.org/10.1093/sjaf/27.1.36.
Eklöf, K., Kraus, A., Weyhenmeyer, G.A., Meili, M., Bishop, K., 2012. Forestry influence by stump harvest and site preparation on methylmercury, total mercury and other stream water chemistry parameters across a boreal landscape. Ecosystems 15, 1308–1320. https://doi.org/10.1007/s10021-012-9586-3.
Elliott, K.J., Vose, J.M., 2011. The contribution of the Coweeta Hydrologic Laboratory to developing an understanding of long-term (1934–2008) changes in managed and unmanaged forests. For. Ecol. Manag. 261, 900–910. https://doi.org/10.1016/j.foreco.2010.03.010.
Erdozain, M., Kidd, K., Kreutzweiser, D., Sibley, P., 2018. Linking stream ecosystem integrity to catchment and reach conditions in an intensively managed forest landscape. Ecosphere 9, e02278. https://doi.org/10.1002/ecs2.2278.
Firke, S., Denney, B., Haid, C., Knight, R., Grosser, M., Zadra, J., 2023. janitor: Simple Tools for Examining and Cleaning Dirty Data..
Fuchs, S.A., Hinch, S.G., Mellina, E., 2003. Effects of streamside logging on stream macroinvertebrate communities and habitat in the sub-boreal forests of British Columbia, Canada. Can. J. For. Res. 33, 1408–1415. https://doi.org/10.1139/x03-070.
Fukushima, K., Tokuchi, N., 2009. Factors controlling the acid-neutralizing capacity of Japanese cedar forest watersheds in stands of various ages and topographic characteristics. Hydrol. Process. 23, 259–271. https://doi.org/10.1002/hyp.7137.
Gerth, W., Li, J.L., Van Driesche, R., Sobota, J., Murphy, C.A., Ganio, L., Skaugset, A., 2022. Local and sub-basin effects of timber harvests on stream macroinvertebrates in Hinkle Creek watershed. For. Ecol. Manag. 505, 119923. https://doi.org/10.1016/j.foreco.2021.119923.
Giri, S., Qiu, Z., 2016. Understanding the relationship of land uses and water quality in Twenty First Century: A review. J. Environ. Manag. 173, 41–48. https://doi.org/10.1016/j.jenvman.2016.02.029.
Growns, I., Davis, J., 1994. Effects of forestry activities (clearfelling) on stream macroinvertebrate fauna in south-western Australia. Mar. Freshw. Res. 45, 963. https://doi.org/10.1071/MF9940963.
Hanna, D.E.L., Lehner, B., Taranu, Z.E., Solomon, C.T., Bennett, E.M., 2021. The relationship between watershed protection and water quality: The case of Québec, Canada. Freshw. Sci. 40, 382–396. https://doi.org/10.1086/714598.
Helliwell, R.C., Aherne, J., Nisbet, T.R., MacDougall, G., Broadmeadow, S., Sample, J., Jackson-Blake, L., Doughty, R., 2014. Modelling the long-term response of stream water chemistry to forestry in Galloway, Southwest Scotland. Ecol. Indic. 37, 396–411. https://doi.org/10.1016/j.ecolind.2013.01.031.
Hou, Y., Wei, X., 2024. Forest Disturbance Thresholds and Cumulative Hydrological Impacts. Water Resour. Res. 60, e2024WR037339. https://doi.org/10.1029/2024WR037339.
Johnson, R.K., Hering, D., 2009. Response of taxonomic groups in streams to gradients in resource and habitat characteristics. J. Appl. Ecol. 46, 175–186. https://doi.org/10.1111/j.1365-2664.2008.01583.x.
Johnson, L.B., Host, G.E., 2010. Recent developments in landscape approaches for the study of aquatic ecosystems. J. North Am. Benthol. Soc. 29, 41–66. https://doi.org/10.1899/09-030.1.
Jordano, P., 2016. Chasing Ecological Interactions. PLoS Biol. 14, e1002559. https://doi.org/10.1371/journal.pbio.1002559.
Kaylor, M.J., Warren, D.R., 2018. Canopy closure after four decades of postlogging riparian forest regeneration reduces cutthroat trout biomass in headwater streams through bottom-up pathways. Can. J. Fish. Aquat. Sci. 75, 513–524. https://doi.org/10.1139/cjfas-2016-0519.
Kreutzweiser, D.P., Capell, S.S., Good, K.P., 2005. Macroinvertebrate community responses to selection logging in riparian and upland areas of headwater catchments in a northern hardwood forest. J. North Am. Benthol. Soc. 24, 208–222. https://doi.org/10.1899/0887-3593(2005)024< 0208:MCRTSL> 2.0.CO;2.
Kreutzweiser, D.P., Hazlett, P.W., Gunn, J.M., 2008. Logging impacts on the biogeochemistry of boreal forest soils and nutrient export to aquatic systems: a review. Environ. Rev. 16, 157–179. https://doi.org/10.1139/A08-006.
Leach, J.A., Buttle, J.M., Webster, K.L., Hazlett, P.W., Jeffries, D.S., 2020. Travel times for snowmelt-dominated headwater catchments: Influences of wetlands and forest harvesting, and linkages to stream water quality. Hydrol. Process. 34, 2154–2175. https://doi.org/10.1002/hyp.13746.
Lecerf, A., Baudoin, J.-M., Besson, A.A., Lamothe, S., Lagrue, C., 2012. Is smaller necessarily better? Effects of small-scale forest harvesting on stream ecosystems. Ann. Limnol. - Int. J. Limnol. 48, 401–409. https://doi.org/10.1051/limn/2012028.
Leigh, C., Bush, A., Harrison, E.T., Ho, S.S., Luke, L., Rolls, R.J., Ledger, M.E., 2015. Ecological effects of extreme climatic events on riverine ecosystems: insights from A ustralia. Freshw. Biol. 60, 2620–2638. https://doi.org/10.1111/fwb.12515.
Leonard, K., David-Chavez, D., Smiles, D., Jennings, L., Alegado, R. ʻAnolani, Manitowabi, J., Arsenault, R., Begay, R.L., Davis, D.D., 2023. Water Back: A Review Centering Rematriation and Indigenous Water Research Sovereignty 16.
Levno, A., Rothacher, J., 1967. Increases in maximum stream temperatures after logging in old-growth Douglas-fir watersheds. U.S. Forest Service.
Löfgren, S., Ring, E., Von Brömssen, C., Sørensen, R., Högbom, L., 2009. Short-term effects of clear-cutting on the water chemistry of two boreal streams in northern sweden: a paired catchment study. AMBIO J. Hum. Environ. 38, 347–356. https://doi.org/10.1579/0044-7447-38.7.347.
Lunn, T., Munks, S., Carver, S., 2017. The impacts of timber harvesting on stream biota – an expanding field of heterogeneity. Biol. Conserv. 213, 154–166. https://doi.org/10.1016/j.biocon.2017.06.025.
Mansuy, N., Burton, P.J., Stanturf, J., Beatty, C., Mooney, C., Besseau, P., Degenhardt, D., MacAfee, K., Lapointe, R., 2020. Scaling up forest landscape restoration in Canada in an era of cumulative effects and climate change. For. Policy Econ. 116, 102177. https://doi.org/10.1016/j.forpol.2020.102177.
Martens, K.D., Devine, W.D., Minkova, T.V., Foster, A.D., 2019. Stream conditions after 18 years of passive riparian restoration in small fish-bearing watersheds. Environ. Manag. 63, 673–690. https://doi.org/10.1007/s00267-019-01146-x.
Mckie, B.G., Malmqvist, B., 2009. Assessing ecosystem functioning in streams affected by forest management: increased leaf decomposition occurs without changes to the composition of benthic assemblages. Freshw. Biol. 54, 2086–2100. https://doi.org/10.1111/j.1365-2427.2008.02150.x.
Millennium Ecosystem Assessment (Program) (Ed.), 2005. Ecosystems and human well-being: wetlands and water synthesis. World Resources Institute, Washington, DC.
Miller, J.D., Schoonover, J.E., Williard, K.W.J., Hwang, C.R., 2011. Whole catchment land cover effects on water quality in the lower kaskaskia river watershed. Water Air. Soil Pollut. 221, 337–350. https://doi.org/10.1007/s11270-011-0794-9.
Mlambo, M.C., Paavola, R., Louhi, P., Soininen, J., Virtanen, R., Muotka, T., 2015. Bioenergy vs biodiversity: effects of intensive forest biomass removal on stream and riparian communities. Forestry 88, 368–375. https://doi.org/10.1093/forestry/cpv008.
Olson, D.M., Dinerstein, E., Wikramanayake, E.D., Burgess, N.D., Powell, G.V.N., Underwood, E.C., D'amico, J.A., Itoua, I., Strand, H.E., Morrison, J.C., Loucks, C.J., Allnutt, T.F., Ricketts, T.H., Kura, Y., Lamoreux, J.F., Wettengel, W.W., Hedao, P., Kassem, K.R., 2001. Terrestrial ecoregions of the world: a new map of life on earth. BioScience 51, 933. https://doi.org/10.1641/0006-3568(2001)051[0933:TEOTWA]2.0.CO;2.
Opendatasoft, 2023. World Administrative Boundaries - Countries and Territories — Opendatasoft [WWW Document]. URL ⟨https://public.opendatasoft.com/explore/dataset/world-administrative-boundaries/information/⟩ (accessed 3.30.24).
Peterman, W.E., Crawford, J.A., Semlitsch, R.D., 2011. Effects of even-aged timber harvest on stream salamanders: support for the evacuation hypothesis. For. Ecol. Manag. 262, 2344–2353. https://doi.org/10.1016/j.foreco.2011.08.030.
Petrokofsky, G., Hooper, O., Petrokofsky, L., Gant, A.E., Harvey, W.J., Willis, K.J., 2021. What are the impacts of the wood pellet industry on biodiversity in Southeastern USA? A systematic evidence synthesis. For. Ecol. Manag. 483, 118773. https://doi.org/10.1016/j.foreco.2020.118773.
Picchio, R., Jourgholami, M., Zenner, E.K., 2021. Effects of forest harvesting on water and sediment yields: a review toward better mitigation and rehabilitation strategies. Curr. For. Rep. 7, 214–229. https://doi.org/10.1007/s40725-021-00146-7.
Pullin, A., Frampton, G., Jongman, R., Kohl, C., Livoreil, B., Lux, A., Pataki, G., Petrokofsky, G., Podhora, A., Saarikoski, H., Santamaria, L., Schindler, S., Sousa-Pinto, I., Vandewalle, M., Wittmer, H., 2016. Selecting appropriate methods of knowledge synthesis to inform biodiversity policy. Biodivers. Conserv. 25, 1285–1300. https://doi.org/10.1007/s10531-016-1131-9.
QGIS.org, 2021. QGIS Geographic Information System.
Qiu, J., Turner, M.G., 2015. Importance of landscape heterogeneity in sustaining hydrologic ecosystem services in an agricultural watershed. Ecosphere 6, 1–19. https://doi.org/10.1890/ES15-00312.1.
Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd, K.A., MacCormack, T.J., Olden, J.D., Ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., Cooke, S.J., 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. 94, 849–873. https://doi.org/10.1111/brv.12480.
Richardson, J.S., Béraud, S., 2014. Effects of riparian forest harvest on streams: a meta-analysis. J. Appl. Ecol. 51, 1712–1721. https://doi.org/10.1111/1365-2664.12332.
Santini, L., Belmaker, J., Costello, M.J., Pereira, H.M., Rossberg, A.G., Schipper, A.M., Ceausu, S., Dornelas, M., Hilbers, J.P., Hortal, J., Huijbregts, M.A.J., Navarro, L.M., Schiffers, K.H., Visconti, P., Rondinini, C., 2017. Assessing the suitability of diversity metrics to detect biodiversity change. Biol. Conserv. 213, 341–350. https://doi.org/10.1016/j.biocon.2016.08.024.

Smith, B.J., Davies, P.E., Munks, S.A., 2009. Changes in benthic macroinvertebrate communities in upper catchment streams across a gradient of catchment forest operation history. For. Ecol. Manag. 257, 2166–2174. https://doi.org/10.1016/j.foreco.2009.02.029.

Strayer, D.L., Dudgeon, D., 2010. Freshwater biodiversity conservation: recent progress and future challenges. J. North Am. Benthol. Soc. 29, 344–358. https://doi.org/10.1899/08-171.1.

Tebo, L.B., 1955. Effects of siltation, resulting from impromer logging, on the bottom fauna of a small Trout stream in the Southern Appalachians. North Carolina Wildlife Resources Commission.

Tickner, D., Opperman, J.J., Abell, R., Acreman, M., Arthington, A.H., Bunn, S.E., Cooke, S.J., Dalton, J., Darwall, W., Edwards, G., Harrison, I., Hughes, K., Jones, T., Leclère, D., Lynch, A.J., Leonard, P., McClain, M.E., Muruven, D., Olden, J.D., Ormerod, S.J., Robinson, J., Tharme, R.E., Thieme, M., Tockner, K., Wright, M., Young, L., 2020. Bending the curve of global freshwater biodiversity loss: an emergency recovery plan. BioScience 70, 330–342. https://doi.org/10.1093/biosci/biaa002.

USDA, 2024. Reforestation Glossary [WWW Document]. URL ⟨https://www.fs.usda.gov/restoration/reforestation/glossary.shtml⟩ (accessed 3.30.24).

Warrington, B., Aust, W., Barrett, S., Ford, W., Dolloff, C., Schilling, E., Wigley, T., Bolding, M., 2017. Forestry best management practices relationships with aquatic and riparian fauna: a review. Forests 8, 331. https://doi.org/10.3390/f8090331.

Webb, A.A., Dragovich, D., Jamshidi, R., 2012. Temporary increases in suspended sediment yields following selective eucalypt forest harvesting. For. Ecol. Manag. 283, 96–105. https://doi.org/10.1016/j.foreco.2012.07.017.

Wickham, H., RStudio, 2023. forcats: Tools for Working with Categorical Variables (Factors).

Wickham, H., 2023b. stringr: Simple, Consistent Wrappers for Common String Operations.

Wickham, H., Chang, W., Henry, L., Pedersen, T.L., Takahashi, K., Wilke, C., Woo, K., Yutani, H., Dunnington, D., Brand, T. van den, Posit, P.B.C., 2024a. ggplot2: Create Elegant Data Visualisations Using the Grammar of Graphics.

Wickham, H., François, R., Henry, L., Muller, K., 2022. dplyr: A Grammar of Data Manipulation. R package.

Wickham, H., Henry, L., RStudio, 2023a. purrr: Functional Programming Tools.

Wickham, H., Hester, J., Francois, R., Bryan, J., Bearrows, S., Software, P., PBC, library), https://github com/mandreyel/ (mio, implementation), J.J. (grisu3, implementation), M.J. (grisu3, 2024b. readr: Read Rectangular Text Data.

Wickham, H., Vaughan, D., Girlich, M., Ushey, K., Software, P., PBC, 2024c. tidyr: Tidy Messy Data.

Willacker, J.J., Eagles-Smith, C.A., Kowalski, B.M., Danehy, R.J., Jackson, A.K., Adams, E.M., Evers, D.C., Eckley, C.S., Tate, M.T., Krabbenhoft, D.P., 2019. Timber harvest alters mercury bioaccumulation and food web structure in headwater streams. Environ. Pollut. 253, 636–645. https://doi.org/10.1016/j.envpol.2019.07.025.

Wu, Y., Chen, J., 2013. Investigating the effects of point source and nonpoint source pollution on the water quality of the East River (Dongjiang) in South China. Ecol. Indic. 32, 294–304. https://doi.org/10.1016/j.ecolind.2013.04.002.

WWF, 2012. Terrestrial Ecoregions of the World | Publications | WWF [WWW Document]. URL ⟨https://www.worldwildlife.org/publications/terrestrial-ecoregions-of-the-world⟩ (accessed 3.30.24).

Xu, Z., Xu, Y.J., 2018. Assessing effectiveness of long-term forestry best management practices on stream water quality at a basin scale—a case study in Southern USA. Environ. Monit. Assess. 190, 108. https://doi.org/10.1007/s10661-018-6497-6.

Yeung, A.C.Y., Lecerf, A., Richardson, J.S., 2017. Assessing the long-term ecological effects of riparian management practices on headwater streams in a coastal temperate rainforest. For. Ecol. Manag. 384, 100–109. https://doi.org/10.1016/j.foreco.2016.10.044.