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Review

The impacts of timber harvesting on stream biota – An expanding field of heterogeneity

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ABSTRACT

Global demand for timber products is increasing. Despite high interest in the environmental impacts of forestry and efforts to improve management practices, little synthesis of these impacts exist. This systematic review unifies the literature on timber harvest impacts on stream biota, quantifies temporal, geographical and taxonomic trends in this forestry research, and appraises widespread methodological approaches. Our findings highlight heterogeneity across studies regarding the response of aquatic biota to timber harvest. Overall we found few consistent responses of taxa to forestry, with variation in the direction and magnitude of observed responses across studies. We also show that the number of publications on this topic increased through till 2008 and has declined since that time. The majority of this research has been conducted in North America with a focus on invertebrates. Additionally, the majority of studies have been retrospective surveys conducted on a stream reach scale over a period of less than five years. We suggest that the most critical gaps for forestry research on aquatic fauna are in underrepresented areas with increasing levels of forestry, particularly in Asia, and on understudied taxa. We also propose that greater emphasis should be placed on gaining more mechanistic understandings of biotic responses to disturbance, through experimentation and more powerful statistical approaches. This will be necessary to improve understanding and predictive capacity of the responses of aquatic biota to increasing global timber harvest. This information is vital for effective management in the face of intensified use of forests.

1. Introduction

Humans dominate the use of terrestrial net primary productivity globally, with much of this involving some form of extraction of 'ecosystem goods and services' from the landscape (Haberl et al., 2007). These extractive processes have ecological impacts through multiple forms of disturbance (Erb et al., 2009). Global demand and production of timber products is increasing. World production of industrial roundwood has increased from 1128 million m^3 in 1965 to 1668 million m^3 in 2005, and is projected to increase by > 40% to 2030 (FAO, 2009). This has seen developments of new regulation and market mechanisms, such as forest certification, to improve sustainable management of forests. Indeed, the area of certified forests in the world has grown considerably in the last decades, with lands certified under the two largest forest certification schemes, PEFC and FSC, now totalling 429 million ha worldwide (Forest Stewardship Council, 2016). With intensified use of forests globally, a comprehensive understanding of the influence of forestry practices on ecological systems is needed. The ecological effects of timber harvest on aquatic ecosystems such as streams have received considerable attention by ecologists, however little synthesis of these effects exists. Here we unify this diverse literature, examining general patterns that can be concluded about the impacts of timber harvest on aquatic fauna. Aquatic ecosystems are ideal systems to study, as they are broadly emblematic of anthropogenic extraction of resources, and are representative of terrestrial and aquatic connections.

There are diverse connections between extraction of timber from the terrestrial ecosystem and stream ecosystems. Upland timber harvesting causes both short and long term impacts to a suite of physical and chemical parameters (Campbell and Doeg, 1989; Davies et al., 2016; Martin et al., 2000), including changes to hydrology (Moore and Wondzell, 2005), channel structure (Bigelow et al., 2007) and water quality (Feller, 2005). Through physical and chemical changes, timber removal can have profound effects on aquatic biota, with major effects typically resulting from sedimentation and increased light penetration to the stream, thereby increasing primary production and water temperature (Gravelle and Link, 2007; Marks and Rutt, 1997). Tree removal may also reduce input of course woody debris (CWD) and litter

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into streams, as well as alter litter composition over time (Gomi et al., 2006). In addition, the removal of riparian trees may increase bank erosion and reduce bank stability (Bunce et al., 2001). These changes will have subsequent impacts on habitat suitability for aquatic species, and may lead to increased mortality, migration of species from the area, or changes in community composition and structure (Gravelle et al., 2009; Herlihy et al., 2005; Patrick et al., 2006).

While it is recognised that timber harvesting can have significant impacts on aquatic biota (Richardson and Beraud, 2014), it is not clear how consistent study findings are, highlighting the need for systematic reviews of the literature. For instance Danehy et al. (2007) found aquatic invertebrate abundance in recently clearfelled stands to be nearly double that of old growth stands, whereas Trayler and Davis (1998) found invertebrate abundance to be 77% lower in logged areas. This variation may be attributed to the diversity and complexity of aquatic systems throughout the world, with responses dependant on environmental variation. This potential for local and landscape level variation to influence biotic responses to harvest has been suggested by previous studies. In a meta-analysis by Richardson and Beraud (2014), for example, observed responses in water chemistry, algae and invertebrates to timber harvesting were analysed in relation to stream width, gradient and regional potential evapotranspiration. Relationships with these environmental variables were weak, however, suggesting that other factors also contribute to variation in responses. Indeed this complexity calls into question whether the existing information in the literature can be used to make broad generalisations about the impacts of forest harvesting on aquatic biota.

To assess the connections between timber harvest and aquatic fauna, we conducted a systematic literature review and meta-analysis with the aim of answering three questions: 1) what has been the temporal, geographic and taxonomic focus of research into harvesting impacts on stream biota? 2) What are the methodological approaches among studies? 3) Is there evidence of a consistent effect of timber harvest on stream biota? This review presents an important step beyond the work of past meta-analyses (e.g. Mellina and Hinch, 2009; Richardson and Beraud, 2014) by incorporating an expansive view of past research efforts, assessing all major animal taxon groups occupying streams, and evaluating additional processes potentially underpinning variation across studies, including extent, intensity and type of harvesting activity, temporal variation in biotic responses, and species and life-stage specific responses. By quantifying past temporal, geographic and taxonomic focuses of research, as well as the methodological approaches of past studies, we highlight research gaps and suggest direction for future research methodologies. This review is the first of its kind to comprehensively and critically integrate research on the impacts of timber harvest on stream biota. Such reviews are vital for the effective conservation management of freshwater systems in the face of increasing forestry activity on a global scale.

2. Methods

2.1. Literature search and publication inclusion/exclusion

A systematic literature search was conducted in May 2016 using ISI's Web of Knowledge. Key-words were chosen to target studies evaluating the impacts of plantation harvest and native forest harvest on invertebrates, fish, amphibians, riparian associated birds and semi-aquatic mammals in streams (Appendix A). Timber harvest encompassed both clearfelled and partially harvested forest, with or without stream buffer zones. The search was restricted to research areas relevant to wildlife. The search was also restricted to peer-reviewed journal articles. It should be noted that 'grey literature' forms a large component of forestry research, but could not be included in this review due to difficulties in accessibility. Resulting publications were exported into Endnote × 7 and duplicates removed. The remaining studies were screened for inclusion based on the following criteria: 1) studies must be published in English, 2) be available in their full text (e.g. conference abstracts were excluded), 3) must represent original research (e.g. review papers were excluded) and 4) must relate to timber harvest impacts on the specified biota in streams. For the purposes of this review, studies addressing elements of forest management other than timber harvest, namely plantation establishment, herbicides/pesticides, roading, drainage, burning and restoration, were considered out of scope. In addition to the literature search, reference and citation lists of relevant reviews were also screened to identify other potentially relevant studies not captured by our initial search. Relevant studies already known to the authors were also checked for inclusion.

2.2. Data collection

Once appropriate studies were identified, data were extracted under the following headings: year of publication, continent where research was conducted, forest type, type of taxa studied (invertebrate, fish, amphibian, bird or mammal), study design (manipulative experiment or retrospective survey), duration of the study, sample scale and method/s of statistical analysis. This data was used to assess general study trends within the field.

Reported results were also extracted for inclusion into a formal meta-analysis of faunal responses to timber harvest. Studies were included in the meta-analysis only when timber harvesting was identified as the major disturbance to the area. Studies with additional disturbers (e.g. mining or agricultural activities) that could not be isolated from forestry were excluded to reduce variation between studies. Additionally, because of the large number of potential measures used to assess invertebrate responses, results for invertebrates were only collected for a pre-chosen group of the most common response metrics. These included abundance, density, biomass, richness, diversity, evenness, functional feeding groups (shredder, grazer, collector-gatherer, filterer and predator) (Cummins and Klug, 1979), and EPT (Ephemeroptera, Plecoptera and Trichoptera).

For inclusion into the meta-analysis, studies had to report either the means of reference and harvest groups, or a correlation with harvest intensity, as well as sample sizes and estimates of variance for each group. Studies without replication to provide estimates of variance, or appropriate reporting of results were noted, but could not be included in the formal meta-analysis. When studies used a before-after-control-impact design (BACI design), we only used the post-treatment results so that the comparisons were made for the same time period. Additionally, where studies reported harvesting effects through time, we focussed on the most recently logged data only, since the most significant changes in invertebrates and other short lived fauna usually occur in the first 2 or 3 years after harvesting (Feller, 2005; Jackson et al., 2007). We extracted data from text and tables manually and from figures using Plot Digitizer version 2.6.8 for Windows, available on the Web (http://plotdigitizer.sourceforge.net/). We also recorded other data relating to harvest practices, including harvesting type (clearfell or partial), proportion of the catchment harvested, presence and width of a stream buffer, time since harvest, and whether harvesting was conducted under a specified code of practice.

2.3. Effect sizes

Meta-analyses are performed using a common measure, an effect size, representing the relationship of interest for all included studies. We used the bias corrected standardised mean difference, Hedges' *g*, statistic as our measure of effect size. For studies based on mean differences between a reference group and one or more treatment groups, Hedges' *g* and associated variance is defined as follows (Borenstein et al., 2009):

$$g = \frac{x_1 - x_2}{S_{within}} \times J \qquad V_g = \left(\frac{n_1 + n_2}{n_1 n_2} + \frac{d^2}{2(n_1 + n_2)}\right) \times J^2$$