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Impacts of forest loss on inland waters: Identifying critical research zones based on deforestation rates, aquatic ecosystem services, and past research effort

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ABSTRACT

Deforestation is a major threat to global aquatic biodiversity and ecosystem services. Regional studies are needed to understand and mitigate impacts of deforestation on local inland waters, yet such studies remain unavailable in many regions of the world where the risks of impact are high, for example in the tropics. Our goal was to identify such understudied regions by quantifying and mapping the global research need and effort on deforestation impacts on inland waters. We defined research need based on countries' deforestation rate, fish diversity, and vulnerability of human populations to freshwater ecosystem degradation, the latter estimated from water scarcity and consumption and trade of local freshwater fish. We quantified research effort by reviewing 1362 publications on deforestation and freshwater ecosystems, thereby providing the first quantitative literature review on this important conservation problem. We found that tropical countries exhibited strong overlap among deforestation, freshwater fish diversity, and vulnerability of human populations to freshwater ecosystem degradation, and therefore have high research need relative to temperate regions. However, we found that the best predictor of research effort on deforestation and aquatic systems was the size of a country's economy (indicated by gross domestic product), not research need. Finally, we uncovered a strong research bias against tropical Africa, the only extensive region of the world that has a high research need and a low research effort. This global analysis suggests that future research effort on deforestation impacts on inland waters should try to alleviate existing biases by increasing interregional cooperation and transfer of research resources to regions of high research need and/or low research effort, with a particular focus on the critical research zone that is tropical Africa.

1. Introduction

Inland waters are among the most threatened of all ecosystems (Sala et al., 2000, Millennium Ecosystem Assessment, 2005, Dudgeon et al., 2006, Strayer and Dudgeon, 2010). Globally, one of the primary anthropogenic drivers of freshwater ecosystem degradation is land use intensification via deforestation and agricultural expansion (Sala et al., 2000, Dudgeon et al., 2006, Vörösmarty et al., 2010, Collen et al., 2014), which can lead to altered hydrology, increased sediment load, warming, and nutrient enrichment (Allan, 2004, Nielsen et al., 2012, Woodward et al., 2014). These impacts not only threaten aquatic biodiversity but also affect many essential ecosystem services provided by freshwater ecosystems, for example fish stocks and provisioning of clean water (Foley et al., 2005, Millennium Ecosystem Assessment, 2005, Dugan et al., 2010, WWAP, 2015). Although land use impacts on inland waters are relatively well-understood in some watersheds, discrepancies in responses of aquatic systems to deforestation suggests that limnological knowledge is only partially transferable across regions, and thus that studies from a variety of regions are critical (see also Lewis, 1987). For instance, even within the tropics, the species richness of fish in tropical rivers from different sites can be increased (Lorion and Kennedy, 2009), reduced (Toham and Teugels, 1999), or unaffected (Bojsen and Barriga, 2002) by deforestation. Regional studies are thus needed to uncover local impacts of land use on inland waters, as well as to understand potential interactions with other stressors specific to certain regions (e.g., Macedo et al., 2013) or to design optimal management strategies that explicitly consider features of the local landscape (e.g., Iñiguez–Armijos et al., 2014). Despite the need for more regional studies, limited resources evidently restrict the number of watersheds that can be studied. As such, we need to identify critical areas for future research based on a consideration of both current research need and past research effort. Our objective in this study is to detect such areas by identifying regions where deforestation is most likely to cause biodiversity loss and/or affect peoples' livelihoods via aquatic ecosystem degradation (i.e., regions with a high research need), but where little research on land use impacts on inland waters has been conducted (i.e., regions with a low research effort).

We hypothesized that critical research areas are more likely to be located in tropical than temperate regions. Many tropical countries are

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characterized by rapid deforestation rates, high freshwater biodiversity, and human populations that are strongly reliant on local freshwater ecosystem services. Indeed, in recent years, deforestation has been most intensive and extensive at tropical latitudes (FAO, 2010, Hansen et al., 2013), and the tropics are also expected to be hotspots of agricultural intensification and expansion in the near future (Laurance et al., 2014). Studies mapping the biodiversity of freshwater taxa for which global distribution data are available suggest that biodiversity is also greater in the tropics (Abell et al., 2008, Collen et al., 2014), as can be the reliance of human populations on freshwater resources; for example, inland fisheries constitute a much more important source of employment and food for human populations in Latin America, Africa, and Asia than in Europe and North America (Allan et al., 2005, Dugan et al., 2010). Infrastructure for water management is also limited in many tropical countries, and investment in water-related technology to improve human water security is low in most tropical regions with a high population density (Vörösmarty et al., 2010). All of these trends suggest that it is critical to monitor impacts of land use changes on tropical inland waters, and that a large fraction of the global research effort on this conservation problem should target tropical watersheds.

Unfortunately, many bibliometric analyses indicate that research effort in environmental sciences is often determined by economic development rather than by research need (e.g., Pasgaard and Strange, 2013). Gross domestic product (GDP) is often the best predictor of the number of research articles published on a given environmental issue in a country (Karlsson et al., 2007, Moustakas and Karakassis, 2009, Pasgaard and Strange, 2013). As such, less-developed regions tend to receive a smaller fraction of the global research effort on a specific ecological topic. For example, much less research has been conducted on invasive species and climate change in tropical Africa than in other regions of the world (Pyšek et al., 2008, Pasgaard and Strange, 2013). Such geographical biases in research effort lead to what has been described as a 'north-south divide' in knowledge availability on ecological issues, whereby 'southern' countries (developing countries of the southern hemisphere) often generate and possess less knowledge about local ecosystems and environmental problems than developed countries in the northern hemisphere (Karlsson et al., 2007). It is likely that research on deforestation and inland waters is no exception to this pattern, which would be paradoxical given the potentially higher research need in tropical (less-developed) countries, as argued above (see also Ramirez et al., 2008). Surprisingly, to our knowledge no quantitative synthesis of the literature on land use impacts on inland waters has been undertaken, such that it remains unknown whether the geographical distribution of research effort on this problem is indeed biased.

Our study aimed to identify areas that should be prioritized for future research on deforestation impacts on inland waters. We assembled a global database of countries' deforestation rates, freshwater fish diversity, and vulnerability of human populations to freshwater ecosystem degradation, the latter being estimated from the relative reliance on a suite of key provisioning services supplied by local inland water ecosystems. Our premise is that countries where those variables overlap strongly have a relatively higher research need. Then, we performed a quantitative literature review on deforestation effects on inland waters to determine predictors of research effort and to identify areas where little research has been conducted. More specifically, our study addressed the following three questions: (1) which countries and/or regions have the strongest overlap among recent deforestation, freshwater fish diversity, and vulnerable human populations? i.e., where is research need highest? (2) Can deforestation rate, freshwater fish diversity, vulnerability of human populations, and/or an indicator of economic development such as GDP predict research effort on effects of deforestation on inland waters? (3) Which countries and/or regions have both a high research need and a low research effort, and should therefore be the focus of future research?

2. Materials and methods

2.1. Data collection

We combined numerous online databases to obtain country-specific information on rates of recent deforestation, freshwater fish biodiversity, vulnerability of human populations to freshwater ecosystem degradation, and research effort (see Table 1 for a list and description of all variables and Fig. S1 for a diagram showing relationships among variables). We conducted our analysis at the country scale because that was the smallest scale at which inland fisheries data were available for most countries of the world. We first collected basic country information from the Statistics Division of the Food and Agriculture Organization of the United Nations (FAOSTAT; FAO, 2013), including total country area, total human population (in 2012), GDP (also in 2012), and GDP per capita (henceforth GDPpc). For rates of recent deforestation, we used two data sources: (1) the 2010 edition of the 'Global Forest Resources Assessment' published by the FAO, which provides forest cover estimates for all countries between 2005 and 2010 (FAO, 2010); and (2) an analysis of global Landsat data conducted by Hansen et al. (2013) that reports forest cover change between 2000 and 2012. With both datasets, we calculated relative forest loss as: $1 -$ (forest cover at the end of the interval $\times$ forest cover at the beginning of the interval^{-1}). Negative values for forest loss represent an increase in forest cover during the interval (due to reforestation, for example). The FAO data are based on official reports from countries that provide information on the area of land allotted to some form of forest land use (parks, tree plantations, etc.). This method can lead to biased estimates of forest cover because of inconsistent land use definitions among countries, inaccurate reporting of land use changes, and because forest land use does not equate to forest cover when land allotted for forest is deforested, e.g., when there is illegal logging or when logging lots are not reforested as planned.

Table 1
Summary table of all variables and metrics used for maps and analyses (see also Fig. S1 for a graphical representation of this information).

Variable	Description and data provenance
Deforestation, fish diversity, vulnerability, and research effort variables	
Forest loss: FAO	% forest cover loss between 2005 and 2010 reported by the FAO (2010). Negative values indicate an increase in forest cover.
Forest loss: Hansen	% forest cover loss between 2000 and 2012 reported by Hansen et al. (2013). Negative values indicate an increase in forest cover.
Fish diversity: fish richness	Number of freshwater fish species (Fishbase), corrected for country area (see methods).
Fish diversity: fish endemics	Number of endemic freshwater fish species (Fishbase), corrected for country area.
Vulnerability: water scarcity	Inverse of average annual renewable freshwater supply per capita (FAOSTAT: Aquastats).
Vulnerability: fish in diet	% of total animal proteins available per capita per day provided by freshwater fish (FAOSTAT: Food balance sheets).
Vulnerability: fish exports	% of GDP contributed by exports of freshwater and diadromous fish (FAOSTAT: Fisheries).
Research effort: publications	Total number of publications covering country (Web of Science).
Metrics combining more than one of the above-listed variables after standardization	
Forest loss	Mean of two forest loss scores.
Fish diversity	Mean of fish richness and fish endemics.
Vulnerability	Mean of water scarcity, fish in diet, and fish exports.
Potential repercussions of ecosystem degradation (PRED)	Mean of fish diversity, water scarcity, fish in diet, and fish exports.
Risk of deforestation impacts (RDI)	Square root of product of forest loss and PRED. Our metric of research need.