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.

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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
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 (Pysek 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 x 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>
<thead>
<tr>
<th>Variable</th>
<th>Description and data provenance</th>
</tr>
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<tbody>
<tr>
<td>Deforestation, fish diversity, vulnerability, and research effort variables</td>
<td></td>
</tr>
<tr>
<td>Forest loss: FAO</td>
<td>% forest cover loss between 2005 and 2010 reported by the FAO (2010). Negative values indicate an increase in forest cover.</td>
</tr>
<tr>
<td>Forest loss: Hansen</td>
<td>% forest cover loss between 2000 and 2012 reported by Hansen et al. (2013). Negative values indicate an increase in forest cover.</td>
</tr>
<tr>
<td>Fish diversity: fish richness</td>
<td>Number of freshwater fish species (Fishbase), corrected for country area (see methods).</td>
</tr>
<tr>
<td>Fish diversity: fish endemics</td>
<td>Number of endemic freshwater fish species (Fishbase), corrected for country area.</td>
</tr>
<tr>
<td>Vulnerability: water scarcity</td>
<td>Inverse of average annual renewable freshwater supply per capita (FAOSTAT: Aquastats).</td>
</tr>
<tr>
<td>Vulnerability: fish in diet</td>
<td>% of total animal proteins available per capita per day provided by freshwater fish (FAOSTAT: Food balance sheets).</td>
</tr>
<tr>
<td>Vulnerability: fish exports</td>
<td>% of GDP contributed by exports of freshwater and diadromous fish (FAOSTAT: Fisheries).</td>
</tr>
<tr>
<td>Research effort: publications</td>
<td>Total number of publications covering country (Web of Science).</td>
</tr>
</tbody>
</table>

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.
The analysis of Landsat data by Hansen et al. (2013) circumvents these limitations to some degree by employing a biophysical definition of forest cover, i.e., forest is defined as land covered with trees, regardless of how the land is used. However, forest cover can also be altered by natural, periodic perturbations such as fire or insect pest outbreaks. Such natural forest loss may have different effects on aquatic ecosystems than anthropogenic deforestation, which often leads to long-lasting land use change and intensification. Given the different limitations of the two datasets, we included both in our analysis to derive an estimate of relative deforestation based on both land use change and physical reduction in forest cover (Table 1).

We quantified freshwater fish biodiversity using fish species checklists available for all countries on Fishbase (Froese and Pauly, 2013). We focused our biodiversity analysis on fishes as they appeared to be the freshwater taxon for which global distribution data at the species-level were most accurate and readily available, and because fishes had been used in previous efforts to map global freshwater biodiversity (Abell et al., 2008). We recognize, however, that fish diversity only captures part of the total variation in overall freshwater biodiversity, as was demonstrated recently by Collen et al. (2014). We used two measures of freshwater fish diversity: species richness and the number of endemic species. Both measures were strongly correlated with country area (Pearson’s $r$ for richness $= 0.5091$; $r$ for number of endemic species $= 0.5397$; both correlation coefficients were calculated with untransformed data). To remove the influence of area on fish diversity (as deforestation variables were area-standardized), we performed linear regressions between diversity (richness or number of endemic species) and country area after log-transforming variables. We used the residuals of these linear regressions as our two measures of diversity for all analyses (Table 1).

We estimated the vulnerability of human populations to freshwater ecosystem degradation based on the assumption that vulnerability results from a high relative usage of provisioning services delivered by local inland waters. We quantified ecosystem usage based on three provisioning services for which there were sufficient global data: supply of freshwater, and inland fisheries as a source of both protein and income. We assumed that the inhabitants of a country would be relatively more vulnerable to freshwater ecosystem degradation when: (1) water scarcity is high (i.e., when supply of freshwater is limited); (2) freshwater fish contribute an important percentage of animal protein supply in the local diet; and (3) trade of freshwater fish constitutes a large fraction of the country’s GDP (Table 1; Fig. S1). Online databases provided by FAOSTAT (FAO, 2013) were used to measure all three ecosystem usage variables. Water scarcity was defined as the additive inverse of renewable freshwater supply per capita (m$^3$ inhabitant$^{-1}$ year$^{-1}$), which the FAO calculates for all countries using estimates of average yearly precipitation. For the relative importance of freshwater fish in local protein supply, we divided the availability of freshwater fish protein (g capita$^{-1}$ day$^{-1}$) by the total availability of animal protein. For trade of freshwater fish, we used estimates of the total export value (in US$ year$^{-1}$) of freshwater and diadromous fish (i.e., all species that complete at least part of their life cycle in freshwater) and quantified their relative economic importance by dividing total exports by the country’s GDP. Ideally, we would have used the total monetary value of fish production rather than fish exports, but monetary values for production are not provided in FAOSTAT (all fisheries production statistics are in units of mass). The % of GDP comprised of fish exports should be a better indicator of potential negative impacts of ecosystem degradation on people’s income than fish production in units of mass, which largely depends on the species of fish that are harvested and which does not necessarily reflect the economic importance of freshwater fisheries to local livelihoods (Dugan et al., 2010). We included diadromous fish because stocks of many diadromous species can be affected by freshwater habitat degradation (e.g., Bradford and Irvine, 2000). Although recreational fisheries have been estimated to represent approximately 12% of global fish harvest (Cooke and Cowx, 2004), we did not include recreational fisheries in our analysis because data on the value of such services are unavailable for most tropical countries. We used the most recent year of data provided for all statistics, which ranged from 2009 to 2012 depending on countries and variables.

To estimate research effort, we performed a literature search in 2013 for studies that measured how deforestation affects at least one biotic or abiotic variable in a freshwater ecosystem (either lotic or lentic). We used Web of Science (Thomson Reuters, 2013) to find articles in the ‘core collection’ using the search terms: (deforestation OR logging OR clearcut’ OR clear-cut”) AND (lake OR river OR stream OR freshwater OR riparian OR swamp OR marsh OR wetland OR catchment). We used ‘logging’, ‘clear-cut’, and ‘deforestation’ as search terms, because papers from different regions and time periods tend to employ different terms. For example, older papers from North America use ‘logging’ more often than ‘deforestation’, while the converse is true for recent papers on tropical countries. Our search yielded 9566 publications, 9489 of which were in a language that one of the authors could read (English, French, or Spanish). We reviewed those 9489 abstracts and retained 1362 relevant publications from 96 countries spanning the years 1968 to 2013. We only included articles where direct effects of deforestation were used as predictor variables (e.g., loss of canopy cover, sedimentation due to logging activity, etc.), or where explicit spatial (forested vs. deforested) or temporal (before vs. after) comparisons were made. We categorized and tallied papers by country, to obtain the total number of publications per country as our measure of research effort. Articles covering more than one country (e.g., studies on transnational river basins) were included in the publication count of all countries described in the study.

2.2. Analyses

All analyses were performed in R version 3.0.2 (R Core Team, 2013). We first excluded all countries for which data were missing for one of the target variables: deforestation, fish diversity, or vulnerability, i.e., a few African and Asian countries and most Pacific and Caribbean island countries. We then explored relationships among deforestation, fish diversity, and vulnerability variables to identify redundant variables that could be combined to minimize collinearity in subsequent analyses. All variables were first log-transformed and standardized (mean of zero, unit variance). We then: (1) calculated Pearson’s correlation coefficients among all variables, and (2) performed a Principal Components Analysis (PCA) to produce a correlation biplot illustrating correlations among variables. The R package ‘vegan’ was used for PCA (Oksanen et al., 2013).

Our first objective was to identify countries where deforestation overlaps with both high fish diversity and vulnerability. To that end, we created two new variables: ‘forest loss’ and ‘potential repercussions of ecosystem degradation’, hereafter referred to as PRED (Table 1; Fig. S1). For ‘forest loss’, we combined both deforestation variables (‘Forest loss: FAO’ and ‘Forest loss: Hansen’) to create a single deforestation variable that incorporates both land use changes and forest cover changes (Table 1; Fig. S1). This was done by calculating the mean of the standardized scores of both deforestation variables, and then re-standardizing the resulting variable. For PRED, we needed to combine vulnerability and fish diversity variables. The two fish diversity variables (richness and endemism) were highly correlated (Pearson’s $r = 0.79$) and thus contained redundant information. Therefore, we first combined both diversity variables into a single ‘fish diversity’ variable, again taking the mean value of standardized scores for both variables and then re-standardizing the resulting scores (Table 1; Fig. S1). PRED was then calculated as the mean value from standardized scores for
'fish diversity', 'water scarcity', 'fish in diet', and 'fish exports' (Table 1; Fig. S1). We used all three vulnerability scores for PRED calculation instead of a single 'vulnerability' score because correlations among the three vulnerability variables were quite low, i.e., each variable contained unique information (maximum Pearson's r among the three variables = −0.19; Table 3). PRED represents the potential (relative) impact of freshwater ecosystem degradation in a country; however, the index was not linked to a particular disturbance. To identify where PRED overlaps geographically with high deforestation rates, we produced a bivariate map with blending color scales for PRED and 'forest loss'. Each country was assigned an integer score for each color scale ranging from 1 to 10 based on deciles (1/10th of samples) calculated from the two variables.

Our second objective was to determine whether research effort can be predicted from deforestation rates, fish diversity, vulnerability, and/or economic development. We performed a negative binomial generalized linear model (GLM) with number of publications as the response variable and forest loss, vulnerability, fish diversity, GDPpc, and total population of the country as predictor variables (refer to Table 1 for a description of variables). Population size and GDPpc were also standardized before the analysis. We included population size as a covariate to control for size effects on research effort, assuming that more populous countries would tend to have a greater number of freshwater ecologists and thus a higher publication count (Karlsson et al., 2007, Pasgaard and Strange, 2013), and because all of our deforestation, fish diversity, and vulnerability metrics were size-standardized using some measure of country size or economic importance (country area, total forested area, population, or GDP). Collinearity among predictor variables was low, with all variance in standardized using some measure of country size or economic importance (maximum tolerance values > 0.7) among all deforestation, fish diversity, and vulnerability variables (Table 3). Deforestation and fish diversity metrics correlated weakly with importance of freshwater fish as a protein source (positive correlation) and with water scarcity (negative correlation; Table 3; Fig. S2). Overall, countries from the same region only showed moderate clustering in multivariate space, indicating considerable intra-regional variation for many variables (Fig. S2). Most countries that showed a strong overlap between forest loss and PRED were located in tropical regions of Central and South America, Africa, and Southeast Asia (Fig. 1). A few other countries outside of these regions also had a high score (≥8) for both deforestation and PRED, namely Sweden, Estonia, and Latvia in Europe, and Pakistan in South Asia (Fig. 1).

A negative binomial GLM indicated that by far the best predictor of research effort (number of publications) was country GDPpc, after controlling for effects of country population size (Table 2). Countries with a higher GDPpc produced more publications on deforestation impacts on inland waters. Forest loss and fish diversity were also significant positive predictors of publication number, but vulnerability was not (Table 2). Much of the variance in publication number was explained by the combination of predictor variables included in the GLM (model pseudo $R^2 = 0.6157$). With respect to the spatial overlap between research effort and RDI, the only large region of the world with high RDI (≥8) and low research effort (≤3) was tropical Africa (Fig. 2). Most countries with high RDI in tropical America and Asia had a high publication count, with the exception of El Salvador, Panama, Paraguay, and the Philippines (Fig. 2). A few additional countries in other regions also had high RDI and low research effort, namely Estonia, Latvia, and Pakistan (Fig. 2).

3. Results

At the global scale, the two deforestation metrics were weakly correlated, indicating that changes in land use only partly correspond to actual changes in tree cover (Table 3; Fig. S2). The only strong correlation ($r > 0.7$) among all deforestation, fish diversity, and vulnerability variables was between the two fish diversity variables (Table 3). Deforestation and fish diversity metrics correlated weakly with importance of freshwater fish as a protein source (positive correlation) and with water scarcity (negative correlation; Table 3; Fig. S2). Overall, countries from the same region only showed moderate clustering in multivariate space, indicating considerable intra-regional variation for many variables (Fig. S2). Most countries that showed a strong overlap between forest loss and PRED were located in tropical regions of Central and South America, Africa, and Southeast Asia (Fig. 1). A few other countries outside of these regions also had a high score (≥8) for both deforestation and PRED, namely Sweden, Estonia, and Latvia in Europe, and Pakistan in South Asia (Fig. 1).

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4. Discussion

By conducting a systematic review of the published literature on deforestation and freshwater ecosystems, and by analyzing country-specific data on deforestation intensity, freshwater fish diversity, and the reliance of human populations on key ecosystem services provided by local inland waters (a proxy of vulnerability), we mapped the global distribution of past research effort and future research need on deforestation impacts on inland waters. Our analyses reached three main conclusions. First, tropical countries exhibit the strongest overlap among deforestation, fish diversity, and vulnerability of human populations to freshwater ecosystem degradation, and therefore have a relatively higher research need. Second, GDP per capita is the best predictor of research effort on deforestation and aquatic systems. Fish diversity and deforestation rates, two variables linked to research need, are also positive predictors of research effort, but vulnerability of human populations to freshwater ecosystem degradation is not. Third, tropical Africa is the only extensive region of the world with a high research need but a low research effort, and therefore constitutes a critical area for future research on deforestation impacts on inland waters. We now discuss in turn each of these main conclusions.

Our finding that research need is highest for tropical countries is consistent with several studies on other ecosystems that have also reported strong coupling among threat intensity, biodiversity, and/or human vulnerability in the tropics. For instance, the majority of biodiversity ‘hotspots’, i.e., areas featuring exceptional concentrations of endemic (plant) species and experiencing exceptional loss of habitat (Myers et al., 2000, p. 853), are located at tropical latitudes. Globally, tropical regions exhibit the strongest overlap between poverty and potential loss of terrestrial vertebrate biodiversity (Sachs et al., 2009). Within tropical Africa, Darwall et al. (2011b) reported a positive correlation at the watershed scale between freshwater biodiversity and human poverty, and Balmford et al. (2001) found strong spatial coincidence among terrestrial biodiversity, human population density, and intensity of land/habitat conversion. The tight coupling between deforestation and PRED in tropical countries will probably continue to intensify, as it is expected that most future deforestation and agricultural expansion will occur in the tropics (Laurance et al., 2014). Tropical deforestation could in turn interact with other anthropogenic disturbances that also tend to be most extensive and/or acute in the tropics, for example overfishing of inland waters (Allan et al., 2005). Our data add to the general conclusion that tropical countries constitute a central arena for conservation action if global objectives of biodiversity conservation are to be met, and should thus be the focus of much conservation research.

Our second important finding was that GDP per capita was the best predictor of research effort, even more than total population of a country, a finding consistent with other bibliometric analyses (Karlsson et al., 2007, Moustakas and Karakassis, 2009, Pasgaard and Strange, 2013). This is not surprising given that high-GDP countries (i.e., members of the Organization for Economic Cooperation and Development) contribute the bulk of global gross expenditure on research and development, employ more researchers per capita, file more patent applications, and author the majority of highly-cited publications across all disciplines of science (King, 2004, Westholm et al., 2004, Karlsson et al., 2007). A lower research effort in tropical (developing) than temperate countries seems to be a common pattern in ecology and in the environmental sciences as a whole, leading to a north-south (developed-developing) divide in scientific knowledge (Karlsson et al., 2007). Research effort in this analysis followed a less dramatic divide, as the publication count of several tropical countries in South America and Southeast Asia were among the highest globally (e.g., Brazil, Indonesia, and Malaysia). Indeed, deforestation rate and fish diversity, both of which are generally higher in the tropics, were also positive predictors of research effort, suggesting that many ‘hotspots’ with high biodiversity and disturbance intensity are well studied. Vulnerability of human communities to ecosystem degradation was however not related to research effort in this analysis, although our metric for human vulnerability is admittedly simple due to limited data availability on freshwater ecosystem services at the

<table>
<thead>
<tr>
<th>Variable</th>
<th>β</th>
<th>Standard error</th>
<th>Δ Deviance</th>
<th>LRT p</th>
</tr>
</thead>
<tbody>
<tr>
<td>Population</td>
<td>2.6359</td>
<td>1.1328</td>
<td>65.275</td>
<td>&lt;0.0001*</td>
</tr>
<tr>
<td>GDP per capita</td>
<td>2.9141</td>
<td>1.1297</td>
<td>90.689</td>
<td>&lt;0.0001*</td>
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<tr>
<td>Forest loss</td>
<td>1.6647</td>
<td>1.1396</td>
<td>13.299</td>
<td>0.0003*</td>
</tr>
<tr>
<td>Fish diversity</td>
<td>1.4827</td>
<td>1.1364</td>
<td>9.4145</td>
<td>0.0022*</td>
</tr>
<tr>
<td>Vulnerability</td>
<td>0.9513</td>
<td>1.1248</td>
<td>0.1958</td>
<td>0.6581</td>
</tr>
</tbody>
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V. Fugère et al. / Biological Conservation 201 (2016) 277–283

Fig. 2. Bivariate map showing overlap between research effort (number of publications) and RDI (risk of deforestation impacts), a score that includes both recent forest loss and PRED (i.e., the two color axes on Fig. 1). Countries in red or purple have a high RDI score but a low number of publications.
global scale. Assuming that locally derived scientific knowledge can improve management of anthropogenic impacts on ecosystem services, conducting research in areas of high human vulnerability should be as much of a priority as studying systems with high biodiversity.

Our third and perhaps most important finding is that most countries in tropical Africa have a high risk of deforestation impacts and yet a low research effort. Bibliometric analyses in other sub-disciplines of ecology have also identified research biases against Africa, for example in the climate change or invasion ecology literature (Pyšek et al., 2008, Pasgaard and Strange, 2013). While the causes of this bias are certainly manifold, one factor likely to exert a strong influence is the relatively low development status of most tropical African countries, where long-lasting socioeconomic problems have led to low government investment in science and destitute research infrastructures (Hassan, 2001). The potential consequences of this research bias are multifaceted. First, land use impacts on African freshwater biodiversity remain largely unknown, yet these impacts are likely substantial. Indeed, the majority of threatened freshwater crabs, fish, and mollusks in Africa occur in poorly-protected watersheds (Darwall et al., 2011b). Second, lack of knowledge on land use impacts on water quality or inland fisheries could also have unrecognized health or economic effects among human populations. For example, deforestation impacts on water temperature and flow regime have been linked to upsurges in malaria vectors in Africa, Asia, and South America (Patz et al., 2000). Finally, the knowledge gap on African freshwater makes it difficult to predict which management or mitigation strategies might be effective locally. For instance, riparian buffer zones are known to successfully reduce impacts of agricultural land use on stream ecosystems in other tropical regions (e.g., Lorion and Kennedy, 2009). Although buffer zone regulations exist in some afrotropical regions, little information is available on, for example, the optimal width of buffer zones to achieve the largest improvement in water quality, or which local riparian tree species are most effective at stabilizing river banks. Such knowledge gaps limit our ability to manage afrotropical inland waters and use limited resources for ecological restoration efficiently (see also Chapman and Chapman, 2003).

It is important to acknowledge that we could have underestimated publication number because we could not find papers published in the so-called ‘grey literature’ with Web of Science, nor could we review abstracts in languages other than English, French, and Spanish (although publications in these three languages accounted for 99.2% of all abstracts returned by our literature search). Such biases are inevitable in bibliometric analyses (e.g., Pyšek et al., 2008, Pasgaard and Strange, 2013); however, we strongly believe that they do not affect the main conclusion of our literature review, namely that research effort is lower in the afrotropics relative to other regions. For example, we know of no limnology journal published in an African language, and the African Journal of Aquatic Science, one of the main outlets for local, applied research, is in English and indexed on Web of Science. French is the other major international language in tropical Africa; yet, although most French-language ecology and hydrology journals are also listed on Web of Science, our literature search only yielded three publications in these sources pertaining to afrotropical countries. There could still be important amounts of data on afrotropical inland waters in sources not available online: we believe that this is unlikely, but it is impossible to prove the absence of such data. Importantly, the lack of readily available scientific information on deforestation impacts on afrotropical inland waters is a major hindrance for freshwater conservation in this region, regardless of whether such information is truly inexistent or simply difficult to access.

To conclude, the biases that we report in this study should direct future research effort on deforestation impacts on inland waters. Simply put, more research on this important conservation problem is needed in tropical Africa (Chapman and Chapman, 2003). In the short term, this could be achieved via increased intercontinental cooperation, whereby more researchers from high-GDP countries would develop collaborations and research programs in Africa (Karlsson et al., 2007, Pyšek et al., 2008, Pasgaard and Strange, 2013). Such cooperation has been very useful to tackle other problems in aquatic ecology; for example, recent biodiversity mapping efforts from the International Union for the Conservation of Nature have made Africa the first continent for which there is a comprehensive, continent-wide inventory of fishes, molluscs, odonates, crabs, and aquatic macrophytes (Darwall et al., 2011a, Darwall et al., 2011b, Clausnitzer et al., 2012). Such novel information should facilitate the study of African inland waters and make them more attractive study systems for freshwater ecologists, which we hope will help palliate the current knowledge gap on how these ecosystems are responding to the dramatic land use changes occurring in this region of the world.

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Appendix A. Supplementary data

The following material is included as online-only files: (1) a diagram illustrating how deforestation, fish diversity, vulnerability, and research effort variables are combined to compute PRED and RDI indices (Fig. S1); (2) a correlation matrix for all deforestation, fish diversity, and vulnerability variables (Table S3); (3) a PCA correlation biplot showing relationships between deforestation, fish diversity, and vulnerability variables (Fig. S2). Supplementary data associated with this article can be found in the online version, at http://dx.doi.org/10.1016/j.biocon.2016.07.012.

Table 3

<table>
<thead>
<tr>
<th>Forest loss (FAO)</th>
<th>Forest loss (Hansen)</th>
<th>Fish richness</th>
<th>Fish endemics</th>
<th>Water scarcity</th>
<th>Fish in diet</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest loss (Hansen)</td>
<td>0.35**</td>
<td>0.49**</td>
<td>0.79***</td>
<td>-0.25**</td>
<td>-0.13</td>
</tr>
<tr>
<td>Fish richness</td>
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<td>0.36**</td>
<td>-0.52**</td>
<td>0.30**</td>
<td>0.06</td>
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<tr>
<td>Fish endemics</td>
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<td>-0.09</td>
<td>-0.43**</td>
<td>0.52**</td>
<td>-0.07</td>
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<tr>
<td>Water scarcity</td>
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<td>0.08</td>
<td>0.06</td>
<td>-0.19*</td>
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<tr>
<td>Fish in diet</td>
<td>-0.17*</td>
<td>-0.01</td>
<td>-0.43**</td>
<td>0.19*</td>
<td>0.01</td>
</tr>
</tbody>
</table>
References


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