The contribution of lakes to global inland fisheries harvest

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Freshwater ecosystems provide numerous services for communities worldwide, including irrigation, hydropower, and municipal water; however, the services provided by inland fisheries – nourishment, employment, and recreational opportunities – are often comparatively undervalued. We provide an independent estimate of global lake harvest to improve biological and socioeconomic assessments of inland fisheries. On the basis of satellite-derived estimates of chlorophyll concentration from 80,012 globally distributed lakes, lake-specific fishing effort based on human population, and output from a Bayesian hierarchical model, we estimated that the global lake fishery harvest in the year 2011 was 8.4 million tons (mt). Our calculations excluded harvests from highly productive rivers, wetlands, and very small lakes; therefore, the true cumulative global fishery harvest from all freshwater sources likely exceeded 11 mt as reported by the Food and Agriculture Organization of the United Nations (FAO). This putative underestimate by the FAO could diminish the perceived importance of inland fisheries and perpetuate decisions that adversely affect these fisheries and millions of people.

Front Ecol Environ 2017; doi:10.1002/fee.1503

Inland water bodies provide multiple ecosystem services, including drinking water, irrigation for agriculture, hydropower generation, recreation, and protein and food security obtained through aquaculture and fisheries harvests (Lynch *et al.* 2016). In some cases, however, these services are incompatible, such as when water withdrawals or dam construction reduces fisheries habitat and productivity (Baron *et al.* 2002). When these conflicts arise, policy makers require estimates of the value of individual ecosystem services to make informed decisions about how to allocate freshwater to various uses. The value of inland fisheries, in particular, has been poorly estimated; not only is assessment capacity limited in many countries, but there is also a lack of consistent methodology for both the economic valuation (Grantham and Rudd 2015) and the biological assessment (Cooke *et al.* 2016) of fish populations.

Fishing in lakes, reservoirs, rivers, and other inland waters (Figure 1) is the primary source of dietary protein and income in some of the world's underdeveloped regions (Lynch *et al.* 2016), and fishing can be an important sector of regional economies elsewhere (eg US DOI and US DOC 2011). The importance of inland capture fisheries is commonly overlooked, in part because their harvest appears to comprise only a small percentage (12% in 2014) of the total wild-capture harvest of fish and other aquatic (including marine) organisms, as routinely compiled by the Food and Agriculture Organization of the United Nations (FAO). Technical and governance barriers often impede accurate measurements of fisheries harvests, which in many cases results in under-reporting; consequently, FAO assessments of inland fisheries harvests are acknowledged to be highly uncertain and underestimated (Beard *et al.* 2011; Welcomme 2011; Bartley *et al.* 2015). The latest available FAO estimate for global fish capture in inland waters was 11.5 million tons (mt) in 2015 (www.fao.org/fishery/statistics/en; accessed 8 May 2017).

By obtaining more comprehensive estimates of harvests and circumventing incomplete reporting of harvest data, scientists and policy makers would be better able to accurately assign a value to inland fisheries as an ecosystem service. Because inland water bodies are so numerous and diffuse, directly estimating inland fisheries harvest at the global scale can be exceedingly difficult (Welcomme *et al.* 2010). For example, many fisheries are located in remote and developing regions that are difficult to access and to conduct assessments within, and many harvests may be consumed for subsistence before any reporting can occur. Moreover, the number and surface area of water bodies where fishing takes place are vast, making comprehensive fisheries assessments impractical. Lakes, reservoirs, and wetlands cover more than 12 million km^2 worldwide (Lehner and Döll 2004).

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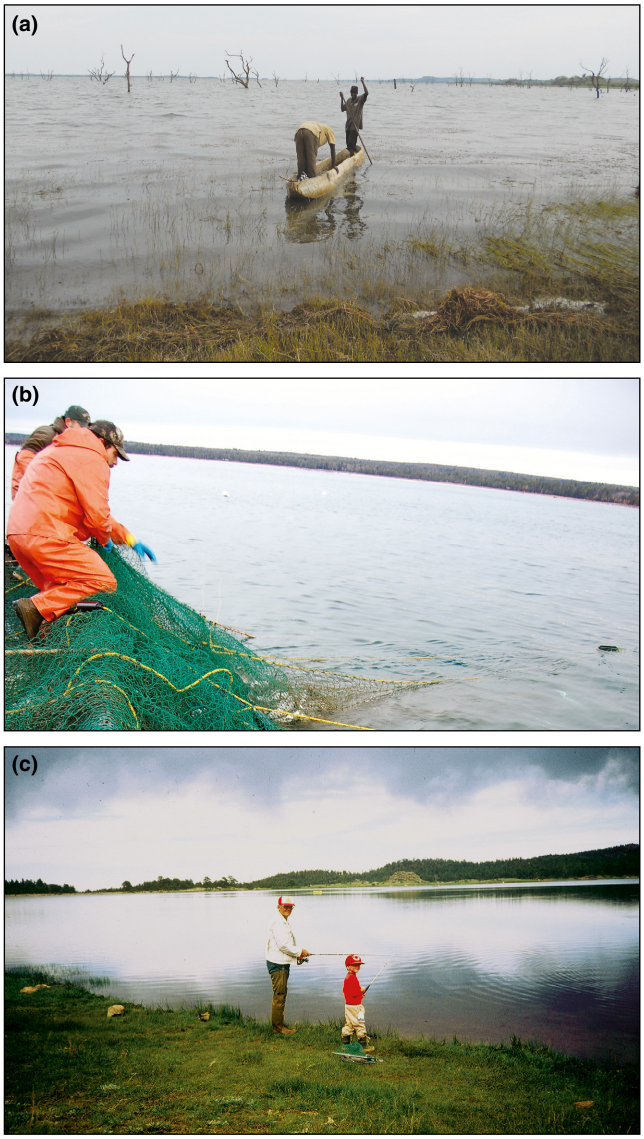

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Figure 1. *Fishing activities including (a) artisanal/subsistence fishing in Lake Itezhi-Tezhi, Zambia, (b) commercial/industrial fishing in Lake Michigan, and (c) the lead author and his grandfather participating in recreational fishing in Dowdy Lake, Colorado.*

The most recent estimate of inland lakes larger than 0.002 km^2 revealed a total surface area of approximately 5.0 million km^2 (Verpoorter *et al.* 2014); given the impossibility of directly monitoring most of the lakes where fisheries may be located, we take the first steps to develop models using remotely sensed data to provide a global estimate of inland fish harvest from freshwater lakes and reservoirs (hereafter referred to collectively as "lakes").

Attempts have recently been made to indirectly estimate global lake fishery harvest, in the absence of direct data. Welcomme (2011) used a simple empirical relationship between lake area and fishery yield to generate what he considered a "crude" and "undoubtedly excessive" estimate of annual global lake fishery harvest of more than 93 mt. More recently, Lymer *et al.* (2016) extrapolated the average yield from different habitats (eg lakes, rivers, wetlands) across continents and generated an area-scaled annual global "theoretical" total yield of 72 mt, of which lakes constituted 20.7 mt. The disparity between these approximations highlights why improved global harvest estimates from lake fisheries are necessary. Here, we provide a new estimate of global lake harvest based on ecological principles, robust model validation, and data independent of FAO estimates.

Two recent publications have provided the foundation for estimating lake harvest using chlorophyll *a* (chl *a*) data captured at the global scale. First, through a meta-analysis, Deines *et al.* (2015) demonstrated a positive relationship between chl *a* concentration and inland fish biomass and fishery yield. Second, Sayers *et al.* (2015) developed and validated a technique for estimating chl *a* concentrations from satellite-based data collected during one month of the 2011 growing season for more than 80,000 lakes greater than 0.1 km^2, providing global coverage of estimated chl *a* concentrations in freshwaters. We combine the findings of these papers to develop a predictive model of lake harvest as a function of chl *a* concentration and regional human population densities. The model is then used to extrapolate fisheries harvests from individual lakes to the global scale, and produce an independent estimate of global lake harvest.

Methods

Conceptually, our approach began with the compilation of chl *a* and data from in situ observations of fish populations, followed by the development and validation of a training model, which estimated model parameters based on a subset of the observed data. Then, the validated training model and parameters were used to predict fisheries harvest in thousands of lakes using satellite-derived estimated chl *a* values, and finally harvest predictions were extrapolated to the global scale (Figure 2). Detailed methods are given in WebPanel 1 and data sources in WebTables 1 and 2. First, a database was compiled that paired fisheries harvest or fisheries-independent biomass with coincident measurements of chl *a* for individual water bodies. Then, using a subset of these data, a Bayesian hierarchical model was trained to estimate fisheries harvest by employing a basic equation: $H_{ij} = q_i \times B_j \times a_j \times E_j$, where harvest H (in kilograms) is the product of fish biomass B (in kilograms per hectare), lake area a (in hectares), regional human population density as a measure of fisheries effort E, and the proportion of biomass harvested by one unit of effort (ie catchability q). The subscript j indexes each lake, and the subscript i indexes the different fishery types possible for the lake (ie Figure 1) that make up the hierarchical component of the model: artisanal/subsistence, commercial/industrial, recreational, and total (the reported sum of multiple types of fisheries). Fish biomass B_j was modeled as a function of chl a_j, and three functional forms for this relationship were tested: linear, asymptotic, and hump-shaped. The linear model was included to represent the simplest possible relationship (Deines *et al.* 2015). The asymptotic and hump-shaped models are consistent with expected declines in fish productivity empirically observed under conditions associated with very high chl *a* concentrations, such as eutrophication, which can decrease water quality and fish biomass (Ney 1996). Using the *rjags* package in R (R Core Team 2012), we ran the models with the JAGS implementation of Markov chain Monte Carlo (MCMC) sampling. To determine if a suitable solution was found for each of the models being trained, we examined whether multiple random MCMC starting points all converged on the same estimated model parameters. Convergence was evaluated by using the Gelmen diagnostic, by visually inspecting traceplots of parameter estimates over the course of each MCMC run, and by examining the shape of posterior parameter distributions collected after convergence was achieved. The best functional form of the fish biomass–chl *a* relationship (ie linear, asymptotic, or hump-shaped) was chosen by testing model predictions using data withheld from the training model.

The best fitting training model – the linear fish-biomass model (see Results section) – was used to predict the total harvest for a single-month "snapshot" of 80,012 lakes (covering 2.07 million km^2) in the summer of 2011 for which chl *a* concentration was estimated remotely via satellite with Medium Resolution Imaging Spectrometer (MERIS) imagery (Sayers *et al.* 2015). Harvest for these snapshot lakes was calculated using satellite-observed chl *a*, the human population within a 100-km buffer around the shoreline of each lake, and the model parameters estimated with the training data. Because we had no knowledge of the type of fishery operated on each of these snapshot lakes, harvests for all lakes were predicted assuming each type of fishery separately, represented by different catchability (q_i) estimates, as well as by the global mean catchability, which represents the average catchability across all fishery types.

To extrapolate harvests to global lakes and reservoirs that occur in the Global Lakes and Wetlands Database (GLWD; Lehner and Döll 2004) but not in our 2011 global snapshot, we calculated the average harvest (kilograms per hectare) of snapshot lakes within each of the Freshwater Ecoregions of the World (FEOW; Abell *et al.* 2008) and multiplied each ecoregion average harvest by that particular ecoregion's total lake surface area that was not already included in our snapshot lakes. Thus, the harvest was estimated for an additional 607,861 km^2 across the globe, for a total of 2.68 million km^2.

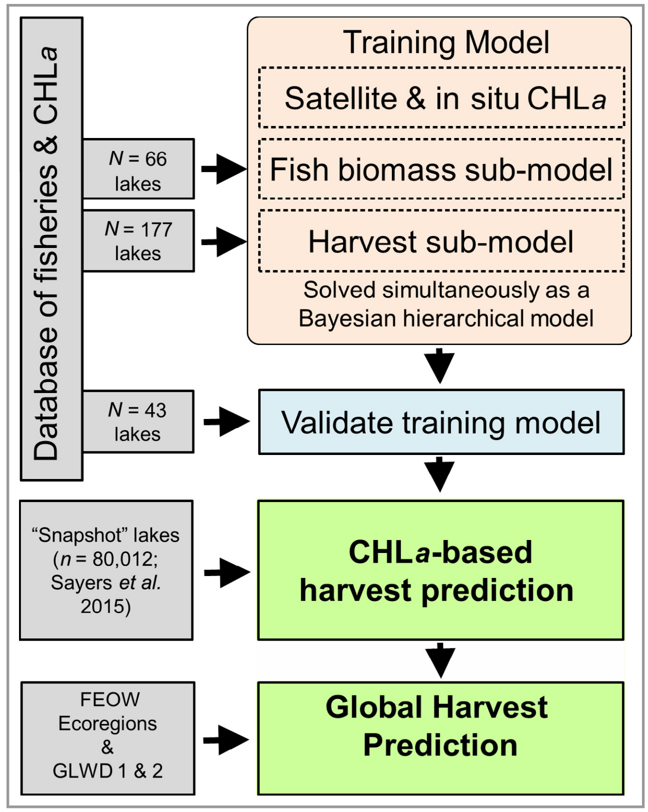

Figure 2. *Conceptual overview of modeling and global harvest estimation process beginning with in situ data collection from literature, databases, researchers, and satellites, followed by development and validation of a training model, prediction of fisheries harvest in over 80,000 lakes globally, and then extrapolation of predictions to the global scale.*

Results

The model prediction results were obtained by assuming a linear relationship between fish biomass and chl *a*, because (1) there was no distinction between the linear and hump-shaped models and (2) the asymptotic model failed to converge and was therefore excluded. The full Bayesian model effectively predicted both fishery-independent biomass and fishery harvest for the training model and withheld validation data (WebPanel 1).

The global distribution of total harvest and by-ecoregion harvest per hectare is mapped in Figure 3. For the 2011 snapshot lakes, the global total harvest using the global mean catchability was 4.8 mt (95% prediction interval [PI]: 0.1–40.7 mt), with an average harvest of 19.5 kg ha^{-1} (95% PI: 0–158 kg ha^{-1}), and varied latitudinally with the highest levels near the northern middle latitudes. For lakes not captured in our global snapshot but mapped in the GLWD, the FEOW-based extrapolation (using the global mean catchability) yielded another 3.7 mt (95% PI: 0.07–35.15 mt), harvested from 166,945 additional waterbodies with an average harvest of 49.6 kg ha^{-1}. Hence, for lakes and

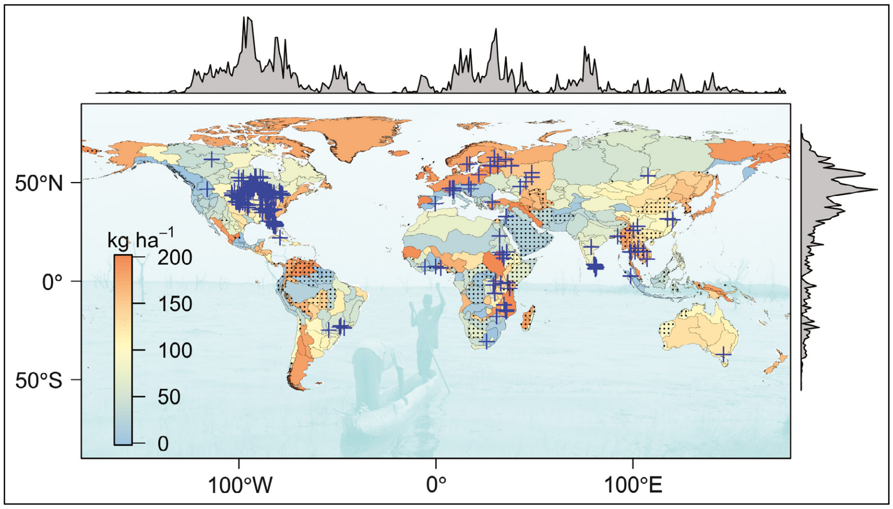

Figure 3. *Average predicted fish harvest (kilograms per hectare, in colored scale) from snapshot lakes in each region of the Freshwater Ecoregions of the World (FEOW). Stippled regions are calculated as the average of lakes in the 2011 snapshot within that region's FEOW major habitat type. The density of total yield by latitude and longitude is plotted along the map margins, excluding the large harvests of the top 0.1% lakes. Blue crosses indicate locations of lakes used in model training and testing.*

reservoirs larger than 0.1 km^2, we estimated a total global harvest of 8.4 mt (95% PI: 0.09–75.9 mt).

Discussion

Our estimate of lake harvest improves upon the FAO's reported total global inland fish harvest, which is suspected to underestimate yields. The FAO is the world's premier resource for national and global fisheries statistics; therefore, its estimates of inland fisheries harvest heavily influence the perception of inland fisheries as a contributor to global food security and to local and national economies. Even though our analysis accounted for only 53% of global lake surface area, due to our exclusion of numerous very small lakes, our final extrapolated estimate of fish harvest from lakes alone still amounted to 79% of the total inland harvest reported by FAO from all types of inland waters in 2011. Given that FAO compilations also include harvests from other important freshwater habitats (eg small lakes, rivers, and wetlands) that when combined likely produce more than 4 mt of harvest, our results support the conclusions of others (Beard *et al.* 2011; Welcomme 2011; Bartley *et al.* 2015) that current FAO estimates of inland fisheries harvest are underestimated. Given the wide range of services provided by inland fisheries and the potential trade-offs between freshwater ecosystem services, the importance of inland fisheries in political, socioeconomic, and environmental contexts is likely also undervalued.

Recent studies have also approximated global inland lake fisheries harvest, but we believe our approach offers a more accurate estimate of lake harvest for several reasons. First, we provide the first estimate based on both ecological theory (ie that fish biomass is influenced by primary production) and fisheries theory (ie that harvest is a function of effort and catchability). In contrast, previous studies used FAO data to predict global lake yield only on the basis of water body size (Welcomme 2011) or the average harvest from a given habitat type on a given continent (Lymer *et al.* 2016). Second, our global database of 286 lakes, for which fisheries-independent or -dependent data were compiled, substantially exceeded the number of lakes used by Lymer *et al.* (2016) to estimate global lake harvest. Furthermore, our application of newly derived data for chl *a* concentrations and a human-population index of effort from more than 80,000 lakes provides the most comprehensive incorporation of lake-specific data to inform harvest estimation thus far. Third, our approach was unique in that we validated our model using withheld data to evaluate the robustness of model predictions.

Our global estimate for the 80,012 lakes for which chl *a* was estimated had relatively large credible intervals (4.8 mt, 95% PI: 0.1–40.7 mt), arising from the use of the mean catchability coefficient among our four fishery types. Our harvest estimates for specific fishery types had less uncertainty (WebFigure 6), but because the relative occurrence of these fisheries types across the globe is unknown, these harvests could not be separately extrapolated to the global scale. While the precision of our estimate was lower relative to what Lymer *et al.* (2016) predicted (±8 mt), we suggest this stems from our explicit incorporation of many sources of uncertainty known to be present for each lake (eg harvest by fishery type, chl *a* , and effort) and in the model assumptions and specification. Improving on-the-ground data collection will be the best way to increase the accuracy and precision of global lake fishing harvest estimates. The model and estimate developed here provide independent verification of the need to support these activities.

A key knowledge gap that contributes to high uncertainty in our model is fishing effort. We used a coarse approximation of effort (human population within 100 km of a lake) owing to the lack of consistent effort data available at the global scale. Investing in a standardized and simple measure of effort across inland water bodies (eg number of fisher-days) would not only enhance the performance of future harvest models but would also directly inform policy makers about the reliance of communities on inland fisheries.

Our model predicted inland yield from about 53% of the global lake surface area, and the majority of lakes that could not be included were relatively small (ie <1 km^2). We were unable to estimate the chl *a* from smaller lakes, given the resolution limitations of satellite images that provide the necessary spectra for chl *a* estimation in freshwaters. Future research could revise the models currently available for satellite imagery, but even then, most of these small lakes are located north of 50° latitude (Verpoorter *et al.* 2014), in areas of the world where population density is relatively low. Fishing effort in these small water bodies may therefore be limited and they may not contribute as much to the global inland fisheries yield as simple area-based models would predict (eg Welcomme 2011).

Harvest from rivers and wetlands were excluded from our global estimate; however, these waterbodies may make substantial contributions to inland harvests (Lymer *et al.* 2016) and food security (McIntyre *et al.* 2016). Improved estimates of fish harvest in rivers and wetlands are urgently needed, and will likely have greater influence on refining total global inland capture estimates than accounting for harvest in the remaining smaller lakes omitted from our estimate. Although the global surface area of rivers is only approximately 0.7 million km^2 (Downing *et al.* 2012), many of the countries that rank within the top 15 highest inland captures reported to the FAO have large, productive river systems, such as the Yangtze (China), Ganges (India and Bangladesh), and Mekong (Thailand, Cambodia, China, Myanmar, and Vietnam) rivers. In contrast to rivers, the surface area of wetlands and marshes likely covers at least three times the surface area of lakes (Lehner and Döll 2004). Fisheries harvest in floodplains, wetlands, and marshes is a relatively understudied topic, but these habitats can be highly productive for fish (Welcomme 2008). New high-resolution land imaging satellite sensors, including instrumentation on the *Landsat-8* and *Sentinel-2* satellites, have recently yielded reasonable estimates of various water constituents, including chl *a*, even in optically complex water (Franz *et al.* 2015). Ideally, this approach could be applied to large rivers and wetlands to further enhance indirect estimates of the global importance of inland fisheries.

Conclusion

Remote-sensing tools have been recommended as a way to provide estimates of inland fisheries harvest around the world (Lorenzen *et al.* 2016) and to better quantify the socioeconomic value of these fisheries (Lynch *et al.* 2016). Here, the model developed – based on satellite-derived chlorophyll concentrations and regional human population densities – indicates that lakes greater than 0.1 km^2 may by themselves account for 79% of recent FAO estimates of total global inland fish capture. Future research to independently estimate the productivity of very small lakes, rivers, and wetland systems would enable a more accurate global estimate of inland fisheries harvest, which could help managers and stakeholders to better understand their importance when making decisions regarding the competing uses of fresh waters and the ecosystem services they provide.

Acknowledgements

Many researchers and agencies contributed data to this project and the full list of these contributions is given in WebTable 2. Dr I Cowx shared helpful insights into many freshwater fisheries that improved this research. JM Deines provided assistance in spatial data visualization. Funding support was provided by the USGS National Climate Change and Wildlife Science Center. Any use of trade, product, or firm names is for descriptive purposes only and does not imply endorsement by the US Government.

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Supporting Information

Additional, web-only material may be found in the online version of this article at http://onlinelibrary.wiley.com/doi/10.1002/fee.1503/suppinfo

