Global proliferation of small hydropower plants – science and policy

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Large-scale electricity policies that embrace renewable resources have led to continued investments in hydropower. Despite evolving viewpoints regarding the sustainability of large hydropower installations, there has been a major increase in support for the widespread development of small hydropower plants (SHPs). A global synthesis reveals that 82,891 SHPs are operating or are under construction (11 SHPs for every one large hydropower plant) and that this number is estimated to triple if all potential generation capacity were to be developed. Fueled by considerable political and economic incentives in recent decades, the growth of SHPs has greatly outpaced available ecological science. We provide evidence for not only the lack of scientifically informed oversight of SHP development but also the limitations of the capacity-based regulations currently in use. The potential indiscriminate expansion of SHPs under the pretense of promoting sustainable energy is concerning, and we identify several important steps to help ensure new scientific advances, effective management, and policy reform in the future.

In a nutshell:
• We estimate that 82,891 small hydropower plants (SHPs) are operating or are under construction in 150 countries and that another 181,976 new plants may be installed if all potential capacity were developed
• Country-level definitions of SHPs vary immensely with respect to maximum generation capacity and include limited consideration of potential descriptors of ecological impacts (eg dam height, reservoir area, and operating procedures)
• Environmental policy and the existing body of scientific knowledge are insufficient to inform SHP development, leading to a chronic underappreciation of the potential socioecological consequences of their proliferation
• We outline the need for stricter and better-informed regulations, integrated watershed management that considers SHPs in aggregate, and information systems to support strategic planning of new construction into the future

One of the greatest challenges of this century is to support growing human societies with electricity policies that embrace environmentally sustainable resources. Hydropower, the power derived from the energy of flowing water, is the world’s primary source of renewable energy, contributing almost three-quarters of the global renewable supply and nearly one-fifth of all electricity production (REN21 2015). Global investments in hydropower peaked in the second half of the 20th century, partly in response to a growing desire to diversify away from thermoelectric facilities and avoid greater dependency on fossil fuels (Oud 2002).

In response to the mounting demand for renewable energy, thousands of new hydropower installations are expected to be built and to commence operation in the coming decades (Zarfl et al. 2015). These activities are most prevalent in developing countries where governments are prioritizing new large dams as the centerpiece of energy plans (Winemiller et al. 2016). Unfortunately, these dams have substantial socioecological costs (Rosenberg et al. 1995). Indeed, public support for new large dams has diminished as the high socioeconomic costs, emissions of greenhouse gases, and negative consequences for valued ecosystem services, including water quantity and quality, biodiversity, and fisheries, are increasingly realized (Ansar et al. 2014; Kahn et al. 2014; Deemer et al. 2016).

Amid evolving conversations regarding large hydropower sustainability, a marked surge of support for small hydropower plants (SHPs) has emerged (Panel 1). The term SHP broadly refers to facilities that produce less electricity and operate in smaller rivers as compared to large hydropower plants (LHPs). However, because SHPs have a diversity of operation modes (eg diversion and non-diversion with or without storage), flow control structures, and environmental impacts (Panel 1), this definition is ambiguous. Political and economic incentives for sustainable energy development initially fueled the growth of SHPs, particularly in Europe and China (Paish 2002; Tang et al. 2012), but now countries across the world consider SHPs to be a critical component of future energy strategies. For instance, more than half of US states have renewable portfolio standards that disallow electricity from LHPs, yet they embrace power produced from SHPs (Kao et al. 2014), due in part to a perception that “smaller” equates to lower socioecological impact (Gleick 1992). As this viewpoint continues to gain traction in public and political arenas, the lack of scientifically informed regulations (Gleick 1992; Erlewein 2013) and the potential indiscriminate expansion of...
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SHPs under the pretext of sustainable energy promotion is concerning (Premalatha et al. 2014).

We provide the first global overview of the expansion of SHPs, summarizing status and trends in an international context, and encouraging the bridging of critical science and policy gaps. First, we explore the rapid growth of the sector and quantify the current and future hotspots of SHP development based on a dataset compiled from the most up-to-date international energy policy reports. The dataset includes national definitions of SHPs, current numbers of SHPs and LHPs, and estimates of future SHP numbers based on countries’ untapped hydropower potential (methods described in WebPanel 1). Second, we expose the global inconsistencies in how SHPs are defined, and argue for the removal of the “small” modifier. Third, we discuss the environmental policies and the scientific knowledge that currently shape the management and regulatory practices of SHPs. Finally, we provide a synopsis of the scholarly literature examining the known or potential ecological impacts of SHPs, and identify the main challenges to ensure that environmental policies inform the worldwide expansion of SHPs.

Global proliferation of SHPs

Our synthesis of the energy policy reports reveals that at least 82,891 SHPs are operating or are under construction in 150 countries (Figure 2a; WebPanel 1). We estimate a tripling of this number to include an additional 181,976 plants that could be installed if all potential capacity were to be developed – of these,
10,569 new projects already appear in national plans (Figure 2b; WebPanel 1). Distinct geographic patterns in SHP numbers are apparent, reflecting differences in socioeconomic conditions, varying regulations and incentives, and contrasting hydrologic potential. China is the global front-runner, with 47,073 SHPs currently operating; the surge was propelled by private investments, technology leadership, and rural electrification programs (Tang et al. 2012; WSHPDR 2016). An additional 26,877 SHPs are operating in Europe, where SHP development not only has a long history but has also received recent attention associated with the need to satisfy international agreements promoting clean energy (Paish 2002; Hermoso 2017). Future plans for SHPs are concentrated in Asia, the Americas, Southern and Eastern Europe, and East Africa. Considering that national dam inventories generally underestimate the number of smaller facilities, we expect that the numbers of SHPs reported here are conservative. Even based on these values, the current number represents more than 91% of the total hydropower installations, dwarfing the number of LHPs \( n = 7721 \); Figure 3a). On average, there are close to 11 SHPs for every one LHP in the world (WebPanel 1). Although representing the vast majority of hydropower plants, SHPs contribute just 11% of the global electricity generation capacity based on hydropower (WebPanel 1).

SHPs are proliferating around the world (Figure 3b; WebPanel 1; IRENA 2017) as a response to governmental incentives in the form of competitive tariffs, as well as investments by the private sector (ie trading energy with the grid or providing lower-cost energy for local industries), programs promoting rural electrification in remote regions, simplified licensing processes, and quick construction time (Egré and Milewski 2002; Tang et al. 2012; WSHPDR 2016). For example, aggressive policies in several European countries have encouraged rapid sector development since the 1980s (Paish 2002; Jesus et al. 2004). Numerous other countries are now duplicating such policy initiatives. In Brazil, a series of incentives and new regulations contributed to a fivefold increase in the number of SHPs over the past two decades (Panel 2). Even in the US, where current conversations typically focus on the removal of aging dams (Bellmore et al. 2016), a recent US Department of Energy report highlights that 65 gigawatts of potential hydropower remain untapped (Kao et al. 2014), and that new hydropower would come predominantly in the form of hundreds of new SHPs.

**Figure 2.** Map depicting (a) the current number of SHPs (82,891) operating or under construction across 150 countries and (b) the estimated number of potential SHPs (181,976), of which at least 10,569 are included in national plans to be implemented in the coming decades. See WebPanel 1 for description of methods. Country-level statistics are available at: https://figshare.com/s/e118ecae964140f16f80.

**Just how “small” are SHPs?**

Our assessment revealed notable disparities in how countries classify hydropower plants as “small” (WebPanel 1). The size of a given hydropower facility is commonly defined according to its generation capacity in watts (hereafter termed “capacity”), which is the maximum capacity of hydropower production assuming optimal hydrologic conditions and turbine efficiency. Capacity-based definitions of SHPs vary substantially, ranging from up to 1 megawatt (MW) for facilities in Germany and Burundi to up to 50 MW for facilities in Canada, China, and Pakistan (Figure 5). About 70% of countries with formal definitions classify SHPs as installations with less than 10 MW, which is increasingly recognized as the international standard (WSHPDR 2016). Of those countries that currently operate SHPs, 15% do not have a formal (or widely accessible) national designation (Figure 5). In addition to considerable variability in SHP definitions
across countries, facilities designated as SHPs may have substantially different dam sizes, reservoir areas, storage capabilities, outlet structures, and operating procedures (Panel 1; Figure 6), all of which are strongly correlated with environmental impacts of dams (Gleick 1992; Poff and Hart 2002; Mbaka and Mwaniki 2015). For instance, two SHPs in Brazil (São Sebastião, Brago Norte II) have the same capacity (10 MW), but differ thirtyfold with respect to their reservoir areas (0.2 and 6.0 km², respectively).

In addition to the limited and internationally inconsistent definitions of SHPs, there are considerable discrepancies in hydropower classification within countries; this means that some nations may support policies that are based on different capacity thresholds. In Russia, contrasting regulations classify SHPs as facilities generating less than either 25 or 30 MW (WSHPDR 2016). SHP definitions remain highly dynamic elsewhere, including in the US and Brazil, where recent amendments increased the upper limits from 5 to 10 MW (Hydropower Regulatory Efficiency Act of 2013) and from 30 to 50 MW (Law 13.360/2016), respectively. Some countries further delineate SHPs into small, mini, micro, and pico hydro classifications (WebPanel 1). For the purposes of this review, we consider SHPs as all those with maximum capacity defined according to the country-specific definition or 10 MW for countries without national definitions.

Panel 2. Brazil as a model of the rapid expansion of SHPs

In Brazil, 1007 SHPs are currently operating, an additional 35 are under construction, and 156 are approved and awaiting final licensing (ANEEL 2016). On average, 33 SHPs have been constructed per year from 2001 to 2016, a growth rate 14 times as fast as that witnessed in the 1990s (Figure 4). By contrast, increases in LHPs have remained constant in recent decades. Massive investments by the private sector after 1995 were stimulated by new regulations within the energy market and by economic incentives, resulting in hundreds of new SHPs (Ferreira et al. 2016). Simultaneously, there was a reformulation of the environmental licensing process (CONAMA 237/1997) that later included the introduction of simplified licensing procedures for projects with perceived “little potential of causing environmental disturbance”, which were defined as SHPs with less than 10 MW (CONAMA 279/2001). This licensing reform was followed by a re-definition in 2003 of what constitutes an SHP, which quadrupled the maximum reservoir area from 3 to 13 km² while maintaining the maximum limit of 30 MW (Ferreira et al. 2016). In November 2016, a new bill was approved, increasing the upper limit of SHPs from 30 to 50 MW (Law Nº 13.360/2016).

Figure 4. Number of Brazilian hydropower facilities in operation since 1970. Although LHPs have demonstrated a constant construction rate for decades, a rapid proliferation in the construction of SHPs commenced in the early 2000s following new regulations and incentives (WebPanel 2). This plot includes 937 hydropower facilities (out of 1227 total) reporting the first date of operation (ANEEL 2016).
Limited environmental regulations for SHPs

The rapid expansion of SHPs is due in part to weak regulatory oversight that has encouraged investments in the private and public sectors. According to a global policy compilation, at least 44 out of 160 countries require a formal environmental licensing process to construct and operate SHPs (WSPDHR 2016), leaving potentially more than two-thirds of the countries without recognized environmental requirements. Certain countries have regulations requiring mitigation actions — such as fishway structures that attempt to facilitate fish movement and standards of minimum flow releases aimed at sustaining human and environmental water needs — when SHPs are constructed. In France, all hydropower installations, regardless of size, must have facilities that promote passage of migratory fish species (Larinier 2008). By contrast, countries such as Costa Rica lack formal rules of minimal flow releases or else adopt arbitrary standards based on the policies of other countries (Anderson et al. 2006).

When present, environmental licensing processes associated with SHPs vary substantially among countries, but are often less rigorous than licensing of LHPs. Installation of LHPs frequently requires Environmental Impact Assessments (EIA), public consultations, management plans, and monitoring programs (Erlewein 2013), whereas the installation of SHPs may involve only a simplified EIA if anything at all. In India, SHP construction (<25 MW) does not necessitate an EIA; instead, only a Detailed Project Report must be approved, and even these evaluations are commonly inadequate (Erlewein 2013). Similarly, in Brazil, only a Simplified Environmental Report is required for constructing SHPs with a capacity of less than 10 MW, but larger SHP projects (10 to 30 MW) are subjected to a licensing process similar to that of LHPs (Panel 2). In the US, SHPs of less than 10 MW are exempt from some licensing requirements; similar exemptions are also granted to hydropower projects up to 40 MW placed along canals associated with agricultural, municipal, or industrial water consumption (Hydropower Regulatory Efficiency Act of 2013). Prior to 2008, EIAs were not mandatory in Turkey for installations up to 50 MW, but now projects between 0.5 and 20 MW require full EIAs (Dursun and Gokcol 2011). These examples reinforce the notion that the “small” in SHP policies continues to be equated with negligible environmental impacts, and a streamlined approval process with inadequate regulatory oversight is applied in many instances.

Perhaps most concerning is that environmental regulations for SHPs are mandated on a single and arbitrary capacity threshold that does not necessarily equate with the magnitude of environmental impacts (Gleick 1992). By pooling diverse hydropower projects, these regulatory frameworks overlook considerable variability in modes of operation, degree of flow modification, dam size, and inundated area, which ultimately define the ecological impacts of dams (Egré and Milewski 2002; Poff and Hart 2002). Brazil and Turkey include reservoir area in their SHP definitions (as large as 13 km² and 15 km², respectively) but these are exceptions (Dursun and Gokcol 2011; Ferreira et al. 2016).

Science lags behind the rapid rise of SHPs

The widespread increase in SHPs continues to greatly outpace advances in scientific knowledge in the environmental field. Of the publications that we reviewed, fewer than 5% explicitly investigated SHPs, even though SHPs represent more than 91% of existing hydropower installations (WebPanel 2). Research on SHPs grew in the 2000s when the sector flourished in many countries, a trend that started more than three decades earlier for LHPs. Research on LHPs has been fundamental to understanding, regulating, and attempting to mitigate the ecological impacts of hydropower (Kahn et al. 2014; Olden 2016); however, we question whether such knowledge is transferable to inform policy and management decisions for SHPs. Furthermore, although generation capacity is the benchmark used to regulate and manage hydropower, only 15% of the papers included in our synthesis reported the capacities of the studied installations (WebPanel 2), making generalizations between SHPs and LHPs even more difficult. In short, the rise in the number of scholarly publications has not been commensurate with the rapid increase in SHPs observed globally.

Emerging evidence for the ecological impacts of SHPs

The diversity of sizes and operation modes of SHPs (Panel 1) produce a myriad of ecological consequences...
that may not necessarily differ from what is expected from LHPs (Cada and Zadroga 1982). Despite relatively slow progress in scientific research, evidence suggests that the environmental impacts of SHPs include those associated with the dam’s construction and land inundation, as well as post-construction alteration to flow regimes, the loss of habitat connectivity, and the cumulative effects of multiple installations. However, the magnitude of such impacts may depend more on the attributes of individual projects and on the landscape context in which they are located, rather than merely being related to an arbitrary size classification (Panel 1; Gleick 1992). Perhaps the greatest difference between SHPs and LHPs is their position in the watershed; SHPs generally occur in smaller rivers as compared to LHPs (Kibler and Tullos 2013). This is problematic given the importance of headwater streams in maintaining hydrologic connectivity, harboring biodiversity, and supporting ecosystem integrity at regional scales (Meyer et al. 2007).

The construction of the main (eg dams, reservoirs, diversion channels, penstock, powerhouses) and accompanying (eg roads, transmission lines, substations) structures are the initial sources of impact. During construction, there are direct impacts of deforestation and land preparation, as well as indirect impacts associated with transportation, construction materials, and energy requirements (Cada and Zadroga 1982; Pang et al. 2015). When SHPs impound water, the newly created reservoirs produce greenhouse gases through mechanisms such as decomposition (Deemer et al. 2016) and inundate terrestrial habitats, potentially threatening biodiversity and compromising ecosystem functions (Benchimol and Peres 2015).

Hydropower dams and diversions not only modify downstream flow regimes, channel morphology, and water temperature but also affect sediment transport and deposition (Baker et al. 2011; Olden 2016). These modifications tend to be more evident in installations with greater storage capacities (Mbaka and Mwaniki 2015), but they are also present for run-of-river SHP schemes (Stanley et al. 2002; Meier et al. 2003; Anderson et al. 2015). Among the various ecological effects (Table 1), artificially warm or cold water is released downstream from smaller dams, depending on the mode of operation and thermal profile of the reservoir, leading to impacts on biological communities (Hayes et al. 2006). The transformation of flowing rivers to shallow, standing water can have numerous con-

Figure 6. Examples of SHPs in (a) Brazil (CGH Abrasa, 1.5 MW), (b) China (Cangpinghe, 9.1 MW), (c) Brazil (PCH Ludesa, 30 MW), and (d) Canada (Rutherford, 49 MW).
sequences that include effects on primary production and the alteration of algae, invertebrate, and fish communities (Kubecka et al. 1997; Jesus et al. 2004; Wu et al. 2010).

Damming rivers can create major conservation problems by fragmenting critical habitats (Gido et al. 2016). Dams and weirs associated with SHPs represent physical barriers by fragmenting critical habitats (Gido 2016). Dams et al. (Kubecka et al. 2003). Given their migration route, only 18% of tagged Atlantic salmon (Salmo salar) reached spawning grounds above a hydropower complex in Scotland (Gowans et al. 2003). Given the huge number of current and planned SHPs, determining the ecological effects of multiple rather than individual installations deserves urgent attention.

### Management and policy

Environmental policies must support robust and science-based licensing regulations for SHPs. Differentiating “small” from “large” hydropower is a primary decision node in most licensing frameworks when determining whether a full EIA (versus a simplified one, or none at all) is required for a new installation. However, a capacity-based criterion alone is insufficient to define expectations regarding the potential environmental impacts of hydropower, especially considering that the thresholds are often arbitrarily defined. Moreover, by focusing exclusively on a single attribute of an installation (namely its generation capacity, the desired product of hydropower), current environmental regulations could run the risk of favoring less productive, ecologically

### Table 1. Examples of ecological effects of SHPs on freshwater biodiversity, organized according to flow control (storage versus non-storage) and presence of a diverting structure (diversion versus non-diversion). Additional examples are included in WebTable 1.

<table>
<thead>
<tr>
<th>Flow control</th>
<th>Structure</th>
<th>Capacity (MW)</th>
<th>Ecological response</th>
<th>Country</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Storage</td>
<td>Diversion</td>
<td>18</td>
<td>Fish species composition modified in response to fragmentation by damming and dewatering. Opportunistic life-history strategists dominate over species exhibiting more complex reproductive requirements</td>
<td>Costa Rica</td>
<td>Anderson et al. (2006)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 10</td>
<td>Downstream decrease in macroinvertebrate density and richness, with the replacement of high-flow-adapted species by low-flow, generalist species</td>
<td>Portugal</td>
<td>Jesus et al. (2004)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 1</td>
<td>Periphytic chlorophyll and biomass showed little difference between diversion canals and mainstream, suggesting minimum effect on nutrient uptake efficiency despite alterations to hydrology</td>
<td>Spain</td>
<td>Izagirre et al. (2013)</td>
</tr>
<tr>
<td>Non-diversion</td>
<td></td>
<td>&lt; 1</td>
<td>Fish condition in reservoirs decreases with compromised integrity of nearshore vegetation</td>
<td>Brazil</td>
<td>Ferreira et al. (2015)</td>
</tr>
<tr>
<td>Non-storage</td>
<td>Diversion</td>
<td>&lt; 10</td>
<td>Fish communities dominated by small-bodied species in dewatered sections of rivers. Average individual weight and total biomass of fish decreased four times in the reduced discharge sections, where biomass losses were proportional to the degree of abstraction</td>
<td>Czech Republic</td>
<td>Kubecka et al. (1997)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt; 1</td>
<td>Benthic macroinvertebrate communities showed modest downstream responses, where high-flow-adapted mayfly and stonefly species exhibited reduced abundance in dewatered stream sections</td>
<td>UK</td>
<td>Copeman et al. (1997)</td>
</tr>
<tr>
<td></td>
<td>Not reported</td>
<td></td>
<td>Benthic algae communities modified after SHP construction. Modification in algae communities and chlorophyll concentrations tend to be more pronounced in the dry season in response to a higher proportion of water abstraction</td>
<td>China</td>
<td>Wu et al. (2009a), (2009b), (2010)</td>
</tr>
</tbody>
</table>
harmful projects over ones that are more productive and ecologically benign. SHP regulations must look beyond capacity and incorporate flow alteration, inundation area, impacts on habitat connectivity, and the cumulative effects of multiple installations.

We recognize the many challenges of conducting detailed EIAs for every potential hydropower project, especially in countries with limited financial and human resources. However, we advocate that EIAs should be compulsory during the licensing process for all SHP projects given the diversity of facility sizes, operation modes, and geographic locations. Adjusting site-specific characteristics to maximize electricity generation requires a wide range of technical solutions, which may create a myriad of environmental changes (Egré and Milewski 2002). By considering SHPs as a homogeneous group in licensing frameworks, policy makers are likely to underestimate the facilities’ potential environmental impacts. EIAs can help to identify specific impacts on the affected ecosystem, quantify threats to biodiversity, address disruptions to coupled human–natural systems (e.g., subsistence fishing, access to agricultural lands, social and cultural values), and propose mitigation actions. Environmental assessments must additionally go beyond individual SHP projects and consider the broader watershed context before new construction is approved. The continued proliferation of SHPs necessitates systematic evaluations that take into account the cumulative effects of current and planned installations, a process that is overlooked by most present-day environmental regulations. By incorporating elements of integrated watershed management (Wang et al. 2016) into hydropower strategic planning, managers can ensure adaptive, multifaceted, and watershed-scale evaluations based on the location and attributes of proposed projects.

Ecological data are critically needed to support management strategies and policy reforms that attempt to minimize the impacts of SHPs. The vast and decentralized nature of SHPs imposes major challenges to the acquisition and compilation of fundamental information, especially when compared to LHPs (Lehner et al. 2011; Zarfl et al. 2015). We argue that the collation of basic attributes of present and future SHPs is fundamental to guide any meaningful strategic planning. Information on geographic location, dam height, reservoir area and volume, capacity, and operation mode could foster a baseline inventory without requiring substantial investment. This information can be used to prioritize projects that meet electricity demands while minimizing harm to the environment.

Several research questions need to be addressed in order to understand the full impacts of SHPs. First, scientists must determine which factors, in addition to capacity, are able to reliably delineate the environmental impacts of hydropower. Second, given the recognized importance of headwater streams for watershed integrity (Meyer et al. 2007), strategic plans must identify the species and ecological processes likely to be at risk from SHP development. Third, the extreme density of SHPs in some areas highlights the need to more rigorously quantify their cumulative impacts (Kibler and Tullos 2013). By addressing these knowledge gaps, the role of science in informing energy policy and watershed management will be strengthened.

SHPs and LHPs are not competing components of the hydropower sector. SHPs are broadly located in different parts of a basin (smaller rivers), financed by different entities (private investment), regulated by different policies, and respond to different energy demands (supplying out-of-grid consumers) as compared to LHPs. Consequently, in environmental policy making, there are political and social motivations to retain the SHP versus LHP classification. For instance, capacity classifications play a role in regulating the energy market and prices of electricity. By contrast, we argue for the removal of the “small” and “large” modifiers describing hydropower plants when conducting environmental assessments and mandating potential mitigation. A hydropower project artificially labeled as “small” should not automatically lead to a faster and less comprehensive licensing process.

Conclusions

Electricity is a basic human need in modern societies, and SHPs have a key role to play in supporting electricity policies that mandate the use of renewable resources. We have described the widespread proliferation of SHPs across the world, and highlighted the potential for continued growth of this sector into the future. The process by which hydropower plants are classified as “small” is based exclusively on the measure of generation capacity, which is arbitrarily chosen and inconsistently applied across countries. Additionally, scientific evidence indicates that the environmental impacts of SHPs are substantial, but existing policies and regulations appear to underestimate these impacts. We argue for stricter and more informed regulations, integrated watershed management plans that consider SHPs in aggregate, and readily available information systems to support strategic and impartial planning for new construction. Until such regulatory mechanisms are in place, it would be wise to reconsider the current pace of SHP expansion globally.

Acknowledgements

We thank E Whattam for assisting in the literature search and R Lee for illustrations. JDO was supported by H Mason Keeler Endowed Professorship from the School of Aquatic and Fishery Sciences at the University of Washington (UW). TBAC was supported by UW and by a grant from CNPq (Science without Borders 203991/2014-1).

References


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