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Major dams and the challenge of achieving “No Net Loss” of biodiversity in the tropics

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Abstract

Dam construction is booming across tropical regions critical for global biodiversity and ecosystem service provision. The principle of “No Net Loss” (NNL)—under which biodiversity impacts of development projects are quantified and fully mitigated—is being increasingly applied to large infrastructure development worldwide, including dams. We discuss the impacts of major tropical dams and associated implementation of NNL policies and outline three major challenges in achieving NNL: (1) overcoming practicalities implementing NNL in highly connected river systems over large spatio-temporal scales; (2) the stakes are high if NNL fails because tropical regions are hyper-diverse, rich in species endemism, and difficult to restore; and (3) inclusion of ecosystem services in NNL design is necessary due to the importance of tropical biodiversity for ecosystem service provision at multiple spatial scales. Overcoming these challenges is crucial when hundreds of dams are planned and under construction across the tropics, many potentially subject to NNL policies.

KEYWORDS

biodiversity offsets, conservation, food security, hydropower, river connectivity, sustainability

1 | INTRODUCTION

There are more than 58,000 large dams (those >15 m in height) currently in operation globally (ICOLD, 2018; Figure 1a). Over half of all large river systems—including eight of the most biogeographically diverse, and the three most biodiverse tropical river basin systems (the Amazon, Congo, and Mekong)—have been dammed (Winemiller et al., 2016; Zarfl, Lumsdon, & Tockner, 2015). The majority of dams are constructed for irrigation (ICOLD, 2018). However, here we focus on those dams that tend to be the most controversial and for which compensatory impact mitigation measures are most often applied: large dams constructed for energy generation. Hydropower currently contributes ~24% of global energy production (ICOLD, 2018). At least 3,700 large dams (>1-MW capacity) are planned or are under construction for hydropower generation; many of these dams are located in tropical regions where rainfall is high and rivers are numerous, and in emerging economies (Finer & Jenkins, 2012; Zarfl et al., 2015). Thus, the decision to construct dams is often intertwined with major financial investment and political dynamics because energy provision is key to economic development and social mobility (Sovacool & Dworkin, 2014).

Problematically, the frequency and severity of droughts are both predicted to rise over the coming decades, particularly across some tropical regions where proposed dam construction is highest. In the Amazon basin for instance, 191 dams are already in operation and a further 246 are planned for construction (Lees, Peres, Fearnside, Schneider, & Zuanon, 2016). Future drought severity across Amazonia is predicted to reduce hydropower output to such an extent as to warrant an increase in energy generated from other power sources,

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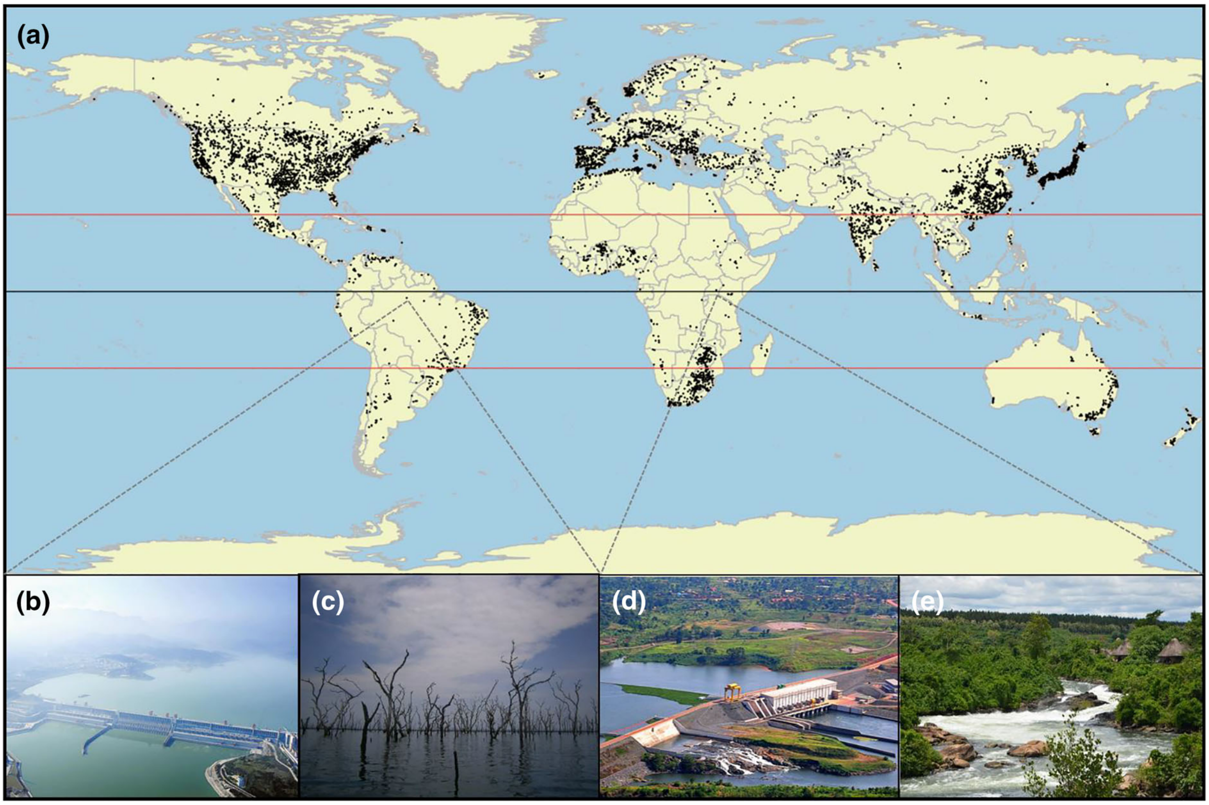

FIGURE 1 (a) Distribution of dams worldwide, based on data extracted from the GRanD dataset v1.01 (Lehner et al., 2011). Red lines bound the tropics. Created on QGIS Geographic Information System v.2.8.1; base data from Natural Earth v.3.1.0. (b) The Balbina Dam, Brazil (credit: JLSolars). (c) Flooded forest and standing dead wood upstream of Balbina (credit: I.L. Jones). (d) The Bujagali dam, Uganda (credit: Bujagali Energy Ltd). (e) The Kalagala Falls, conserved as part of the "No Net Loss" strategy for Bujagali (credit: V.F. Griffiths). Readers are directed to the online article for the colour version of this figure [Colour figure can be viewed at wileyonlinelibrary.com]

including fossil fuels, to meet energy deficits (Prado et al., 2016). Furthermore, ongoing deforestation has also been shown to reduce hydropower generation across Amazonia, because deforestation leads to reduced rainfall and lower river levels: deforestation and rainfall models of the Xingu River basin predict a 75% reduction in energy production from the Belo Monte dam complex by 2050 for example (Stickler et al., 2013). Thus, the long-term viability and energy security provided by tropical hydropower is debated (Fearnside, 2016b; Gibson, Wilman, & Laurance, 2017; Prado et al., 2016).

"No Net Loss" (NNL) policies—under which economic development impacts on biodiversity and ecosystem service provision are quantified and fully mitigated—are increasingly widespread (Maron et al., 2016). In a number of cases, NNL strategies have been used in an attempt to manage and fully compensate for the socioecological impacts of major hydropower projects (Griffiths, Bull, Baker, & Milner-Gulland, 2018; Sonter et al., 2018). In this article, given the projected expansion of major hydropower development in the tropics, we seek to explore specific challenges that might arise when applying NNL to such projects in tropical habitats. We do this by first discussing the trade-offs between energy provision and social and environmental costs, focussing on the biodiversity costs of large dam construction. We then describe recent advances in improving tropical dam sustainability and current biodiversity impact mitigation strategies. The implementation of NNL in large dam projects is then discussed by focussing on a specific case study from Uganda. Finally, our perspectives on the key challenges for achieving NNL with tropical dams are outlined.

2 | ENERGY PROVISION VERSUS SOCIAL AND ENVIRONMENTAL TRADE-OFFS

2.1 | Tropical dams provide only limited social benefits and can lead to energy injustices

Our focus here is upon mitigation of biodiversity impacts. However, due to the high number of semi-subsistence river-dependent people, and issues over land rights that are common to tropical regions, it is important to consider that dam construction can also cause myriad social impacts including the permanent displacement of people, alongside other social and energy injustices acting at a range of spatial and temporal scales (Sovacool & Dworkin, 2014). For instance, the energy produced by dams can be expensive for the public and/or be monopolized by the extractive industry: in Amazonia, for example, the 2,430-km^2 Tucuruí dam powers aluminium smelting rather than providing affordable and reliable energy provision for domestic use (Fearnside, 1999). Moreover, few people are employed once dam construction is complete, leading to high rates of rural unemployment; goods produced using hydropower are often exported as a raw material, further limiting employment opportunities that may otherwise have been created by high-value goods production in-country (Fearnside, 2016a; Prado et al., 2016).

2.2 | Carbon emissions associated with tropical dam construction

Despite being a renewable energy source, tropical dams can emit significant quantities of greenhouse gases including carbon dioxide and methane (Fearnside & Pueyo, 2012). Carbon emissions from dams are associated with concrete production and heavy vehicle use during construction. In lowland tropical regions, carbon is also lost through the inundation of tropical forest habitat during reservoir filling: forests are rarely logged prior to inundation, and the decomposition of submerged vegetation releases carbon dioxide and methane (Fearnside & Pueyo, 2012). Furthermore, long-term forest degradation and deforestation associated with human immigration via construction roads, also results in significant carbon emissions (Chen, Powers, de Carvalho, & Mora, 2015; Gibson et al., 2017). Indeed, recent analyses have shown that six Amazonian dams planned for construction have predicted carbon emissions that are comparable with thermal power plants, and higher emissions compared with equivalent solar or wind power development (de Faria, Jaramillo, Sawakuchi, Richey, & Barros, 2015).

2.3 | Dam construction affects both aquatic and terrestrial biodiversity

The biodiversity impacts of inundating both aquatic and terrestrial habitats act at a range of spatial and temporal scales and across international boundaries (Castello & Macedo, 2016). At the basin scale, fish migrations and population dynamics are disrupted in reservoirs and downstream of dams, leading to a loss of fish biomass and diversity, as well as endemic species extinctions. In regions that are highly biodiverse and centres of species endemism such as Amazonia, dam-induced disruption to fisheries can be detrimental to globally important aquatic biodiversity, as well as the economic and food security of river-dependent people over huge areas (Latrubesse et al., 2017; Lees et al., 2016; Ziv, Baran, Nam, Rodriguez-Iturbe, & Levin, 2012). Furthermore, dams alter natural river flow regimes, by, for example, removing seasonal flood pulses that are critical for ecosystem service provision, productivity, and biodiversity (Sabo et al., 2017; Timpe & Kaplan, 2017). The alteration of river flows can also lead to the loss of unique riverine habitats such as rocky outcrops and ephemeral sand beaches used by a range of other aquatic and terrestrial taxa including birds, bats, and freshwater turtles (see table 1 in Lees et al., 2016, for a comprehensive summary of biodiversity impacts downstream of Amazonian dams).

Although aquatic biota are disproportionately impacted by dam construction (Castello & Macedo, 2016; Lees et al., 2016), the biodiversity impacts of dams are not limited to aquatic taxa and extend beyond the confines of river and reservoir boundaries, impacting often globally important terrestrial habitats such as tropical forests (Gibson et al., 2017; Latrubesse et al., 2017). For instance, in low-lying regions such as the Amazon basin, large areas of hyper-diverse tropical forests that are a centre for global biodiversity are inundated during reservoir filling (Fearnside, 2006; Gibson et al., 2017). Terrestrial habitat remaining above the reservoir water line as island archipelagos is subject to chronic local species extinctions, which continue for decades after dam construction is complete (Jones, Bunnefeld, Jump, Peres, & Dent, 2016). For example, ongoing local mammal extinctions have been reported on islands within the Chiew Larn reservoir in Thailand (Gibson et al., 2013), whereas birds have been locally extirpated in the Thousand Island Lake in China (Yu, Hu, Feeley, Wu, & Ding, 2012) and in the Tucuruí reservoir in the Amazon (Bueno, Dantas, Henriques, & Peres, 2018). In the Balbina Dam (Brazilian Amazon; Figure 1b,c), which is associated with the strictly protected ~940,000-ha Uatumã Biological Reserve as an offset (Table 1), local extinctions and biological community collapse on reservoir islands have been reported for mammals (Benchimol & Peres, 2015b; Palmeirim, Benchimol, Vieira, & Peres, 2018), lizards (Palmeirim, Vieira, & Peres, 2017), invertebrates, (Storck-Tonon & Peres, 2017), and plants (Benchimol & Peres, 2015a; Jones, Peres, Benchimol, Bunnefeld, & Dent, 2017; Jones, Peres, Benchimol, Bunnefeld, & Dent, 2019).

In addition, the construction of access roads increases human populations in the vicinity of dams, indirectly exacerbating the biodiversity costs of dams through increased hunting pressure and deforestation: roads associated with the construction of the Belo Monte dam are predicted to trigger an additional 4,000–5,000 km^2 of forest loss by 2030, above the ~1,500 km^2 of forests lost through reservoir creation itself, for example (Barreto et al., 2014). Moreover, following the completion of dam construction when labour is no longer required, inflated rural populations become increasingly reliant upon forest resource extraction for subsistence. Logging and bushmeat hunting, as well as the establishment of small-scale farming, lead to significant degradation of remaining forest and biodiversity surrounding dams (Fearnside, 2008; Peres et al., 2010; Peres & Lake, 2003).

3 | RECENT ADVANCES IN IMPROVING TROPICAL DAM SUSTAINABILITY

Given the trade-offs between the need for energy production and biodiversity conservation, several recent studies have proposed strategies for minimizing the biodiversity impacts of tropical dams, so as to increase their ability to retain biodiversity and maintain ecosystem service provision in the long term (LeRoy Poff & Olden, 2017). First, the location and number of dams required to produce the desired amount of energy can be better assessed by revising energy policies to reflect realistic scenarios of climate change and future energy security needs (Fearnside, 2016b; Prado et al., 2016; Winemiller et al., 2016). Second, sophisticated analyses can be used to assess basin-scale environmental impacts using tools such as the Dam Environmental Vulnerability Index (Latrubesse et al., 2017). Finally, the potential for harnessing technological improvements in dam construction to create "designer" river flow regimes, which have been modelled so as to minimize

TABLE 1 A sample of large dam projects associated with biodiversity offsets, as a result of an NNL-type objective

Dam	Year operation began	Country	Value (million USD)	NNL of biodiversity required by	Ecosystem services considered
Amaila Falls Hydropower	Awaiting construction	Guyana	ND	ND	ND
Bujagali Hydropower	2012	Uganda	900[a]	Lender	Y
Bumbuna Hydroelectric	2009	Sierra Leone	91.8	Lender	N
Ingula Pumped Storage	2017	South Africa	3,500	National policy	Y
Lom Pangar	2016	Cameroon	430	Lender	N
Manaus Energia Balbina	1987	Brazil	730	Corporate	Y
Nam Theun 2 Hydropower	2010	Laos	2,000	Lender	N
La Breña II	2008	Spain	ND	ND	ND

Note. NNL might be required by national policy, performance standards set by financial lenders (“lender”), or a voluntary commitment on the part of the developer (“corporate”). Consideration of ecosystem services is incorporated into NNL strategy in some cases. Unless otherwise specified, data are extracted from Sonter et al. (2018).

Abbreviation: ND, not disclosed; NNL, “No Net Loss.”

[a] Value taken from International Finance Corporation documentation.

impacts or even enhance downstream fisheries production, can be explored (Sabo et al., 2017). In each of these cases, the approach is to minimize dam construction and/or the disruption caused by them. However, the current dam construction portfolio reflects the time lag between project proposal and financing through to completed construction: for example, the idea for the Belo Monte dam in Brazil was first raised in 1975, but licensing for the dam was blocked over two decades before construction commenced in 2011 (Hochstetler, 2011). Thus, the potential for using innovative strategies to manage the biodiversity impacts of dams remains relatively untested, generating questions surrounding whether dams should be constructed in tropical regions when other renewable energy generation methods, such as wind and solar, are available (Fearnside, 2016b; Gibson et al., 2017). However, assuming that in some cases dams will be built in the tropics to meet energy demands, a strategy for mitigating residual biodiversity impacts is required, and that is where the actors involved might turn to NNL policy.

National legislation, financial lender standards, and voluntary corporate commitments might all lead to biodiversity impact mitigation measures being required for a given dam project (Maron et al., 2016). “Best practice” guidelines have been proposed by dam developers to guide the mitigation of biodiversity impacts (International Energy Agency, 2000, 2006; World Commission on Dams [WCD], 2000). These best practice mitigation measures include minimizing the area flooded per unit of energy produced and protecting habitat of an equivalent area to the flooded zone. However, many of the strategies outlined lack long-term monitoring, which hinders the quantification of their efficacy and hence their ability to demonstrate effective outcomes (WCD, 2000). The International Hydropower Association (a non-profit organization composed of corporate and individual membership) has also developed the Hydropower Sustainability Assessment Protocol (HSAP; International Hydropower Association, 2018). The HSAP is a voluntary non-binding auditing tool that aims to enable dam project proponents and investors to identify and address gaps in meeting good practice targets for dams by scoring various aspects of social and environmental impacts, from dam project conception through to the operation stage. Unlike the WCD (2000) framework, the HSAP does not require any definitive action to be taken to mitigate negative social and ecological impacts identified, only that impacts be “scoped:” therefore, it would be unclear to what extent dams audited under the HSAP would have carried out any robust impact mitigation measures. As with current NNL and Environmental Impact Assessment practices, the HSAP does not outline any mechanism or obligation for dam developers, governments, or investors to monitor the long-term efficacy of any impact mitigation measures put in place—in turn meaning that evidence of any effective biodiversity conservation would be lacking. Crucially, certain potential long-term and basin-scale impacts, such as extinction debts and loss of river connectivity, do not currently have any “best practice” impact mitigation strategies proposed (International Energy Agency, 2000; Kareiva, 2012; Latrubesse et al., 2017; Prado et al., 2016).

4 | NNL AND DAM DEVELOPMENT

NNL has become an increasingly widespread conservation objective in recent decades (Maron et al., 2016). Under an NNL objective, developers seek to quantitatively predict and mitigate all negative impacts associated with a given development project, generally through the application of a mitigation hierarchy of increasingly less desirable actions (avoidance, minimization, remediation, and finally, offsetting; Bull, Gordon, Watson, & Maron, 2016). So, in the case of a forthcoming dam construction project and having quantified the area and condition of habitat likely to be submerged during operation, for instance, the application of the mitigation hierarchy might involve slight redesign (to avoid and minimize the loss of habitat where possible) and ultimately the restoration of a comparable area of similar but impoverished habitat nearby (as an offset).

On the basis of specific case studies, it has been demonstrated that the application of the mitigation hierarchy can feasibly result in successfully mitigated biodiversity impacts for large infrastructure developments, including both the preventative measures (avoidance and minimization; e.g., Sahley et al., 2017) and the compensatory measures designed to achieve overall NNL (remediation and biodiversity offsets; e.g., Pickett et al., 2013). Conversely, however, it has also been shown that NNL strategies can fail if, for example, adequate compliance is not achieved on a project level (Lindenmayer et al., 2017), and there are multiple other challenges that may result in NNL not being achieved, such as ecological uncertainties and the use of inappropriate baselines for evaluating outcomes (Bull, Suttle, Singh, & Milner-Gulland, 2013).

Most studies into the actual implementation of NNL policies relate either to single projects or to regional policies, with very few exploring multinational implementation—in part, due to a lack of wider data transparency (Bull & Strange, 2018; Sonter et al., 2018). As such, it is not straightforward to examine the type of infrastructure project, or even sector, for which NNL policies have generally been implemented on specific projects. However—given both that dam projects are often associated with significant social and ecological impacts and also may in a number of cases rely upon project cofinance—it would be surprising if there were not numerous examples worldwide of dams required to achieve an NNL objective. Indeed, in a non-comprehensive dataset constructed by Sonter et al. (2018), eight out of 70 major development projects required to implement biodiversity offsets to achieve NNL were dams (Table 1). Clearly, mitigation measures with an NNL objective are already being applied in the context of at least some dam projects. In fact, there have also been recent calls for the mitigation hierarchy to encompass all infrastructure developments (Arlidge et al., 2018). Here, we therefore consider whether there is anything special about tropical dam projects that might preclude the application of the NNL objective and associated mitigation measures.

4.1 | Case study: Application of NNL to the Bujagali Hydropower Project in Uganda

Here, we select as a case study the Bujagali Hydropower Project ("Bujagali"; Figure 1d) in Jinja, Uganda. Originally conceived in 1999, Bujagali was finally officially commissioned by the Government of Uganda with financing from the World Bank Group in 2005 (Esmail, 2017). As a result of performance standards associated with the receipt of project finance, Bujagali was required to achieve a NNL objective for biodiversity impacts associated with construction and operation. Construction of the dam was completed in 2012, and the so-called Kalagala Biodiversity Offset ("Kalagala") was designed and implemented in order to fully compensate for the residual impacts of the development (Griffiths et al., 2019), after other measures implemented under the mitigation hierarchy.

As reported in public domain project documentation, predicted impacts of the Bujagali dam include those that were ecological (loss of riparian and tropical forest habitat, island inundation, and changes to regional hydrology) and social (resettlement, loss of agricultural land, and loss of culturally important spiritual sites; Griffiths et al., 2019). Though we do not consider the broader social impacts such as resettlement here, as part of achieving NNL, it is increasingly realized that those social impacts directly tied to biodiversity losses and gains, such as food security, should be considered (Griffiths et al., 2018). Consequently, Kalagala involved (amongst other NNL activities; International Finance Corporation [IFC], 2017[1]):

- set asides of riparian habitat downstream of Bujagali to protect ecological and spiritual values (the Kalagala Falls; Figure 1e);
- promotion of ecotourism activities to encourage wealth generation in the region;
- government commitments not to develop power generation capacity in future that could adversely impact Kalagala; and
- enhanced protection of three Forest Reserves (Mabira, Kalagala, and Nile Bank).

Five years post-construction of the dam and implementation of associated mitigation measures, progress with implementing the Kalagala Offset (in terms of both ecological outcomes and stakeholder perceptions) is being assessed by the IFC (2017) as part of a project refinancing deal from the World Bank. Preliminary findings suggest mixed stakeholder perceptions on the desirability of mitigation measures (Griffiths et al., 2019), and though offset measures have been put in place (IFC, 2017), an assessment of ecological outcomes has yet to be completed.

Moreover, a major challenge that has arisen is commenced construction of another major hydropower dam (the Isimba Hydropower Project, "Isimba") downstream of Bujagali—a dam that threatens the integrity of certain measures implemented under Kalagala but that has different funders who do not require achievement of NNL (Esmail, 2017; Griffiths et al., 2019). It is not currently known what impacts Isimba will have on Kalagala, but if the result is to restrict the effectiveness of offset measures for Bujagali, the Government of Uganda will need to explore alternative mitigation measures (IFC, 2017). Such a situation highlights the importance of assessing large-scale and trans-international boundary impacts of dam construction, particularly when multiple dams are planned within a catchment (Latrubesse et al., 2017).

5 | PERSPECTIVES ON THE KEY CHALLENGES FOR ACHIEVING NNL WITH TROPICAL DAMS

We suggest that there are at least three major challenges faced when attempting to achieve an NNL objective in the context of dams that are specific, if not entirely limited, to tropical regions:

1. Overcoming practicalities of implementing NNL in highly connected river systems over large spatio-temporal scales

Tropical rivers typically have large catchments, and the cumulative impact of dams on tributaries can impact the flow regime of the whole river system at a vast spatial scale. For example, the Amazon river and

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[1] https://disclosures.ifc.org/#/projectDetail/ESRS/39102.

its watershed is ~6 million km^2 and host the world's largest continuous zone of floodplains and wetlands covering >1 million km^2: the cumulative impacts of existing and planned dams will directly impact terrestrial and aquatic systems downstream of all of these dams and also affect the Amazon's estuary and sediment plume (Latrubesse et al., 2017). Furthermore, biodiversity impacts can happen both immediately (i.e., flooding habitat for reservoir creation) and over much longer timescales as remaining habitat slowly degrades due to breakdown in ecosystem functioning (Jones et al., 2016). Thus, the biodiversity impacts should be considered cumulatively not only at the basin scale (Latrubesse et al., 2017) but also over longer temporal scales (Barreto, 2014; Jones et al., 2016).

2. The stakes are high if NNL fails because tropical regions are hyper-diverse, rich in species endemism, and difficult to restore

Tropical regions are highly biodiverse, hosting an exceptionally high number of endemic species (Mace, Masundire, & Baillie, 2005). Tropical forests alone may contain ~300 tree species per hectare, often represented by a single individual (Gentry, 1988; Pitman et al., 2001), and >80% of the 2,500 species of fish in Amazonian river systems are endemic (Lees et al., 2016; Nogueira et al., 2010). The direct loss of aquatic and terrestrial habitats through reservoir creation and downstream of dams therefore risks local species extinctions including endemic species. Tropical habitats can be hard or even impossible to restore, and if endemic species or habitat types are lost, these cannot be replaced (Lamb, Erskine, & Parrotta, 2005). Thus, the biodiversity stakes are particularly high if NNL fails in tropical regions. Furthermore, multiple terrestrial and aquatic components interact to form highly productive systems that can be fundamentally disrupted by dams, for example by removing or altering seasonal flood pulses (Timpe & Kaplan, 2017; Ziv et al., 2012). Thus, complex biotic and abiotic interactions at the ecosystem level need to be considered to achieve NNL across the catchment.

3. Inclusion of ecosystem services in NNL design is necessary due to the importance of tropical biodiversity for ecosystem service provision at multiple spatial scales

Tropical regions are highly productive and deliver substantial ecosystem goods and services, relied upon at the regional, national, and global scales for food security, local economies, and climate regulation (Foley et al., 2007). For instance, the high levels of primary productivity in tropical forests leads to the uptake and sequestration of ~1.19-Pg carbon per year, which plays a critical role in regulating global climatic patterns and mitigating climate change (Pan et al., 2011). Yet tropical systems are being eroded by anthropogenic disturbance, and dam construction is an emerging driver of the loss of critical terrestrial and aquatic habitats (Gibson et al., 2017; Nilsson, Reidy, Dynesius, & Revenga, 2005). Finally, over 150 million people worldwide rely on rivers for food security, and dams in highly productive river basins such as the Mekong threaten ecosystem goods and services including one of the most highly productive fisheries in the world (Sabo et al., 2017). Achieving NNL for dams that cumulatively cause global impacts to biodiversity and ecosystem service provision is a particular challenge, when it is not standard for dams to consider ecosystem services as part of NNL strategies (Sonter et al., 2018; Table 1).

6 | CONCLUSIONS

The implementation of NNL policies for tropical dams is still in its infancy, and therefore, much more work is needed to evaluate the long-term efficacy of any NNL mitigation strategies put in place. Though current strategies for tropical dams likely do not go far enough in terms of impact mitigation to have demonstrably met an NNL objective, NNL strategies that have been implemented may still have reduced some of the negative biodiversity impacts of dams compared with the counterfactual of development without any NNL objectives. For example, Brazil's Balbina Dam—widely regarded as an ecological disaster—is nonetheless associated with creation of the ~940,000-ha Uatumã Biological Reserve. Had strict protection of the highly biodiverse old-growth tropical forest to the east of the former Uatumã River bank not been provided, the biodiversity loss associated with Balbina would doubtless be far higher as frontier lands were opened up to anthropogenic exploitation (Barlow et al., 2016). However, using a “business as usual” reference scenario upon which to assess achievement of NNL should be cautioned against in general, as small biodiversity “gains” relative to the business as usual baseline, may lead to “tick-box” achievement of the biodiversity conservation objective, when there may still be substantial overall loss of biodiversity (Maron et al., 2018)

NNL polices for tropical dams clearly must go much further to meet both NNL objectives and to satisfy conservation stakeholders, incorporating, for example, downstream biodiversity impacts and loss of globally important ecosystem services. Indeed, when the long-term social and food security impacts of dams are also included in NNL objectives, and considerations of cross-border impacts are made, the challenge of achieving and assessing NNL outcomes for tropical dams becomes even greater (Bull, Baker, Griffiths, Jones, & Milner-Gulland, 2018). Given that we identify at least three major challenges to achieving NNL to biodiversity regarding major tropical dams—(1) overcoming practicalities of implementing NNL in highly connected river systems over large spatio-temporal scales; (2) the stakes are high if NNL fails because tropical regions are hyper-diverse, rich in species endemism, and difficult to restore; and (3) inclusion of ecosystem services in NNL design is necessary due to the importance of tropical biodiversity for ecosystem service provision at multiple spatial scales—we recommend that if tropical dam development is required, NNL strategies should be a prerequisite of dam licensing.

These NNL strategies would include a clearly defined reference scenario, and long-term and independent monitoring of efficacy, ensuring that if biodiversity is lost despite mitigation measures in place, further mitigation measures can be taken throughout the construction, operation, and potential decommissioning phases of dam development. NNL strategies would also explicitly address the social impacts arising from impacts to ecosystem services over a large "area of influence" (Bull et al., 2018). Finally, NNL strategies would be highly conservative because the biodiversity stakes are so high should they fail, and because there is considerable uncertainty over long-term impacts and appropriate thresholds for biodiversity loss that cannot be offset (Maron et al., 2018). We stress that considering the far-reaching barriers to achieving NNL for tropical dams outlined here, alternative energy generation methods may in many cases need to be sought in tropical regions, if biodiversity and associated ecosystem services are to be truly safeguarded.

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