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REVIEW PAPER

Hydropower and the future of Amazonian biodiversity

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Abstract In an effort to ensure energy independence and exploit mineral resources, the governments of Amazonian countries are embarking on a major dam building drive on the basin's rivers, with 191 dams finished and a further 246 planned or under construction. This rush to harvest the basin's vast renewable energy capacity has come without proper consideration of the likely negative environmental externalities on the world's most speciose freshwater and terrestrial biotas. Here we highlight the economic drivers for hydropower development and review the literature to summarise the impacts of dam building on Amazonian biodiversity. We identify both direct and indirect impacts through the anticipated loss, fragmentation and degradation of riparian habitats. We then propose a series of measures to assess, curb and mitigate the impacts of destructive dams on Amazonian biodiversity.

Keywords Freshwater · Connectivity · Fish · Endemic · Mining · Deforestation

Introduction

Humans have been building dams for over 5000 years, but the pulse of dam-building in the last century has altered riverine ecosystems more extensively than any other anthropogenic activity, leaving two-thirds of the world's large rivers fragmented by dams (Nilsson et al.

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2005). This rise in dam construction is predominantly driven by greater electricity demands and a shortfall in global hydropower output of under a quarter of the estimated 14,576 TeraWatt/year in latent technical potential (IJHD 2010), most of which now lies in tropical rivers.

Amazonia has latterly become synonymous with dam development, an unsurprising target given that water drained across the basin's 6.8 million km^2 accounts for 18 % of global scale river discharge (Meybeck and Ragu 1996). The neighbouring Amazon and Tocantins watersheds (which form most of the Brazilian 'Legal Amazon' region), account for 6 % of global hydropower resources. After having already built 191 dams (including small dams), the nine Amazonian countries are planning to develop 243 additional dams across the Amazon Basin (RAISG 2013), mostly in southern Amazonia (Fig. 1).The largest operational and under-construction hydroelectric power plants are Venezuela's Guri with a 10,325-megawatt (MW) capacity and Brazil's 11,233-MW Belo Monte on the Xingu river. Brazil will be most heavily impacted, with 397 dams (143 operational or under-construction and 254 planned, ANEEL 2016).The lower and middle parts of the Amazon and its tributaries (which already have 34 operational dams) will be affected by the greatest number of new large dams, whose ecological footprint is far greater; with 16 of the 79 planned dams larger than the 30-MW cut-off that officially defines 'large' dams in Brazil (RAISG 2013). Here we highlight the drivers of the current major push by Amazonian countries to dam the basin's rivers, explore the direct and indirect impacts on the region's super speciose biota, and identify a roadmap of guidelines to avoid or mitigate the detrimental impacts of dams on the basin's biodiversity.

Dams and energy security

Ostensibly, energy security encompasses not just capacity, but also the inherent trade-offs between the relative availability, affordability, and safety of different energy sources and services and achieving a balanced strategy for the water-energy nexus (Winzer 2012). Hydropower is a favourite choice of energy strategists as it is considered a predictable and typically price-competitive technology with an up to ~90 % water-to-wire conversion efficiency (Kumar et al. 2011), which can make significant contributions to both base load and peak load demands (Kahn et al. 2014). Brazil is unique among all major economies in that it already generates ~80 % of its electricity from hydroelectric plants along fluvial gradients, albeit with an increasing reliance on more expensive thermal power as a back-up during times of insufficient rainfall (Prado et al. 2016). In order to satisfy its increasing energy demands (including inefficiency and waste) Brazil is required to add ~5000 MW each year for the next decade to its current 129,452 MW generating capacity (MME/EPE 2013). Brazil's energy planners favour hydropower over alternatives such as wind, solar and energy conservation because dams are perceived as the least expensive and most reliable option (Prado et al. 2016). However, the pattern for dam construction in Brazil and throughout the world is one of massive cost overruns and systematic delays in project completion, as shown by a recent world-wide review of hundreds of dams (Ansar et al. 2014). For example, by 2013 the cost of the Belo Monte Dam was already approximately double the amount originally budgeted (Pereira 2013), and the final total will likely far exceed that milestone. More important still, decision making on dams essentially considers only the monetary expenses incurred by the

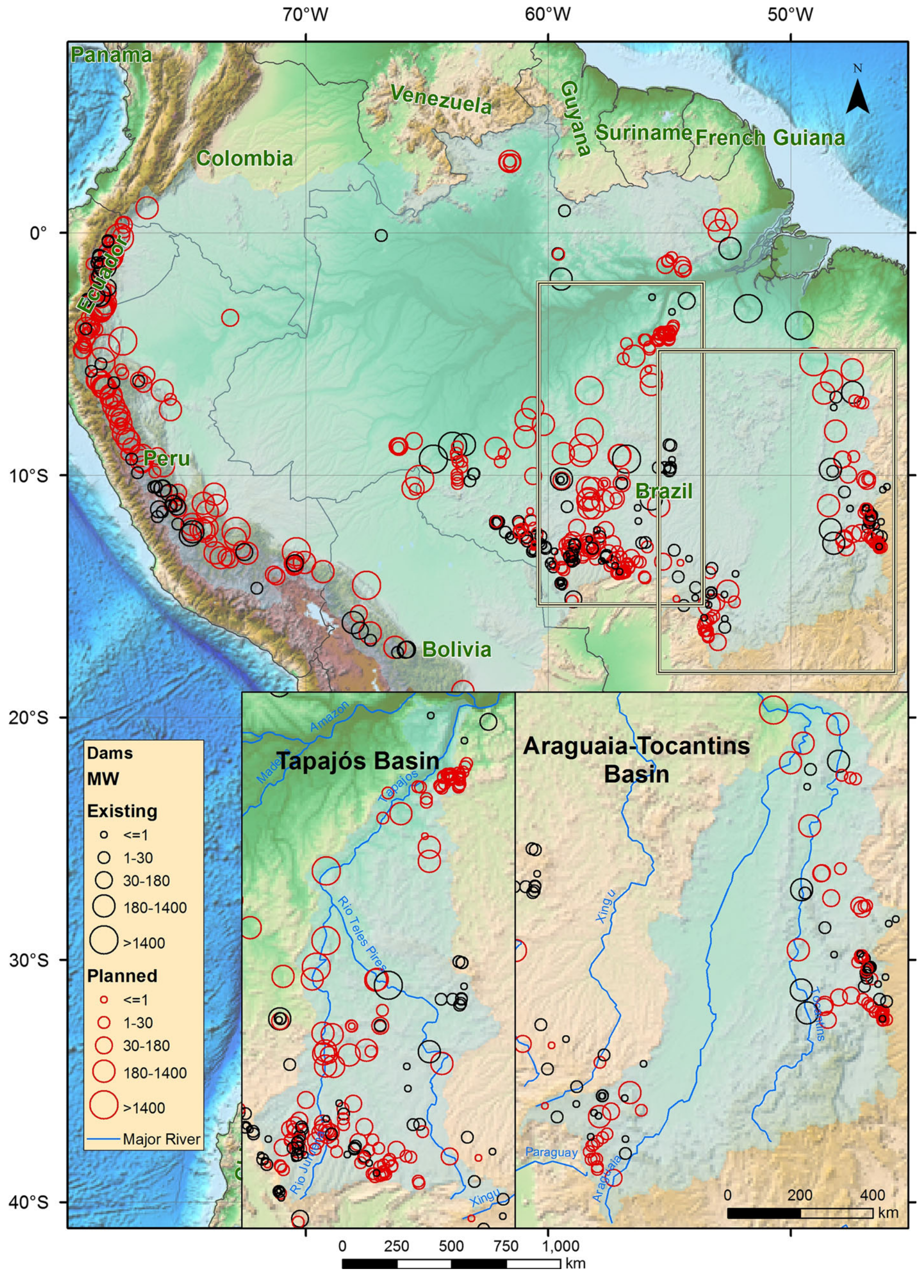

Fig. 1 Geographic distribution and power output (in MW) of the 191 completed and under-construction dams (*black circles*) and 246 planned dams (*red circles*) across the Amazon Basin. Sizes of *circles* are proportional to hydropower output. Elevation above sea level is shown on the background (data extracted from Finer and Jenkins 2012; Aneel 2016). Note that most dams within lowland Amazonia are concentrated along only a few tributaries of the Amazon River, including highly controversial plans amounting to 165 and 107 dams within the Tapajós and Araguaia-Tocantins river basins, respectively (see *inset* maps). (Color figure online)

proponents, ignoring non-financial costs such as biodiversity loss and impacts on local human populations (e.g., Fearnside 2015).

Brazil uses little coal: 13 plants generating just 2.5 % of the total electricity (ANEEL 2016); were Brazil to eschew building more dams, the path of least resistance to expand electricity supply would likely be energy from vast recently unveiled deposits of onshore and offshore oil and gas. However, like many tropical countries, Brazil also has the option of supplying all additional power without recourse to polluting fossil fuels, using the country's huge and largely untapped solar and wind energy resources (Baitelo et al. 2013; Moreira 2012). These renewable technologies, which have a diffuse geographic potential (in contrast to hydropower), cause relatively insignificant impacts on biodiversity through localised land-use change and some direct wildlife mortality and disturbance, for example through collisions with wind turbines (Drewitt and Langston 2006). The geopolitical development frontier expansion plans of Brazil's Ministry of Mines and Energy favour hydropower (65 % of the total in 2022), although these also include some wind power, biomass and natural gas (MME/EPE 2013). Most of the planned hydroelectric expansion will come from new dams in Amazonia, whose rivers are less saturated by hydroelectric plants than other Brazilian biomes and involve much lower compensation costs from permanent inundation of local communities and private lands.

However, a major incentive for investing in Amazonian hydropower sources, where local energy demand is currently low, are government goals to process domestic mineral resources, rather than merely export cheap ore to overseas markets (e.g., Fearnside 2016a, b). The contribution of mining to Brazil's gross domestic product (GDP) increased from 1.6 to 4.1 % between 2000 and 2011 and production is anticipated to increase 3–5 fold by 2030 (MME 2011) helped by new political and legislative frameworks, which include draft legislation to enact a new Mining Code (Bill 37/2011) and develop new mines in protected areas (PAs) (Bill 3682/2012) and indigenous lands (Bill 1610/96, see www.camara.leg.br). The expansion of the hydropower network, particularly the gigantic Belo Monte Dam, will thus have a major secondary impact in facilitating expansion in regional mining operations for bauxite, nickel, copper and gold. For example, a massive 1305 km^2 gold-mining concession has been granted to a Canadian company in the bed of the Xingu river's 'Big Bend' (Fig. 3a, Poirier 2012), which will become exposed when the Belo Monte Dam diverts 80 % of the river's flow from this 100-km stretch. Developing the Araguaia-Tocantins and Madeira waterways will make longer stretches of major rivers more navigable, reducing transportation costs for agricultural exports, especially soybeans (Castello et al. 2013), both from central Brazilian agricultural heartlands and new peri-Amazonian agribusiness frontiers in Brazil, northern Bolivia, and southern Peru (Killeen 2007). Other widely-cited positive impacts of hydropower facilities such as mitigating freshwater scarcity, irrigation and flood control services (e.g., Kumar et al. 2011) are less pertinent to Amazonia.

Impacts on biodiversity

In comparison to the environmental impacts of traditional fossil-fuel based systems with their centralised contribution to air pollution, acid rain, and global climate change, renewable energy systems may have much smaller (but widely dispersed) environmental impacts (Fig. 2, Akella et al. 2009). Like all other renewables, there are environmental and social issues affecting hydropower deployment opportunities, and these vary depending on each project's type, size and local conditions. Scholarly debate and media interest on the detrimental impacts of hydropower infrastructure in Amazonia has largely focused on the displacement of human populations (including inundation of indigenous territories), loss of habitat for charismatic vertebrates (e.g., Alho 2011), and questions over whether tropical dams are truly 'green' energy sources, with considerable mounting evidence that many are net greenhouse gas emitters (Fearnside and Pueyo 2012). Impacts of Amazonian dam projects have decisive ecological ramifications at local, regional and global scales (see summary in Table 1), and we believe that these impacts need to be better considered on a case-by-case basis and new policies developed to either reject or mitigate plans to construct new dams. In order to fully document the range of potential impacts we carried out a search (Table 1) of the scientific literature to document the range of impacts of dams on the basin's terrestrial and aquatic biodiversity. We searched the published literature including experimental and observational studies of dam impacts, to rigorously assess the generality of biodiversity impacts. We located studies using Web of Science and Google Scholar by searching for several combinations of search terms: Amazonia(n), dam(s), hydroelectric, biodiversity, conservation, fish, bird(s), mammal (s), invertebrate(s), plant(s), reptile(s), amphibian(s), Brazil(ian), Andes, flooding, protected area(s), extinction (the final search was conducted on 4 February 2016). Additional papers were located by searching the reference sections of these articles. We divide consequences for biodiversity into 'direct impacts', resulting from habitat loss and/or modification resulting directly from dam construction and 'indirect impacts' on regional biodiversity catalysed by cascade effects on regional development trajectories.

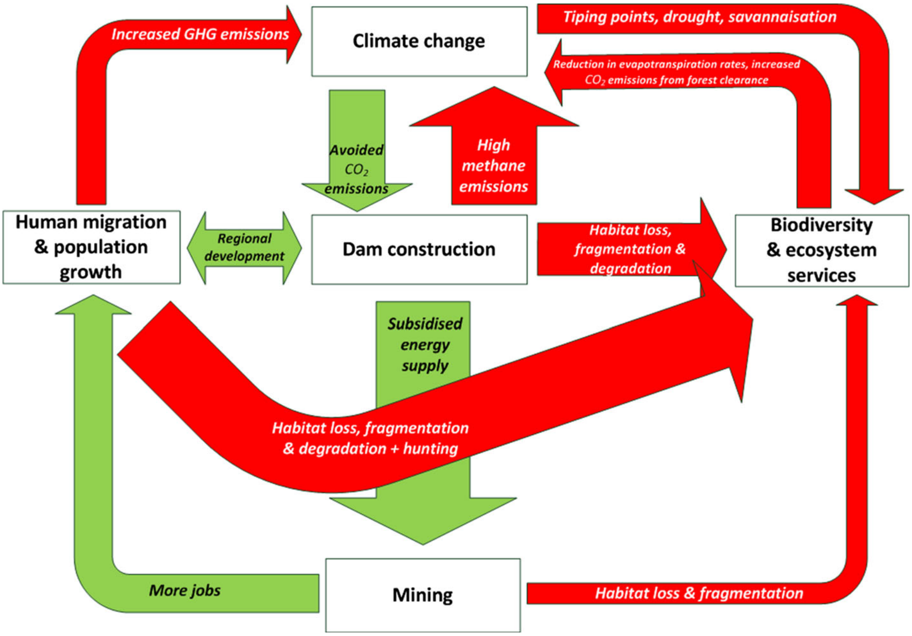

Fig. 2 Simplified conceptual map of interactions between dam construction, mining, human population growth, biodiversity and climate change. *Arrow* width is roughly proportional to effect size, *red arrows* indicate negative impacts (reductions and/or negative growth in the target field) and *green arrows* represent positive impacts (increase and/or positive growth in the target field. (Color figure online)

Table 1 Generalized impacts of major hydroelectric dams on both the aquatic and terrestrial biodiversity throughout lowland Amazonia at varying spatial scales

Habitat type	Taxonomic groups affected		Extinction process	Scale and magnitude of impact	Source
	Aquatic	Terrestrial			
River channel	Large migratory fish (e.g. *Prochilodus nigricans*, *Semaprochilodus* sp., *Brachyplatystoma rousseauxii*, *B. capapretum*, *B. vaillantii*)		Migratory dis-connectivity	Basin-wide declines or extinctions if species fail to reach headwater breeding grounds	Ribeiro et al. (1995), Isaac (2008)
	All aquatic life		Deterioration of water quality	Local extinction of species dependent on well oxygenated river stretches	Killeen (2007), Liermann et al. (2012), Sá-Oliveira et al. (2015a)
			Changing turbidity levels to which species are regionally adapted	Regional declines and extinctions above and below dams	McAllister et al. (2001), Liermann et al. (2012), Sá-Oliveira et al. (2015a)
Floodplain	Many fish and aquatic invertebrates, 50 % of the fish species in the Xingu for example use the floodplain		End of seasonal flood cycle	Regional declines and extinctions below dams	Isaac (2008)
	Many fish and other aquatic vertebrates		Loss of food sources from seasonally flooded forests	Regional declines in local fisheries both in the reservoir areas and below dams	Goulding (1980)
		Migratory bird species	Loss of ephemeral habitat, e.g. Lesser Yellowlegs *Tringa flavipes*	Significant loss of staging habitats	Sutherland et al. (2012)

Table 1 continued

Habitat type	Taxonomic groups affected		Extinction process	Scale and magnitude of impact	Source
	Aquatic	Terrestrial			
Fluvial Rocky outcrops	Many endemic fish (e.g. rapids-dwelling Loricariidae catfishes) and invertebrates		Permanent submergence of breeding habitats, food sources and shelters; changes in water quality and velocity	Local (stretch) to basin-wide declines or extinctions if species are unable to use other habitats	Isaac (2008), Liermann et al. (2012)
		Nyctinomops sp. bats, *Atticora melanoleuca*	Permanent submergence of breeding habitats	Basin-wide declines or extinctions if species fail to find or adapt to other habitats	Haffer (1994)
	Podostemaceae riverweeds		Permanent submergence of rocky habitats	Local (stretch) to basin-wide declines or extinctions, given high rates of micro-endemism	Philbrick et al. (2010)
Ephemeral sandy river beaches	Freshwater turtles e.g. *Podocnemis* sp.		Permanent submergence of breeding habitats	Regional declines and extinctions below dams	Alho (2011)
		Bird species e.g. Black Skimmers *Rhynchops niger*, Large-billed Terns *Phaetusa simplex*		Regional declines and extinctions below dams	De Luca (2006)
Fluvial (vegetated) islands		Microendemic plant communities	Permanent submergence below dams	Regional declines and extinctions below dams	Ferreira et al. (2013)
		Range and habitat restricted birds and other vertebrates e.g. Blackish-gray Antshrike *Thamnophilis nigrocinereus*	Permanent submergence of habitat below dams		Bird et al. (2012)

Table 1 continued

Habitat type	Taxonomic groups affected		Extinction process	Scale and magnitude of impact	Source
	Aquatic	Terrestrial			
Várzea and *Igapó* forests	Many fish and aquatic invertebrate species		End of seasonal flood cycle including permanent inundation or irregular/unpredictable floods	Regional declines in the reservoir areas and below dams	Goulding (1980), Killeen (2007)
		Range and habitat restricted birds e.g. Varzea Piculet *Picumnus varzeae*	End of seasonal flood cycle including permanent inundation or irregular/unpredictable floods	Regional declines and local extinctions in the reservoir areas and below dams	Alho (2011)
		Arboreal mammal species with high degree of flooded forest habitat specificity, including primates, echimyid rodents and marsupials			Goulding (1980), Killeen (2007)
Terra firme forests		Large-bodied birds and mammals	Over-hunting in surrounding landscapes surrounding	Regional, new access roads and influx of people—increased hunting pressure	Alho (2011)
		All *terra firme* forest species	Loss of habitat through permanent inundation of some upland areas	Local, relatively little *terra firme* habitat lost	Killeen (2007), Alho (2011), Benchimol and Peres (2015a, b)
			Fragmentation and loss of habitat through deforestation	Regional, influx of money and people result in accentuated deforestation rates	Killeen (2007), Barreto et al. (2011), Finer and Jenkins (2012)
All	All species		Habitat loss and degradation following regional climate changes stimulated by deforestation and accentuated by increased methane output	Local, regional and global	Fearnside (1995), Stickler et al. (2013)

Direct impacts

Dams are not randomly distributed across river basins; they need to be located on significant altitudinal gradients, typically descending from plateaus 200–1000 m above sea level and on rivers with stable channels rather than meandering floodplains, disproportionately affecting more dissected regions and their biotas. Dams replace turbulent river sections with still water bodies, impacting flow and temperature regimes and sediment transport (Liermann et al. 2012; Fearnside 2013). This shift from lotic (fast-flowing) to more lentic (still) waters favours generalist or invasive species over specialist range-restricted and endemic species that require fast-flowing rivers (Sá-Oliveira et al. 2015b; Winemiller et al. 2016; Table 1) and exposed rocky islets, eventually leading to a significant loss of beta (regional) diversity (Agostinho et al. 2008). Operational rules designed to optimise energy production by dams throughout their seasonal cycle do not consider the ecological needs of the biota, drastically reducing the natural cycle of flood pulses and masking or eliminating environmental triggers necessary for the onset of fish spawning and the phenology of fruit/seed production in the flooded forests that sustain local fisheries (Goulding 1980).The dams themselves inhibit both downriver sediment flow and organismal migration up and downstream. Severance of nutrient connectivity is likely to be most acute downstream of Andean-Amazonian dams, whose rivers supply the vast majority of the sediment, nutrients, and organic matter to the main stem Amazon, ultimately affecting aquatic communities and marine processes thousands of kilometres away (McClain and Naiman 2008; Finer and Jenkins 2012).

Fish are the most celebrated dam casualty: changes in water depths, discharge, and sediment deposition patterns in reservoirs and dam tailwaters simplify or remove the niches for many species, and dams themselves obstruct migration to spawning or feeding grounds and fragment populations along the fluvial continuum (Agostinho et al. 2008; Sá-Oliveira et al. 2015a). Major hydroelectric reservoirs often vastly augment the extent of freshwater environments but these typically provide low-quality habitat for aquatic biotas, including both fish populations and their apex-predators, such as giant otters (Palmeirim et al. 2014). The Neotropical freshwater biota is severely under-inventoried, with 30–40 % of the freshwater fish fauna still undescribed; Amazonia hosts over 2500 fish species, 80 % of which are endemic, many with extremely small range sizes (Nogueira et al. 2010; Winemiller et al. 2016; Fig. 2b).There are 285 restricted-range fish species in the Amazon and Tocantins-Araguaia hydrographic regions, meaning that nearly 11 % of the regional fish biodiversity can be considered potentially threatened (Junk et al. 2007). Brazil's Ministry of Environment (MMA) recently completed an evaluation of the conservation status of its freshwater fishes, revealing that 71 species are threatened in the Amazon basin, most of which (nearly 70 %) by existing hydroelectric power plants or those planned to be built in the next decade (MMA 2014). However, the nominal protection afforded by the Brazilian Red List has already been subject to a number of legal challenges (e.g., Lees 2015) and its future integrity is far from secure.

In the case of the Belo Monte Dam on Brazil's Xingu River, among the nearly 450 fish species occurring in this river basin, at least 44 ($\sim$ 10 %) are considered endemic, one third of which are under direct extinction risk by the construction of this dam (Isaac 2008, JZ *unpubl. data*). Furthermore, the loss of diadromous (species which migrate between fresh and salt water habitats) and potamodromous (migratory species restricted to freshwater) fish and crustaceans has cascade impacts on up and downstream nutrient transfers, including economic losses in local fisheries (Fearnside 2014a; Fig. 3c; Table 1). Our knowledge of migratory behaviour for most species is very poor, and more spectacular discoveries, such as the previously undocumented mass-migration of juvenile pencil catfish (*Trichomycterus barbouri*), are to be expected (Miranda-Chumacero et al. 2015). It seems likely that the construction of many dams may put an end to such events before they are even known and subject to scientific scrutiny.

PAs are not guarantors of the integrity of aquatic ecosystems, particularly under the current political climate in which both state and federal executive branches continue to erode the legal protection of Brazilian parks and reserves. Of the 191 dams completed or underway, 13 (7.6 %) fully or partially overlap existing PAs, whilst 36 (14.6 %) of the planned dams would also downgrade or downsize existing PAs (RAISG 2013). Dam advocates argue that impacts can be mitigated by fish ladders and faunal translocations, yet the former are impermeable to many fish species in large Amazonian rivers (e.g., Agostinho et al. 2011; Fig. 3c) and translocations into habitats with resident populations already at carrying capacity are likely a worthless exercise (Alho 2011). The loss of endemic rheophilous fish species (restricted to fast-flowing water) resulting from the destruction or flooding of rapids cannot be mitigated by such actions.

◀**Fig. 3** **a** The 'Big Bend'region of Brazil's Xingu River in March 2011 (P. M. Fearnside). The Belo Monte Dam, one of the world's most controversial hydroelectric projects, will leave this 100-km stretch of river with only 20 % of its natural flow. The "Big Bend," which the Brazilian government insists is not directly impacted by the dam, has a unique fauna and a human population, including two indigenous territories, which depend on the river's fish. Image (**b**) depicts an undescribed species (*Hypancistrus sp. nov.*) in the same genus as the zebra pleco, which is a micro-endemic restricted to deeper portions of the 'Big Bend', despite efforts by ornamental fish collectors to locate other populations of this new species outside this area (L. Sousa). Fish passage (**c**) at Brazil's Santo Antônio Dam on Brazil's Madeira River in May 2012 (P.M. Fearnside). Unfortunately, the major commercial species of "giant" catfish have so far been unable to locate the entrance to these passages, since they instinctively follow the main current. The socioeconomic impacts of this loss are felt in Bolivia and Peru, as well as Brazil. The Jamanxim River near Novo Progresso, Pará in August 2006 (A. C. Lees) (**d**) with fluvial rocky outcrops typical of Brazilian and Guiana Shield rivers—a microhabitat likely to be inundated on this stretch by the construction of the 881-MW Jamanxim dam. Underwater photograph (**e**) of a zebra pleco *Hypancistrus zebra* (*left*) with an *Ancistrus* sp. (*right*) hiding in rocks on the Xingu's 'Big Bend' (L. Sousa). The zebra pleco is a popular ornamental fish, described only 23 years ago by Isbrucker and Nijssen (1991), and is virtually restricted to the 'Big Bend'. Given this restricted distribution and imminent threat, it was recently officially upgraded from "Vulnerable" to "Critically Endangered" by the Brazilian Red List (ICMBio 2012). Great dusky swifts (*Cypseloides senex*) (**f**) roosting behind the waterfalls of the Cachoeiras do Curuá on the Serra do Cachimbo in southern Pará in August 2006 (A. C. Lees). Two small hydroelectric power plants have subsequently been constructed upstream of this site: PCH (Pequena Central Hidrelétrica) Salto do Curuá and PCH Salto do Buriti. Subsequent environmental impacts on these birds are unknown but Amazonian waterfalls are home to globally-important colonies of several swift species for which basin-wide Red List assessments are required

Furthermore, understanding the magnitude of likely aquatic faunal extinction induced by the dam-building processes is hindered by a lack of information on the taxonomy, breeding habits, productivity, and seasonal dynamics of Amazonian fishes (Junk et al. 2007; Castello et al. 2013). Exemplifying the uncertainty surrounding cryptic Amazonian biodiversity, Hrbek et al. (2014) recently described a new river dolphin, the Araguaian boto *Inia araguaiaensis* from the Araguaia River basin in south-eastern Brazilian Amazonia, which they anticipate will likely move straight onto the global Red List if the taxon is recognised by the International Union for Conservation of Nature. Regardless of taxonomic level, populations of river dolphins in this region are the most threatened in Amazonia (Araújo and Wang 2015).

Species occupying fluvial rocky outcrops (Fig. 3d) on the Brazilian and Guiana Shields are particularly threatened (Table 1). Without a change in policy, we anticipate a near total loss of these rare microhabitats in most stretches. These are crucial habitats for many rheophilic species, such as an entire radiation of Podostemaceae riverweeds (Philbrick et al. 2010) and micro-endemic armoured catfish such as the zebra pleco *Hypancistrus zebra* (Fig. 3e, Isbrucker and Nijssen 1991; Reis 2013). Moreover, such rocky outcrops are the main reproduction sites for many other restricted-range fish species and even for 'terrestrial' vertebrates such as *Nyctinomops* bats and the black-collared swallow *Atticora melanoleuca* (Table 1). Similarly, flow reduction over waterfalls may also have serious biodiversity impacts. The Salto das Andorinhas and Salto de Dardanelos waterfall complex on the Aripuanã River in northern Mato Grosso hosts globally-important colonies of swifts—1.5 million white-collared swifts *Streptoprocne zonaris* were estimated to occupy this site in 1994 (De Luca et al. 2009). The construction of the 261-MW Dardanelos Dam will likely have negative consequences for these and other waterfall-nesting Amazonian swift species (Fig. 3f) if a reduction in flow leaves them exposed to terrestrial predators. Flooding of adjacent *terra firme* and seasonally-flooded *várzea* and *igapó* forests will reduce forest habitat availability to terrestrial biota, as will associated infrastructure improvements in the region. This will lead to the endangerment of floodplain and river island–dependent species which will lose significant proportions of their already-small global ranges (Bird et al. 2012).

Major dams also profoundly alter the structure of terrestrial biotas with insular forest communities stranded within vast archipelagos formed by hydroelectric reservoirs. Heavy-wooded tree species in primary forest islands created by the 26-year-old Balbina Dam of central Amazonia have been gradually replaced by short-lived pioneers, resulting in a staggering taxonomic and functional decay of tree assemblages (Benchimol and Peres 2015a). This also resulted in major losses of forest carbon storage in both lowland areas flooded by the reservoir and upland forests above the maximum water level.

Ironically, although many of the species threatened by dams in Amazonian Brazil are strictly protected by Brazilian law from hunting, sale or unlicensed collection (Law No. 9605/1998—Articles 29, 34 & 53), there are legal provisions to allow their complete extirpation by dam-building projects (Fearnside 2014b).This is in contrast to legal provisions protecting the biodiversity of the Brazilian Atlantic Forest biome (Law No. 11.428/2006) by prohibiting the suppression of primary (or advanced secondary) vegetation hosting threatened species if the intervention would threaten their survival. A bill (3486/1989) proposing similar protection for the Amazonia biome was never sanctioned into law. Summarising, these direct impacts most acutely affect primarily aquatic biota through physical changes in water flow and quality flow, river system fragmentation and loss of specific micro-habitats (Table 1). We also note that the definition of 'direct' may be weak as cascade impacts within food-webs might be better described as 'indirect' effects, although given the wholesale changes to rivers following partial-impoundment it is likely that only extremely 'generalist' predators could fail to be impacted by direct changes to aquatic systems.

Indirect impacts

If mismanaged, indirect effects following dam construction have the potential to profoundly affect regional biodiversity in the absence of effective government command-and-control (Table 1). Once construction contracts terminate, the suddenly-unemployed construction workers often join other migrants and resort to exploitative activities such as illegal deforestation (Fearnside 2008). For example, Belo Monte is expected to trigger an *additional* 4000–5000 km^2 of forest loss by 2031 on top of that expected from business-as-usual scenarios (Barreto et al. 2011). Improved infrastructure in the form of roads, power grids and waterways has the potential to reverse recent gains in reducing Amazonian deforestation rates, as formerly financially marginal agricultural lands become more profitable, resulting in denudation, fragmentation and further degradation of remaining forest habitats. Loss of vegetation cover will result in drier climates (Nepstad et al. 2008), particularly in eastern Amazonia, reducing river water discharge and consequently hydropower output. Dam projects in the southern and eastern portion of the basin are already embedded within the infamous Amazonian 'Arc of Deforestation', the aggressively expanding agricultural frontier. The synergistic interaction between dam building and development could enhance positive feedback mechanisms that fuel forest fire dynamics with far-reaching consequences for biodiversity loss and the potential for future regional economic stagnation as river flows decline and power output decreases (Oliveira et al. 2013; Stickler et al. 2013). As such the indirect effects of dam building threaten to spill over to impact a substantial proportion of the basin's terrestrial biota (Table 1) in watersheds with suitable conditions for dam construction.

The way forward

Where possible, major dams should not be built in the lower reaches of Amazonian rivers (which typically have greater environmental impacts) and the focus should be shifted to smaller headwater hydropower stations located upstream and along tertiary tributaries. Biodiversity impacts may be lessened in these areas, which may already be 'naturally fragmented' by waterfalls (Grill et al. 2015) although the cumulative environmental impacts of many small dams are still considerable (see e.g., Premalatha et al. 2014) and pose a particularly important threat to the upper Xingu River aquatic biodiversity hotspot (Alho et al. 2015). To understand the relative impacts of a mixture of large and small dams, full river catchment environmental analyses are needed, as stated in the proposed Environmental Licensing Law (bill 3729/2004). In this case consideration should be given to either building dams in series or distributing them among tributaries, whichever proves to be the best option in a given catchment, and keeping dam-free stretches of rivers that contain representative sections of the original landscape (including stretches with rapids). These catchment analyses should be accompanied by a full trade-off analysis required to balance the negative externalities likely to afflict the region's socio-biodiversity with realistic estimates of energy production (Winemiller et al. 2016). Cumulative impacts of dam building need to be better assessed, which should accompany a thorough overhaul of the whole environmental impact assessment procedure for dam construction (e.g., de Lima and dos Santos 2015). Existing legal requirements for the protection of native species need to be adhered to; dams should not be built if they are likely to lead to the extinction of restricted-range taxa as is expected to occur given current business-as-usual scenarios. The legislative integrity of the exemplary protected-area network in Brazilian Amazonia needs to be maintained, rescinding recent political actions aimed at unilaterally reducing the boundaries of protected areas and indigenous lands (Ferreira et al. 2014; Marques and Peres 2015).

Measures are needed to assess and curb the expansion of destructive dams and mitigate their negative impacts. These need to be subject to thorough trade-off analyses on a case-by-case basis to assess their relative merits as there is currently no 'silver bullet' to tackle energy supply issues in the region (Prado et al. 2016). Diversifying macroeconomic energy plans and reducing dependence on hydropower through investments in other 'renewable' technologies such as wind generation, photovoltaic power and other alternatives, such as concentrated solar power and gasification of waste, will both increase efficiency and reduce costs over time (Kahn et al. 2014). Reducing power-line transmission losses and grid connection miscalculations involving existing hydropower projects will save considerable amounts of energy (Prado et al. 2016). Investing in modernising older hydropower plants, which is less costly than developing new dams, causes smaller environmental and social impacts, and requires less time for implementation ought to be a priority.

Conclusion

Our review highlights how Brazil's reliance on hydropower may not be justified from an energy security perspective and how the current dam-building regime will have a pervasive influence on the process of human disturbance in lowland Amazonia. We anticipate the widespread loss, fragmentation and degradation of riparian and terrestrial habitats resulting in varied direct and indirect impacts on indigenous biota. If mismanaged, as appears to be the case with the current business-as-usual scenario, the pulse of new dams in Amazonia threatens to catalyse further forest loss and threaten, either directly or indirectly, many restricted-range species with global extinction.

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