MINI REVIEW

The vulnerability of Amazon freshwater ecosystems

Leandro Castello[1], David G. McGrath[1,2], Laura L. Hess[3], Michael T. Coe[1], Paul A. Lefebvre[1], Paulo Petry[4], Marcia N. Macedo[1], Vivian F. Renó[5], & Caroline C. Arantes[2]

[1] The Woods Hole Research Center, Falmouth, Massachusetts, USA
[2] Instituto de Pesquisa Ambiental da Amazônia, Santarém, Pará, Brazil
[3] Earth Research Institute, University of California, Santa Barbara, California, USA
[4] The Nature Conservancy, Latin American Conservation Region, Boston, Massachusetts, USA
[5] Instituto Nacional de Pesquisas Espaciais, São José dos Campos, São Paulo, Brazil

Keywords
Conservation; ecosystem goods and services; floodplain; hydrologic connectivity; policy; protected areas; wetlands.

Correspondence
Leandro Castello, The Woods Hole Research Center, 149 Woods Hole Rd, Falmouth, MA 02540, USA.
Tel: +1.508.1564; fax: +1.508.444.1864
E-mail: lcastello@whrc.org

Received
25 June 2012
Accepted
18 December 2012

Editor
Dr. David Strayer

doi: 10.1111/conl.12008

Abstract

The hydrological connectivity of freshwater ecosystems in the Amazon basin makes them highly sensitive to a broad range of anthropogenic activities occurring in aquatic and terrestrial systems at local and distant locations. Amazon freshwater ecosystems are suffering escalating impacts caused by expansions in deforestation, pollution, construction of dams and waterways, and overharvesting of animal and plant species. The natural functions of these ecosystems are changing, and their capacity to provide historically important goods and services is declining. Existing management policies—including national water resources legislation, community-based natural resource management schemes, and the protected area network that now epitomizes the Amazon conservation paradigm—cannot adequately curb most impacts. Such management strategies are intended to conserve terrestrial ecosystems, have design and implementation deficiencies, or fail to account for the hydrologic connectivity of freshwater ecosystems. There is an urgent need to shift the Amazon conservation paradigm, broadening its current forest-centric focus to encompass the freshwater ecosystems that are vital components of the basin. This is possible by developing a river catchment-based conservation framework for the whole basin that protects both aquatic and terrestrial ecosystems.

Introduction

Since the 1980s, the attention of the scientific, public, and policy arenas concerning environmental issues in the Amazon basin has focused almost entirely on forests and their biodiversity. Three decades of effort have generated an understanding of some key biophysical transitions in the basin, and established a network of protected areas—largely designed to preserve forest biodiversity—that now epitomizes the Amazon conservation paradigm (e.g., Soares-Filho *et al*. 2010; Davidson *et al*. 2012). Market and financial incentives are now emerging to reduce greenhouse gas emissions from deforestation and forest degradation (i.e., REDD+; Nepstad *et al*. 2009).

Despite such remarkable advances, little attention has been paid to the poorly managed freshwater ecosystems that are vital components of the Amazon basin. Freshwater ecosystems are connected via the hydrological cycle to adjacent systems: laterally (water-land), longitudinally (up- and down-stream), and vertically (atmosphere-surface water-ground water; Ward 1989, Pringle 2003). The hydrological connectivity of freshwater ecosystems makes them highly sensitive to a broad range of anthropogenic impacts occurring in both aquatic and terrestrial ecosystems at local and distant locations. Globally, this hydrological connectivity has exacerbated the impacts caused by the large populations typically found near freshwater ecosystems, creating some of the most altered systems on Earth (Malmqvist & Rundle 2002; Carpenter *et al*. 2011).

How vulnerable are freshwater ecosystems in the Amazon to leading anthropogenic pressures? This question is

Table 1 Geographical areas of the main Amazon river basins, freshwater ecosystems, and all protected areas. The Amazon mainstem includes adjacent small river basins. Data sources are shown in Figure 1

River	Basin area (10^3 km^2)	Freshwater ecosystem area (10^3 km^2)	Protected area (10^3 km^2)
Madeira	1,317.3	209.9	353.2
Araguaia-Tocantins	754.6	135.2	121.1
Negro	711.5	119.4	404.4
Tapajós	492.4	22.2	203.9
Xingu	492.3	37.0	286.2
Purus	368.1	36.0	199.0
Marañon	358.4	70.9	62.7
Ucayali	356.2	41.5	82.3
Caquetá-Japurá	255.9	31.9	89.2
Juruá	189.3	20.8	77.7
Trombetas	119.1	7.4	111.3
Putumayo-Içá	117.8	20.3	20.2
Napo	101.9	10.6	27.0
Amazon mainstem	1,251.3	231.8	541.3
Total	6,886.6	994.9	2,579.5

key because freshwater ecosystems are generally highly complex, biodiverse, and productive (Junk 1993; Bayley 1995; Naiman & Decamps 1997). Damage to them greatly impacts Amazonians, who historically have been so dependent on freshwater ecosystem goods and services that they have been called "water peoples" (Furtado *et al*. 1993; Kvist & Nebel 2001). To address this question, here we review: (1) the main freshwater ecosystems in the basin, (2) the goods and services they provide, (3) the main drivers of degradation, and (4) the capacity of existing management strategies to protect these ecosystems.

Amazon freshwater ecosystems

Amazon freshwater ecosystems—including all permanently or seasonally flooded areas such as streams, lakes, floodplains, marshes, and swamps—are connected to atmospheric, terrestrial, and oceanic systems via the hydrologic cycle. Moisture blown from the Atlantic Ocean falls as precipitation over the basin's 6.9 million km^2 (Figure 1a; Table 1). Sixty-five percent of that rainfall returns to the atmosphere via evapotranspiration (Costa & Foley 1999). The remainder drains forest and savanna ecosystems and recharges the freshwater ecosystem network, which routes to the Atlantic Ocean 18% of global river discharge (Meybeck & Ragu 1996).

Freshwater ecosystems cover between 14 and 29% of the Amazon basin area: they have been mapped over 1 million km^2, and data for the Central Amazon indicate the riparian zones of small streams may cover an additional 1 million km^2 (Tables 1 and 2; Figure 1; Junk 1993; Melack & Hess 2010). Freshwater ecosystems vary over the basin mainly as a function of scale, geomorphology, water chemistry, and inundation characteristics, forming at least nine distinct freshwater ecosystem types (Table 2).

The freshwater ecosystem network originates with the riparian zones of small streams, which usually flood intermittently and irregularly in response to local rainfall and runoff. Although generally small, the riparian zones of low-order streams are the primary aquatic-terrestrial interface zone. These semiterrestrial zones influence, and are influenced by, the water channel through exchanges of water, nutrients, and organic matter (Naiman & Decamps 1997; Williams *et al*. 1997).

As small stream waters flow downstream into larger rivers, water level variations often reflect the predictable seasonality of regional rainfall in the form of annual flood-pulses on the order of 10 m (Junk *et al*. 1989). These flood-pulses remobilize riverbed sediment, forming floodplains that may be very extensive, up to tens of kilometers wide in sediment- and nutrient-rich rivers such as the mainstem Amazon (Hess *et al*. 2003). River floodplains possess extensive and diverse plant communities distributed along a flooding gradient, with herbaceous and shrub communities usually located at the margins of lakes and channels, and forests occupying higher ground along levees (Junk *et al*. 2012). The annual advance and retreat of river waters over the floodplains induce large lateral exchanges of organic and inorganic materials between river channels and floodplains that increase primary production (Melack and Forsberg 2001).

Nonriverine savannas and swamps, with inundation depths generally less than 1 m, also occupy large regions of the basin (Figure 1; Table 2). The Llanos de Moxos of Bolivia and the Bananal and Roraima savannas of Brazil are seasonally inundated grasslands, sedgelands, and open woodlands (Hamilton *et al*. 2002; Valente & Latrubesse 2012), while Peru's Marañon-Ucayali interfluvial region is dominated by semi- to permanently inundated peat-accumulating palm swamps (Räsänen 1993). Blackwater "campina" ecosystems, which are mosaics of shrub, forest, sedge, and algal mats, occur in flat interfluves of the middle Negro region. Seasonally inundated "campos marajoaras"—grass, sedge, and aquatic macrophyte savannas, long utilized for cattle and water buffalo ranching—occupy much of Marajó Island at the mouth of the Amazon (Figure 1; Smith 2002).

Freshwater ecosystem goods and services

Amazon freshwater ecosystems provide a wealth of goods and services. Riparian zones of small streams filter and

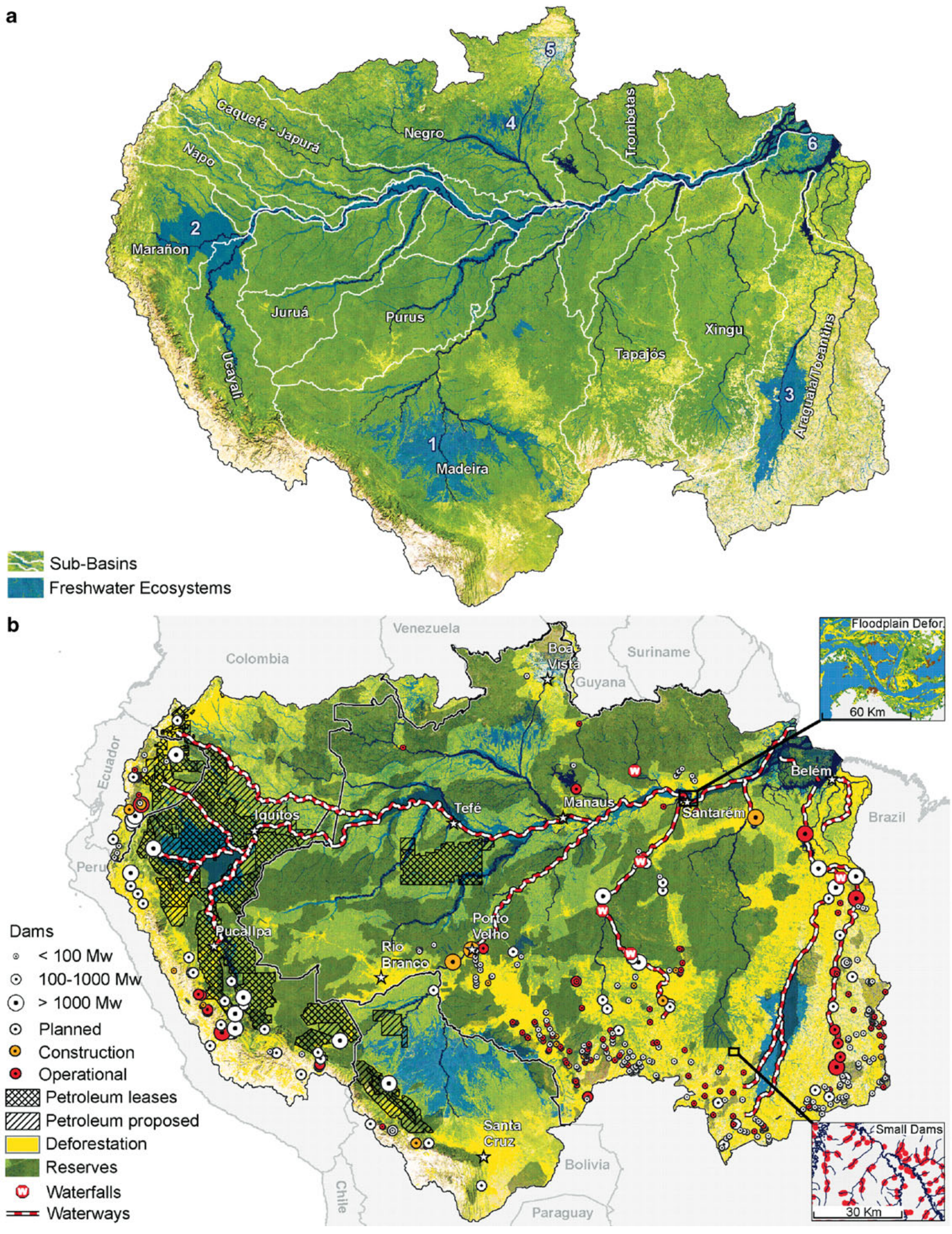

Figure 1 (a) The Amazon Basin, showing the main river sub-basins, including the Araguaia-Tocantins. Numbers indicate Llanos de Moxos savannas (1), Marañon-Ucayali palm swamps (2), Bananal savannas (3), Negro campinas (4), Roraima savannas (5), and campos marajoaras (6). (b) The main drivers of wetland degradation for which basin-wide data are available, and the protected area network. Data sources: Freshwater ecosystem extent data for the Amazon basin are from Melack & Hess (2010), and for the Araguaia-Tocantins and estuary sub-basins are from L. L. Hess (unpublished data). River channel network data are from ANA (ANA 2012). Sub-basin boundaries are from Melack & Hess (2010) and L. L. Hess (unpublished data). Basin-wide deforestation data are from Eva *et al*. (2004), showing all areas classified as under human use (e.g., agriculture) in both forests and savanna or cerrado ecosystems. Floodplain deforestation data are from Renó *et al*. (2011). Oil exploration data are from Finer *et al*. (2008), denoting areas available to be leased for oil exploration, and proposed areas for future lease for oil exploration. Data on hydroelectric dams are from PROTEGER (2012) for Ecuador, Colombia, Peru, and Bolivia, and from ANEEL (2012) for Brazil. Small dams data for the Xingu basin are from Macedo. (2012). Protected area data were compiled by Soares-Filho *et al*. (2010). Waterways data from IIRSA (www.iirsa.org), Brito (2001), and Junk & Piedade (2005) are planned waterways.

Table 2 Extent and land cover of Amazonian freshwater ecosystems

Main freshwater ecosystem types and regions	Area ($km^2 \times 10^3$)[a]	Land cover (%)[b]		
		Water	Nonforest	Forest
Mapped at basin-wide scale				
Floodplain of the mainstem Amazon[c]	118.8	22	22	55
Floodplains of major tributaries[d]				
Whitewater[e]	97.2	9	20	70
Blackwater[f]	21.6	25	20	53
Clearwater[g]	48.5	40	18	40
Llanos de Moxos savannas	141.4	3	66	30
Bananal savannas	62.7	1	63	35
Marañon-Ucayali palm swamps	90.3	1	23	75
Negro campinas	21.4	1	40	58
Campos marajoaras (Marajó Island)	24.9	4	32	63
Other freshwater ecosystems[h]	399.1	3	25	70
Total mapped area	1025.9	8	32	59
Not mapped at basin-wide scale				
Riparian zones of small streams[i]	Junk (1993) estimated that riparian zones of small streams may cover up to 1 million km^2 of the basin.			
High-elevation freshwater ecosystems[j]	Area is likely less than 70,000 km^2.			

[a]Mapped at 100 m resolution for Amazon basin (strictly defined), Amazon estuary, and Tocantins-Araguaia basins at elevations $<$ 500 m asl (Hess *et al*. 2003; Melack & Hess 2010). The mapped areas are shown in Figure 1.

[b]Water: permanent to semipermanent lakes, and channels of rivers and streams; forest: closed-canopy tree cover, including palms; nonforest: open-canopy tree cover (woodland), shrub, and herbaceous cover.

[c]From confluence of Marañon and Ucayali rivers to Atlantic Ocean.

[d]Includes reaches with stream order $\geq$ 7 based on SRTM DEM at 15 arcsecond resolution. Water type designations follow Araújo-Lima & Ruffino (2003) and Moreira-Turcq *et al*. (2003).

[e]Ucayali, Pachitea, Marañon, Huallaga, Napo, Javari-Yavari, Itui, Içá-Putumayo, Juruá, Japurá-Caquetá, Purus, Ituxi, Tapauá, Padauari, Branco, Uraricoera, Tacutu, Madeira, Madre de Dios, Beni, Mamoré rivers.

[f]Jutaí, Coari, Negro, Uaupés-Vaupés, Unini, Catrimani, Jauaperi rivers.

[g]Guaporé-Iténez, Roosevelt, Aripuanã, Tapajós, Teles Pires, Juruena, Jamanxim, Arinos, Xingu, Iriri, Arraias, Trombetas, Jari, Araguaia, Mortes, Tocantins, Anapu, Pacajá, Pará, and Guamâ rivers.

[h]Floodplains of mid-order rivers and streams, reservoirs, and small savannas and swamps.

[i]Low-order streams with floodplains $<$ 150–200 m wide.

[j]Includes river floodplains and marsh-bog wetlands at elevations $>$ 500 m asl (Otto *et al*. 2011); estimated upper limit assumes that freshwater ecosystems cover 7.5% of total area.

regulate runoff from terrestrial ecosystems, maintaining water quality, buffering flows during high discharge periods, and sustaining flows during low discharge periods (Naiman & Decamps 1997). This promotes soil infiltration and maintains the conditions needed for many life forms (Junk & Piedade 2005).

Life forms are extremely diverse in Amazon freshwater ecosystems, though not fully documented. The basin possesses the most diverse fish fauna, with close to 2200 species recognized (Albert *et al*. 2011). Diversity also is high among birds and trees, with about 1,000 flood-tolerant tree species, and over 1000 bird species in the lowlands that contain most freshwater ecosystems (Junk 1989; Stotz *et al*. 1996).

Some freshwater plant communities are extremely productive. Levee forests and macrophyte communities (i.e., *Echinochloa polystachya*) dominate primary production in nutrient- and sediment-rich river floodplains, reaching some of the highest known rates of primary productivity (Junk *et al*. 1989; Melack & Forsberg 2001). Recent studies estimate total net primary productivity along river floodplains to be about 300 Tg C yr^{-1} in a 1.77 million km^2 quadrat of the basin (Melack *et al*. 2009), and basin-wide CO_2 outgassing from rivers and streams to exceed 1.2 Mg C ha^{-1}, a transfer comparable to that of terrestrial sequestration (Richey *et al*. 2009).

Freshwater ecosystem goods and services have supported Amazonians for millennia. Early indigenous peoples lived near freshwater ecosystems and relied largely on the harvest of animals and forest products (Roosevelt 1999). Even today, many Amazonians live near rivers, which they rely on for transport, everyday water use, and resource exploitation (Junk & Piedade 2005). For example, extraction of the açaí fruit (*Euterpe oleracea*) in the estuary region generates $60–300 million a year (Brondízio 2008). The harvest of freshwater ecosystem animals is a particularly important activity. Many terrestrial animals inhabit riparian zones, either temporarily or permanently, to drink water and feed on fruits, leaves, and other animals (Junk & Piedade 2005), becoming vulnerable to Amazonians who historically have hunted along riparian zones (Bodmer *et al.* 1999).

The most important freshwater animals for Amazonians are lateral migratory fishes. Fishes such as *Arapaima* spp. and *Prochilodus nigricans* live in floodplain lakes or river channels, respectively, during low water periods, and migrate laterally into vegetated floodplain habitats during high water (Fernandez 1997; Castello 2008a). In vegetated floodplain habitats, especially in nutrient- and sediment-rich rivers, fish larvae find nursery conditions that increase their survival rates, and fish of all ages find plenty of food (e.g., detritus, leaves, fruits), which allows them to grow rapidly (Goulding 1980; Castello 2008b). Seasonal lateral migrations thus increase fish population biomass in river floodplains, and that fish biomass is dispersed regionally as those fishes migrate longitudinally along river channels, are eaten by nonlateral migrant species (e.g., *Brachyplatystoma rouseauxii*), or are fished (Bayley 1995). Abundant lateral migratory species dominate regional fishery yields of more than 425,000 tons/yr (Bayley 1998). Per capita fish consumption is high: in the Brazilian Amazon, it now averages 94 kg/yr in riverine populations and 40 kg/yr in urban populations, rates that are 5.8 and 2.5 times the world average, respectively (Isaac & Almeida 2011).

Growing impacts

There is mounting evidence that the structure and function of Amazon freshwater ecosystems are being increasingly impacted by rapid expansions in infrastructure and economic activities. Four main drivers of freshwater ecosystem degradation are recognized: deforestation, construction of dams and navigable waterways, pollution, and overharvesting (Figures 1 and 2).

Deforestation

Conversion of native vegetation, here referred to as deforestation, has altered at least 697,770 km^2 (10%) of the basin, mostly due to expansion of agriculture and cattle ranching in the southeastern "arc of deforestation" (Figure 1; Eva *et al.* 2004). Deforestation in the uplands increases water runoff and stream discharge through decreased evapotranspiration (Hayhoe *et al.* 2011) and alters the morphological and biogeochemical conditions of freshwater ecosystems through soil erosion and increased export of terrestrial sediments into streams (Neill *et al.* 2001). These local processes can have profound effects at regional scales. For example, deforestation of ~50% of the Tocantins and Araguaia basins (Figure 1) has increased year-round water discharge by 25% and shifted the flood pulse by one month in those rivers (Costa 2004; Coe *et al.* 2009).

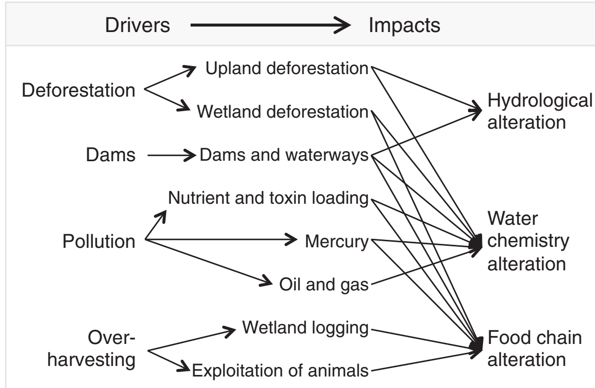

Figure 2 Schematic diagram of the main drivers of freshwater ecosystem degradation in the Amazon and associated impacts.

In floodplains, deforestation reduces the abundance and diversity of highly productive plant communities that sustain abundant animal populations (e.g., fishes; Melack & Forsberg 2001). In the Lower Amazon, 56% of the mainstem floodplain was deforested between 1970 and 2008, mostly for cattle ranching (Figure 1; Renó *et al.* 2011). In the riparian zones of small streams and rivers, deforestation can lower water quality, increase water temperature, and alter biotic assemblage composition and production through increased sediments and removal of structures that provide habitat for aquatic biota (Williams *et al.* 1997; Neill *et al.* 2001). However, there are no basin-wide data on the extent of riparian or floodplain deforestation.

Dams and waterways

Expanding energy demands and agricultural and cattle ranching activities have led to a proliferation of dams (Finer & Jenkins 2012; Macedo 2012). There are 154 hydroelectric dams of all sizes in operation, 21 under construction, and a large but unknown number of small dams in small streams built to provide drinking water for cattle; there are some 10,000 such small dams in the headwaters of the Xingu alone (Figure 1; ANEEL 2012; Macedo 2012; PROTEGER 2012). There also are governmental plans to build an additional

277 hydroelectric dams in the basin (Figure 1). However, there are no detailed environmental impact assessments for dams in the Amazon, as most dams were constructed before baseline ecological data were collected (La Rovere & Mendes 2000; Gunkel *et al*. 2003). Dams generally disrupt the longitudinal connectivity of rivers, altering sediment transport dynamics and fish longitudinal migrations (Poff & Hart 2002; Agostinho *et al*. 2008). Many dams also alter river water temperature through the release of thermally stratified waters from the reservoirs, dramatically altering community species composition downstream (Ward & Stanford 1979). Finally, dams also reduce downstream flood-pulse variability, especially high flood maxima, which disrupts lateral connectivity between river channels and adjacent floodplains and riparian zones (Poff & Hart 2002). This disrupts fish lateral migrations and lateral exchanges of nutrients and sediments, thus altering biogeochemical cycles, reducing biological production, and restructuring plant and animal communities (Bayley 1995; Nilsson & Berggren 2000).

Current governmental plans call for establishing 15,114 km of navigable waterways (i.e., *hidrovias* in Portuguese) to promote transport of commodities such as soybeans (Figure 1; Brito 2001; IIRSA 2012). Establishing waterways generally requires deepening of shallow areas, removing natural obstacles such as rocks, and straightening of winding stretches of the river channels. Such alterations can be minor in large rivers (e.g., Amazon mainstem), but they can dramatically impact the morphology and hydrology of smaller rivers and associated floodplains (e.g., Marajó waterway; Figure 1).

Pollution

There are three main point- and nonpoint sources of pollution in the Amazon, though their impacts have yet to be quantified. Agricultural runoff carries nitrogen and phosphorus from fertilizers and toxic chemicals from pesticides and herbicides into freshwater ecosystems (Williams *et al*. 1997). Nitrogen and phosphorus loading can increase primary production in small streams, creating algal blooms, hypoxic conditions, and altered food web structures (Neill *et al*. 2001). Pesticides bioaccumulate in food webs and can seriously harm the health of the animals ingesting them (Ellgehausen *et al*. 1980). Another pollutant is mercury, which can be released from soils by deforestation or directly into waters when it is used to extract gold (Lacerda & Pfeiffer 1992). Mercury becomes very harmful when anoxic conditions transform its inorganic form into its organic form, methylmercury, which can be absorbed into living tissue and bioaccumulate (Mergler *et al*. 2007). Commercial fishes in the Amazon river have methylmercury concentrations higher than that permitted by Brazilian health law (Beltran-Pedreiros *et al*. 2011). A third source of pollution is oil exploration, which has been expanding in the western Amazon (Finer *et al*. 2008; Figure 1). An estimated 114 million tons of toxic wastes and crude oil have been discharged in the Ecuadorian Amazon alone (Jochnick *et al*. 1994). Waters near oil fields have shown concentrations of hydrocarbon-related toxins over 100 times greater than those permitted by North American or European regulations, and have been linked to human health problems (Sebastián & Hurtig 2004). However, there are no basin-wide data on freshwater ecosystem pollution, except an estimate of 5000 t of mercury contamination since the start of gold mining in the basin (Lacerda & Pfeiffer 1992; Junk & Piedade 2005).

Overharvesting

Harvesting of plant and animal species in an unsustainable fashion, here referred to as overharvesting, is the most significant historical driver of Amazon freshwater ecosystem degradation. Despite a lack of basin-wide data on overharvesting of freshwater timber resources, selective logging is thought to already have reached unsustainable levels for several economically important species in floodplain forests (e.g., *Ceiba pentandra*; Albernaz & Ayres 1999). Data also are sparse on the overharvesting of animal communities, but an analysis of available population assessments reveals the "fishing-down" process of Welcomme (1999; Castello *et al*. 2011a). In the fishing-down process, historical increases in exploitation reduce the mean body size of harvested animals through the progressive depletion of high-value, large-bodied species. Mean maximum body length of the main species harvested in the basin in 1895 was ~206 cm, while for all 18 species dominating fishery yields in 2007 it was only ~79 cm (Figure 3). The three main species harvested in the early 1900s are now considered endangered; and of the 18 species that now dominate fishery yields, one is considered to be endangered and four have been found to be overexploited in at least one region of the basin (Figure 3; Veríssimo 1895; Barthem & Goulding 2007). Although the depletion of large, commercially important species has decreased mean maximum body length of the main species harvested (Figure 3), it must be noted that this reduction also occurs due to the natural tendency of expanding fisheries to increase harvests of small-bodied, highly abundant species (e.g., *Prochilodus* spp). Overharvesting of freshwater ecosystem plant and animal species has multiple adverse impacts. Whereas the impacts caused by loss of plant species are similar to those caused by riparian

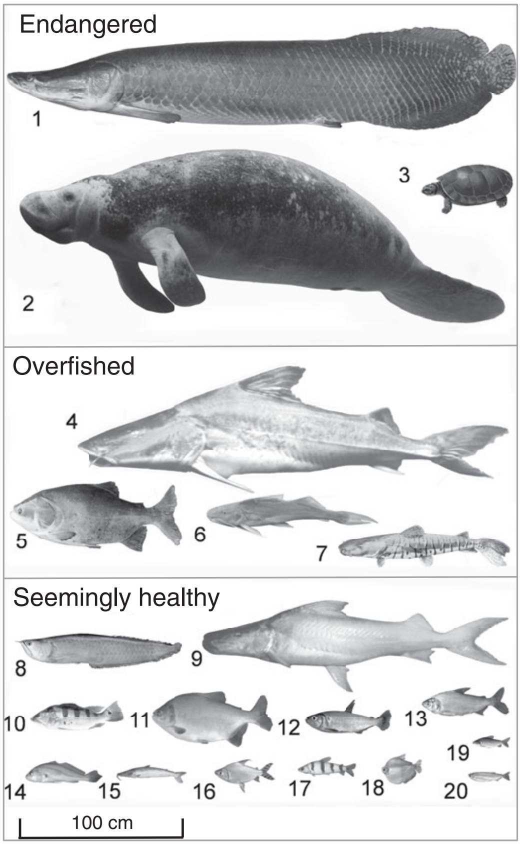

Figure 3 The fishing-down process in the Amazon, illustrating historical decline in mean body size of the main harvested resources due to overharvesting. In 1985, fishery yields were dominated by species or species-groups in the top panel (Veríssimo 1895), which now are all considered to be endangered. Present fishery yields are dominated by the 17 species or species-groups shown in the middle and bottom panels, as well as species-group 1 in the top panel (Barthem & Goulding 2007). The data supporting the occurrence of the fishing-down process in the Amazon are as follows. Species or species-group codes are presented in parentheses, followed by the maximum body length of the species or mean maximum body length of the species-groups (from Santos (2006) and Barthem & Goulding (2007)), followed by a population assessment study if it exists: (1) 300 cm, *Arapaima* spp. (Castello & Stewart 2011a; Castello *et al*. 2011b); (2) 280 cm, *Trichechus inunguis* (Marmontel 2008); (3) 40 cm, *Podocnemis* spp. (Tortoise & Freshwater Turtle Specialist Group 1996); (4) 250 cm, *Brachyplatystoma filamentosum* (Petrere *et al*. 2004); (5) 100 cm, *Colossoma macropomum* (Isaac & Ruffino 1996); (6) 100 cm, *Brachyplatystoma vaillantii* (Barthem & Petrere 1995); (7) 100 cm, *Pseudoplatystoma* spp. (Isaac & Ruffino 1999); (8) 100 cm, *Osteoglossum bicirrhosum*; (9) 180 cm, *Brachyplatystoma roussseauxii*; (10) 55 cm, *Cichla* spp.; (11) 70 cm *Piaractus brachypomus*; (12) 50 cm, *Brycon* spp.; (13) 50 cm, *Prochilodus nigricans* (Freitas *et al*. 2007); (14) 45 cm, *Plagioscion* spp.; (15) 40 cm, *Hypothalmus* spp.; (16) 35 cm, *Semaprochilodus* spp. (Freitas *et al*. 2007); (17) 34 cm, *Schizodon* spp., *Leporinus* spp., *Rhytiodus* spp.; (18) 24 cm, *Mylossoma* spp., *Myleus* spp., *Metynnis* spp.; (19) 24 cm, *Curimata vittata*, *Potamorhina* spp.; (20) 22.5 cm, *Triportheus* spp. Scientific names follow Reis *et al*. (2003). Photo credits to Donald J. Stewart, except photo for species code 2, which is anonymous.

deforestation, loss of apex fish species such *Arapaima* spp. may alter food web structure, water quality, and nutrient cycles (Estes *et al*. 2011). Though poorly studied, depletion of megaherbivores (e.g., manatees and capybaras) has been implicated in historical overgrowth of macrophytes on floodplains (Junk 2000).

Insufficient monitoring and management

Curbing freshwater ecosystem degradation requires adaptive environmental management, which at a minimum requires monitoring data on (1) location and extent of freshwater ecosystems, (2) indicators of ecosystem integrity, and (3) drivers of degradation (Figure 2). Such monitoring data must be collected and analyzed periodically to generate resource assessments that, in turn, guide the development and implementation of policies and management activities.

Unfortunately, many of the data needed to manage Amazon freshwater ecosystems do not exist (Junk & Piedade 2004). Although data exist on the location and extent of most lowland freshwater ecosystems, there are no basin-wide data on the location of high-elevation freshwater ecosystems or the riparian zones of small streams, which are thought to be the most extensive freshwater ecosystem type. Similarly, data exist on the location of upland deforestation and current and planned hydroelectric dams, but there are no basin-wide data on the location and extent of pollution, overharvesting of animal and plant species, small dams, or deforestation of floodplains and riparian zones. Such lack of data makes it difficult to assess the vulnerability of the various freshwater ecosystems to identify management priorities. It also conceals a crisis from the science, public, and policy arenas, delaying much-needed action.

Management capacity is similarly deficient. Although there are management and conservation strategies with the potential to protect Amazon freshwater ecosystems, such strategies are not intended for freshwater ecosystems, have design and implementation deficiencies, or fail to account for the hydrologic connectivity of freshwater ecosystems. Protected areas cover some 2,580,118 km^2 or 37% of the basin if they are defined as "all public areas under land-use restrictions that contribute to protecting native ecosystems, even if they were created for purposes other than environmental conservation" (Table 1; Figure 1; Soares-Filho *et al*. 2010). The protected area network provides protection against overharvesting and riparian deforestation, but does not protect freshwater ecosystems from the far-reaching impacts of dams, pollution, and upland deforestation outside protected areas. This is largely because the protected area network ignores river catchment areas, which comprise "the vast majority of physical, chemical and biological processes affecting river systems" (Wishart & Davies 2003). Most protected areas in the Amazon were established based on the biogeography of terrestrial taxa (Peres & Terborgh 1995), and very few protect freshwater ecosystems specifically (e.g., Pacaya-Samiria and Mamirauá reserves). The inability of protected areas to adequately protect freshwater ecosystems is illustrated by the Xingu National Indigenous Park, where local indigenous livelihoods are threatened by declines in water quality and fish populations caused by deforestation in headwater areas outside park boundaries (Rosenthal 2009). Another example is the Madeira River basin, which is threatened by oil exploration, deforestation, and dams in the headwaters, even though protected areas cover 26% of its catchment area (Table 1).

Water resources legislation exists in most Amazonian countries. For example, Brazil established the following essential management principles: (1) water is a finite resource that has multiple uses; (2) water is vulnerable to human activities; (3) management must be made at the catchment scale; and (4) management must be decentralized and participatory (Setti 2004). In many cases, however, national water resources laws cannot adequately protect Amazon freshwater ecosystems, because they follow national borders that do not always encompass whole catchments. In addition, water resources legislation is largely unimplemented, leaving huge areas unmanaged. For example, until 1999 the environmental management agency in the municipality of Tefé in Brazil had only eight employees and did not even possess a boat to do its job in an area that has no roads and is roughly the size of Italy (Crampton *et al.* 2004). Finally, water resources laws focus on water itself, not on freshwater ecosystems, probably because they reflect historical concerns about ensuring quantity and quality of water to meet multiple demands in populated regions. Other legislation may complement national water resources legislation. For example, in Brazil, the Forest Code protects riparian vegetation (Law 4.771 of 1965) and the Fishery Code regulates aquatic fauna extraction activities (Decree-Law 221 of 1967). But no law or set of laws fully considers the structure and function of Amazon freshwater ecosystems, and that is the case even for the floodplains of the Amazon mainstem, which is by far the best studied Amazon freshwater ecosystem (Vieira 2000; Junk & Piedade 2004).

Community-based natural resource management (CBM) systems, developed by riverine communities to ensure food security via the implementation of harvest restrictions (e.g., fishing gear, place, and season), provide another source of protection to Amazon floodplains (McGrath *et al.* 1993). These CBM systems can sustainably manage living resources that are sedentary or have small geographical ranges (Castello *et al.* 2009). However, such CBM systems cannot manage entire river basins unless they are integrated into larger-scale institutional frameworks, something that is only beginning to happen in some regions (McGrath *et al.* 2008; Castello *et al.* 2013).

Potential consequences

The current lack of monitoring and management capacity leaves Amazon freshwater ecosystems largely vulnerable to escalating degradation. Until the drivers of degradation are curbed, many of the alterations in hydrology, water chemistry, and food webs observed in the southeastern Amazon can be expected to continue to spread over the south and west regions of the basin (Figures 1 and 3). Although it is difficult to predict the cumulative impacts of future degradation, ecological theory predicts that the principal threat to freshwater ecosystems is alteration of natural hydrology (Vannote *et al.* 1980; Junk *et al.* 1989). Hydrological alterations in the Amazon basin stem mainly from three sources: large-scale deforestation, which significantly alters river discharge and flood-pulse magnitude (Coe *et al.* 2009); dams, which reduce flood-pulse amplitude (Poff & Hart 2002); and climate change, which is expected to decrease regional rainfall and river discharge while increasing the frequency of extreme droughts (Malhi *et al.* 2009). Altogether, such hydrological alterations are expected to significantly lower the magnitude of flood-pulses and increase the frequency and severity of low-water events (Costa *et al.* 2004). Among various impacts, these hydrological alterations could threaten riverine livelihoods and food security through disruptions of the lateral migration of commercial fishes and their associated fishery yields, as observed elsewhere in the world (Jackson & Marmulla 2001).

Toward a catchment-based conservation framework

We have shown that neither protected areas, national water resource legislation, nor CBM schemes can separately or jointly adequately protect Amazon freshwater ecosystems against current pressures. Conserving Amazon freshwater ecosystems requires addressing human impacts in the aquatic and terrestrial ecosystems that compose river catchments. It also requires matching the continental scale of many drivers of degradation, including multigovernmental initiatives to develop regional energy and transport infrastructure (e.g., IIRSA

2012). It is therefore necessary to shift the Amazon conservation paradigm—broadening its current forest-centric focus to encompass the basin's freshwater ecosystems. This is possible by developing a catchment-based conservation framework for the whole basin that protects, not only varied and productive aquatic ecosystems, but also biodiversity- and carbon-rich terrestrial ecosystems.

Such a conservation framework could be similar to the multiple-use zoning framework proposed by Abell *et al.* (2007), which integrates various freshwater ecosystem use strategies occurring inside and outside protected areas into a whole basin management strategy that balances human uses and ecosystem integrity. Such a framework is more likely to succeed if it is developed through collaborative partnerships involving science institutions, public management agencies, local communities, and the private sector (Poff *et al.* 2003). Examples of collaborative partnerships in the Amazon include the BR-163 participatory planning process and the development of river floodplain comanagement in the Lower Amazon region (Campos & Nepstad 2006; McGrath *et al.* 2008). Large-scale collaborative partnerships could integrate existing protected areas, water resource and other relevant legislation, and CBM systems with developing schemes to pay for forest carbon storage services such as REDD+, all of which lay important foundations for catchment management (e.g., Thieme *et al.* 2007; Nepstad *et al.* 2011; Stickler *et al.* 2009). National water resource laws could provide a sound policy framework if they defined *water resources* in a way that encompassed the ecological requirements for maintaining the integrity of freshwater ecosystems. The framework could be operationalized basin-wide under the Amazon Cooperation Treaty, which was signed by all Amazonian countries in part to handle freshwater ecosystem issues.

How exactly such a catchment-based conservation framework should be developed and implemented is an issue that requires further consideration. Among the many enormous challenges raised is the need for sufficient information, scientific and managerial capacity, and strong governance institutions at multiple scales. However, it must be noted that the Amazonian society is relatively well positioned to develop and implement such a framework, for it possesses two unparalleled advantages: (1) it can use its rapidly developing experience with environmental management to learn from global experiences in freshwater ecosystem mismanagement; and (2) it can reinvent freshwater ecosystem management and conservation while its freshwater ecosystems are relatively pristine. What is critically missing to address the vulnerability of Amazon freshwater ecosystems is scientific and policy action before it is too late.

Acknowledgments

We thank D. J. Stewart for help in producing Figure 3, B. S. Soares-Filho for sharing protected area data, and M. Aguirre (International Rivers) for sharing data on dams. Funding support to L.C. was provided by the Gordon & Betty Moore Foundation, and to L.H. was provided by the NASA Terrestrial Ecology Program. John Melack, David Strayer, and two anonymous reviewers provided valuable feedback.

Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher's web site:

Disclaimer: Supplementary materials have been peer-reviewed but not copyedited.

References

Abell, R., Allan, J.D. & Lehner, B. (2007). Unlocking the potential of protected areas for freshwaters. *Biol. Conserv.*, **1**, 48-63.

Agostinho, A.A., Pelicice, F.M. & Gomes, L.C. (2008). Dams and the fish fauna of the neotropical region: impacts and management related to diversity and fisheries. *Braz. J. Biol.*, **4**, 1119-1132.

Albernaz, A.L.K.M. & Ayres, J.M. (1999). Selective logging along the middle Solimões River. Pages 135-151 in C. Padoch, J.M. Ayres, M. Pinedo-Vasquez, A. Henderson, editors. *Várzea: diversity, development, and conservation of Amazonia's whitewater floodplains*. New York Botanical Garden Press, Bronx, New York, .

Albert, J.S., Petry, P. & Reis, R.E. (2011). Major biogeographic and phylogenetic patterns. Pages 21-58 in J. Albert, R.E. Reis, editors. *Historical biogeography of neotropical freshwater fishes*. University of California Press, Berkeley.

[ANA] Agência Nacional das Águas. (1 May 2012; www2.ana.gov.br/)

[ANEEL] Agência Nacional de Energia Elétrica. (1 May 2012; www.aneel.gov.br/)

Araujo-Lima, C.A.R.M. & Ruffino, M.L. (2003). Migratory fishes of the Brazilian Amazon. Pages 233-301 in J. Carolsfield, B. Harvey, C. Ross, A. Baer, editors. *Migratory fishes of South America: biology, fisheries and conservation status*. International Development Research Centre, Ottawa.

Barthem, R.B. & Petrere, M. (1995). Fisheries and population dynamics of the freshwater catfish *Brachyplatystoma vaillantii* in the Amazon estuary. Pages 329-340 in N.B. Armantrout, R. Wolotira, editors.*Proceedings of the World Fisheries Congress*. Oxford, and IBH Publishing, Oxford.

Barthem, R. & Goulding, M. (2007). *An unexpected ecosystem: the Amazon as revealed by fisheries*. Amazon Conservation Association Press, Lima.

Bayley, P.B. (1995). Understanding large river-floodplain ecosystems. *Bioscience*, **3**, 153-158.

Bayley, P.B. (1998). *Aquatic biodiversity and fisheries management in the Amazon*. United Nations, World Bank, Washington, D.C.

Beltran-Pedreiros, S., Zuanon, J., Leite, R.G., Peleja, J.R.P., Mendonça, A.B. & Forsberg, B.R. (2011). Mercury bioaccumulation in fish of commercial importance from different trophic categories in an Amazon floodplain lake. *Neotrop. Ichthyol.* **9**, 901-908.

Bodmer, R.E., Puertas, P.E., Garcia, J.E., Dias, D.R. & Reyes, C. (1999). Game animals, palms, and people of the flooded forests: management considerations for the Pacaya-Samiria National Reserve, Peru. Pages 203-232 in C. Padoch, M.A. Ayres, M. Pinedo-Vasquez, A. Henderson, editors. *Várzea: diversity, development, and conservation of Amazonia's whitewater floodplains*. New York Botanical Garden Press, New York.

Brito, M. (2001). Eixos Amazônicos de Integração e Desenvolvimento: obras e empreendimentos. Pages 321-326 in A. Veríssimo, J.P.R. Capobianco, A. Moreira, D. Sawyer, I. Santos, L.P. Pinto, editors *Biodiversidade na Amazônia Brasileira*.Estação Liberdade, Instituto Socioambiental, São Paulo.

Brondízio, E.S. (2008). *The Amazonian caboclo and the Acaí palm: forest farmers in the global market*. Advances in Economic Botany Monograph Series, Vol 16. New York Botanical Garden Press, New York.

Campos, M.T. & Nepstad, D.C. (2006). Smallholders, the Amazon's new conservationists. *Conserv. Biol.*, **20**, 1553-1556.

Carpenter, S.R., Stanley, E.H. & Zanden, M.J.V. (2011). State of the world's freshwater ecosystems: physical, chemical, and biological changes. *Annu. Rev. Environ. Resour.* **36**, 75-99.

Castello, L. (2008a). Lateral migration of *Arapaima gigas* in floodplains of the Amazon. *Ecol. Freshwater Fish*, **17**, 38-46.

Castello, L. (2008b). Nesting habitat of pirarucu *Arapaima gigas* in floodplains of the Amazon. *J. Fish Biol.* **72**, 520-1528.

Castello, L., Viana, J.P., Watkins, G., Pinedo-Vasquez, M. & Luzadis, V.A. (2009). Lessons from integrating fishers of arapaima in small-scale fisheries management at the Mamiraua′ Reserve, Amazon. *Environ. Manage.* **43**, 197-209.

Castello, L. and Stewart, D.J. (2010). Assessing CITES non-detriment finding procedures for Arapaima in Brazil. *J. Appl. Ichthyol.* **26**, 49-56.

Castello, L., McGrath, D.G. & Beck, P. (2011a). Resource sustainability in small-scale fisheries in the Lower Amazon. *Fish. Res.* **110**, 35-365.

Castello, L., Stewart, D.J. & Arantes, C.C. (2011b). Modeling population dynamics and conservation of arapaima in the Amazon. *Rev. Fish Biol. Fish.*, **21**, 623-640.

Castello, L., McGrath, D.G., Arantes, C.C. & Almeida, O.T. (2013). Accounting for heterogeneity in small-scale fisheries management: the Amazon case. *Mar. Policy*, **38**, 557-565.

Coe, M.T., Costa, M.H. & Soares-Filho, B.S. (2009). The influence of historical and potential future deforestation on the stream flow of the Amazon river-land surface processes and atmospheric feedbacks. *J. Hydrol.*, **369**, 165-174.

Costa, M.H. & Foley, J.A. (1999). Trends in the hydrologic cycle of the Amazon basin. *J. Geophys. Res.*, **104**, 14189-14198.

Costa, M.H. (2004). Large-scale hydrological impacts of tropical forest conversion. Pages 590-597 in M. Bonell, L.A. Bruijnzeel, editors. *Forests, water and people in the humid tropics*. Cambridge University Press, Cambridge.

Crampton, W.G.R., Castello, L. & Viana, J.P. (2004). Fisheries in the Amazon várzea: historical trends, current status, and factors affecting sustainability. Pages 76-95 in K. Silvius, R. Bodmer, J.M.V. Fragoso, editors. *People in nature: wildlife conservation in South and Central America*. Columbia University Press, New York.

Davidson, E.A., Araújo, A.C. de Artaxo, P., Balch, J.K., Brown, I.F., Bustamante, M.M.C., Coe, M.T., DeFries, R.S., Keller, M., Longo, M., Munger, J.W., Schroeder, W., Soares-Filho, B.S., Souza, C.M. & Wofsy, S.C. (2012). The Amazon basin in transition. *Nature*, **481**, 321-328.

Ellgehausen, H., Guth, J.A. & Esser, H.O. (1980). Factors determining the bioaccumulation potential of pesticides in the individual compartments of aquatic food chains. *Ecotoxicol. Environ. Safety*, **4**, 134-157.

Estes, J.A., Terborgh, J., Brashares, J.S., Power M.E., Berger, J., Bond, W.J., Carpenter, S.R., Essington, T.M., Holt, R.D., Jackson, J.B.C., Marquis, R.J., Oksanen, L., Oksanen, T., Paine, R.T., Pikitch, E.K., Ripple, W.J., Sandin, S.A., Scheffer, M., Schoener, T.W., Shurin, J.B., Sinclair, A.R.E., Soulé, M.E., Virtanen, R. & Wardle, D.A. (2011). Trophic downgrading of planet earth. *Science*, **6040**, 301-306.

Eva, H.D., Belward, A.S., Miranda, E.E., Bellaz, C.M., Gond, V., Huber, O., Jones, S., Sgrenzaroli, M. & Fritz, S. (2004). A land cover map of South America. *Global Change Biol.*, **10**, 731-744.

Fernandez, C.C. (1997). Lateral migration of fishes in Amazon floodplains. *Ecol. Freshwater Fish*, **6**, 36-44.

Finer, M. & Jenkins, C.N. (2012). Proliferation of hydroelectric dams in the Andean Amazon and implications for Andes-Amazon connectivity. *PLoS ONE*, **7**(4), e35126.

Finer, M., Jenkins, C.N., Pimm, S.L., Keane, B. & Ross, C. (2008). Oil and gas projects in the western Amazon: threats to wilderness, biodiversity, and indigenous peoples. *PLoS ONE*, **8**, e2932.

Freitas, C.E.C., Nascimento, F.A. & Sousa, R.G.C. (2007). Levantamento do estado de explotação dos estoques de curimatá, jaraqui, surubim, e tambaqui. Pages 77-100 in M.J. Petrere, editor. *O setor pesqueiro na Amazônia: Análise da situação atual e tendências do desenvolvimento a indústria da* *pesca*. Projeto Manejo dos Recursos Naturais da Várzea, Manaus.

Furtado, L.G., Leitão, W. & Melo, A.F. (eds.) (1993). *Povos das águas, realidade, e perspectivas na Amazônia*. Ministério de Ciência e Tecnologia, Conselho Nacional de Pesquisa, Museu Paraense Emilio Goeldi, Belém.

Goulding, M. (1980). *The fish and the forest*. University of California Press, Berkeley.

Gunkel, G., Lange, U., Walde, D., Rosa, J.W.C. (2003). The environmental and operational costs of Curuá-Una, a reservoir in the Amazon region of Pará, Brazil. *Lakes Reservoirs: Res. Manage.*, **3–4**, 201-216.

Hamilton, S.K., Sippel, S.J. & Melack, J.M. (2002). Comparison of inundation patterns among major South American floodplains. *J. Geophys. Res. Atmos.*, **107**, 8038.

Hayhoe, S., Neill, C., McHorney, R., Porder, S., Lefebvre, P., Coe, M.T., Elsenbeer, H. & Krusche, A. (2011). Conversion to soy on the Amazonian agricultural frontier increases streamflow without affecting stormflow dynamics. *Global Change Biol.*, **17**, 1821-1833.

Hess, L. L., Melack, J. M., Novo, E. M. L. M., Barbosa, C. C. F. & Gastil, M. (2003). Dual-season mapping of wetland inundation and vegetation for the central Amazon basin. *Remote Sens. Environ.*, **87**, 404-428.

[IIRSA] Initiative for Integration of Regional Infrastructure in South America. (2012). (18 June 2012; www.iirsa.org)

Isaac, V.J. & Almeida, M.C. (2011). *El consumo de pescado en la Amazonia brasileña*. COPESCAALC Documento Ocasional. No 13. FAO, Rome.

Isaac, V.J. & Ruffino, M.L. (1996). Population dynamics of tambaqui (*Colossoma macropomum*) Cuvier, in the Lower Amazon, Brazil. *Fish. Manage. Ecol.*, **3**, 315-333.

Isaac, V.J. & Ruffino, M.L. (1999). Dinâmica populacional do surubim tigre, *Pseudoplatystoma tigrinum* (Valenciennes, 1840) no Médio Amazonas (Siluriformes, Pimelodidade). *Acta Amazônica*, **29**, 463-476.

Jackson, D.C. & Marmulla, G. (2001). The influence of dams on river fisheries. Pages 1-44 in G. Marmulla, editor. *Dams, fish and fisheries: opportunities, challenges and conflict resolution*. Food & Agriculture Organization, Fisheries Technical Paper 419, Rome.

Jochnick, C., Norman, R. & Zaidi, S. (1994). Rights violations in the Ecuadorian Amazon: the human consequences of oil development. *Health Hum. Rights*, **1**, 82-100.

Junk, W.J. (1989). Flood tolerance and tree distribution in central Amazonian floodplains. Pages 47-64 in L.B. Holm-Nielsen, I.C. Nielsen, H. Balslev, editors. *Tropical forests: botanical dynamics, speciation and diversity*. Academic Press, New York.

Junk, W.J. (1993). Wetlands of tropical South America. Pages 679-739 in D. Whigham, H. Dykyjová, editors. *Wetlands of the world: inventory, ecology, and management*. Kluwer Academic Publishers, London.

Junk, W.J. (2000). The central Amazon River floodplain: concepts for the sustainable use of its resources. Pages 75-94 in W.J. Junk, J.J. Ohly, M.T.F. Piedade, M.G.M. Soares, editors. *The central Amazon floodplain: actual use and options for a sustainable management*. Backhuys Publishers, Lieben.

Junk, W.J. & Piedade, M.T.F. (2004). Status of knowledge, ongoing research, and research needs in Amazonian wetlands. *Wetlands Ecol. Manage.*, **13**, 597-609.

Junk, W.J. & Piedade, M.T.F. (2005). The Amazon river basin. Pages 63-117 in L.H. Fraser, P.A. Keddy, editors. *The world's largest wetlands: ecology and conservation*. Cambridge University Press, Boston.

Junk, W.J., Piedade, M.T.F., Schöngart, J. & Wittmann, F. (2012). A classification of major natural habitats of Amazonian white-water river floodplains (várzeas). *Wetlands Ecol. Manage.*, **20**, 461-475.

Kvist, L.P. & Nebel, G. (2001). A review of Peruvian flood plain forests: ecosystems, inhabitants, and resource use. *Forest Ecol. Manage.*, **150**, 3-26.

La Rovere, E.L. & Mendes, F.E. (2000). *Tucuruí Hydropower Complex, Brazil, A WCD Case Study Prepared as an Input to the World Commission on Dams*. World Commission on Dams, Cape Town.

Lacerda, L.D. & Pfeiffer, W. (1992). Mercury from gold mining in the Amazon environment: an overview. *Química Nova*, **2**, 155-160.

Macedo, M. (2012). Seeing the forest for the streams: A multi-scale study of land-use change and stream ecosystems in the Amazon's agricultural frontier. *Ph.D. Thesis in Ecology, Evolution, and Environmental Biology, 152*, Columbia University, New York.

Malhi, Y., Aragão, L.E.O.C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowskia, P., Sitche, S., McSweeney, M. & Meir, P. (2009). Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proc. Natl. Acad. Sci.*, **106**, 20610

Malmqvist, B. & Rundle, S. (2002). Threats to the running water ecosystems of the world. *Environ. Conserv.*, **29**, 134-153.

Marmontel, M. 2008. *Trichechus inunguis*. IUCN Red List of Threatened Species (1 May 2012; www.iucnredlist.org)

McGrath, D.G., Castro, F., Futemma, C., Amaral, B.D. & Calabria, J. (1993). Fisheries and evolution of resource management on the Lower Amazon floodplain. *Hum. Ecol.*, **21**, 167-195.

McGrath, D.G., Cardoso, A., Almeida, O.T. & Pezzuti, J. (2008). Constructing a policy and institutional framework for an ecosystem-based approach to managing the Lower Amazon floodplain. *Environ. Dev. Sustainability*, **10**, 677-695.

Melack, J.M., Novo, E.M.L.M., Forsberg, B.R., Piedade, M.T.F. & Maurice, L. (2009). Floodplain ecosystem processes. Pages 525-541 in M. Keller, M.G. Bustamante, P.S. Dias, editors. *Amazonia and global change*. American Geophysical Union, Washington, D.C.

Melack, J.M. & Hess, LL. (2010). Remote sensing of the distribution and extent of wetlands in the Amazon basin. Pages 43-60 in W.J. Junk, M.T.F. Piedade, F. Wittmann, J. Schöngart, P. Parolin, editors. *Amazonian floodplain forests: ecophysiology, biodiversity and sustainable management*. Springer-Verlag, Berlin.

Melack, J.M. & Forsberg, B.R. (2001). Biogechemistry of Amazon floodplain lakes and associated wetlands. Pages 235-274 in M.E. McClain, R.L. Victoria, J.E. Richey, editors. *The biogeochemistry of the Amazon basin*. Oxford University Press, New York.

Mergler, D., Anderson, H.A., Chan, L.H.M., Mahaffey, K.R., Murray, M., Sakamoto, M. & Stern, A.H. (2007). Methylmercury exposure and health effects in humans: a worldwide concern. *AMBIO*, **36**, 3-11.

Meybeck, M. & Ragu, A. (1996). *River discharges to the oceans: an assessment of suspended solids, major ions and nutrients*. Environment Information and Assessment Report, UNEP, Paris.

Moreira-Turcq, P., Seyler, P., Guyot, J.L. & Etcheber, H. (2003). Exportation of organic carbon from the Amazon and its main tributaries. *Hydrol. Process.*, **17**, 1329-1344.

Naiman, R. & Decamps, H. (1997). The ecology of interfaces: riparian zones. *Ann. Rev. Ecol. Systematics*, **28**, 621-658.

Neill, C., Deegan, L., Thomas, S. & Cerri, C. (2001). Deforestation for pasture alters nitrogen and phosphorus in small Amazonian streams. *Ecol. Appl.*, **11**, 1817-1828.

Nepstad, D., Soares-Filho, B. S., Merry, F., Lima, A., Moutinho, P., Carter, J., Bowman, M., Cattaneo, A., Rodrigues, H., Schwartzman, S., McGrath, D.G., Stickler, C.M., Lubowski, R., Piris-Cabezas, P., Rivero, S., Alencar, A., Almeida & Stella, O. (2009). The end of deforestation in the Brazilian Amazon. *Science*, **326**, 1350-1351.

Nepstad, D.C., Soares-Filho, B.S. & McGrath, D.G. (2011). Systemic conservation, REDD, and the future of the Amazon basin. *Conserv. Biol.*, **25**, 1113-1116.

Nilsson, C. & Berggren, K. (2000). Alterations of riparian ecosystems caused by river regulation. *Bioscience*, **50**, 783-792.

Otto, M., Scherer, D. & Richters, J. (2011). Hydrological differentiation and spatial distribution of high altitude wetlands in a semi-arid Andean region derived from satellite data. *Hydrol. Earth Syst. Sci.*, **15**, 1713-1727.

Peres, C. & Terborgh, J. (1995). Amazonian nature-reserves: an analysis of the defensibility status of existing conservation units and design criteria for the future. *Conserv. Biol.*, **9**, 34-46.

Petrere, M., Barthem, R.B., Cordoba, E.A. & Gomez, B.C. (2004). Review of the large catfish fisheries in the upper Amazon and the stock depletion of piraíba (*Brachyplatystoma filamentosum* Lichtenstein). *Rev. Fish Biol. Fish.*, **14**, 403-414.

Poff, N.L.R., Allan, J.D., Palmer, M.A., Hart, D.D., Richter, B.D., Arthington, A.H., Rogers, K.H., Meyer, J.L. & Stanford, J.A. (2003). River flows and water wars: emerging science for environmental decision making. *Front. Ecol. Environ.*, **6**, 298-306.

Poff, N. & Hart, D. (2002). How dams vary and why it matters for the emerging science of dam removal. *Bioscience*, **8**, 659-668.

Pringle, C. (2003). What is hydrologic connectivity and why is it ecologically important? *Hydrol. Process.*, **17**, 2685-2689.

[PROTEGER] Fundación PROTEGER, International Rivers, ECOA. (2012). Dams in Amazonia. (1 May 2012; www.dams-info.org)

Räsänen, M. (1993). La geohistoria y geologia de la Amazonia Peruana. Pages 43-67 in R. Kalliola, M. Puhakka, W. Danjoy, editors. *Amazonia peruana: vegetación humeda tropical en el llano subandino*. Proyecto Amazonia, Universidad de Turku, Lima.

Reis, R.E., Kullander, S.O. & Ferraris, C.J. (2003). *Check list of the freshwater fishes of south and central America*. EDIPUCRS, Porto Alegre.

Renó, V.F., Novo, E.M.L.M., Suemitsu, C., Rennó, C.D. & Silva, T.S.F. (2011). Assessment of deforestation in the Lower Amazon floodplain using historical landsat MSS/TM imagery. *Remote Sens. Environ.*, **115**, 3446-3456.

Richey, J.E., Krusche, A.V., Johnson, M.S., da Cunha, H.B. & Ballester, M.V. (2009). The role of rivers in the regional carbon balance. Pages 489-504 in M. Keller, M.G. Bustamante, P.S. Dias, editors. *Amazonia and global change*. American Geophysical Union, Washington, D.C.

Roosevelt, A.C. (1999). Twelve thousand years of human-environment interaction in the Amazon floodplain. Pages 371-392 in C. Padoch, M.A. Ayres, M. Pinedo-Vasquez, A. Henderson, editors. *Várzea: diversity, development, and conservation of Amazonia's whitewater floodplains*. New York Botanical Garden Press, New York.

Rosenthal, E. (2009). *An Amazon culture withers as food dries up*. New York Times, July 25: A1.

Santos, G.M., Ferreira, E.J.G. & Zuanon, J.A.S. (2006). *Peixes comerciais de Manaus*. Ibama/ProVárzea, Manaus.

Sebastián, S.M. & Hurtig, A.K. (2004). Oil exploitation in the Amazon basin of Ecuador: a public health emergency. *Pan Am. J. Public Health*, **3**, 205-211.

Setti, A.A. (2004). Legislation and institutional systems for water resources management in Brazil and their relevance to the Amazon. Pages 167-202 in L.E. Aragón, M. Clüsener-Godt, editors. *Issues of local and global use of water from the Amazon*. UNESCO, Montevideo.

Smith, N. (2002). *Amazon sweet sea: land, life, and water at the river's mouth*. University of Texas Press, Austin.

Soares-Filho, B., Moutinho, P., Nepstad, D., Anderson, A., Rodrigues, H., Garcia, R., Dietzsch, L., Merry, F., Bowman, M., Hissa, L., Silvestrini, R. & Maretti, C. (2010). Role of Brazilian Amazon protected areas in climate change mitigation. *Proc. Natl. Acad. Sci.*, **107**, 10821-10826.

Stickler, C.M., Nepstad, D.C., Coe, M.T., McGrath, D.G., Rodrigues, H.O., Walker, W.S., Soares-Filho, B. & Davidson, E.A. (2009). The potential ecological costs and cobenefits of REDD: a critical review and case study from the Amazon region. *Global Change Biol.*, **12**, 2803-2824.

Stotz, D.F., Fitzpatrick, J.W., Parker, T.E.I. & Moskovits, D.K. (1996). *Neotropical birds: ecology and conservation*. University of Chicago Press, Chicago.

Thieme, M., Lehner, B., Abell, R., Hamilton, S. K., Kellndorfer, J., Powell, G. & Riveros, J. C. (2007). Freshwater conservation planning in data-poor areas: an example from a remote Amazonian basin (Madre de Dios River, Peru and Bolivia). *Biol. Conserv.*, **135**, 484-501.

Tortoise & Freshwater Turtle Specialist Group. 1996. *Podocnemis unifilis*. IUCN Red List of Threatened Species (1 May 2012; www.iucnredlist.org)

Valente, C.R. & Latrubesse, E.M. (2012). Fluvial archive of peculiar avulsive fluvial patterns in the largest Quaternary intracratonic basin of tropical South America: the Bananal Basin, Central-Brazil. *Palaeogeogr. Palaeoclimatol. Palaeoecol.*, **356–357**, 62-74.

Vannote, R.L., Minshall, G.W., Cummins, K.W., Sedell, J.R. & Cushing, C. E. (1980). The river continuum concept. *Can. J. Fish. Aquat. Sci.*, **37**, 130-137.

Veríssimo, J. (1895). *A Pesca no Amazônia*. Livraria Clássica Alves and Companhia, Rio de Janeiro.

Vieira, R.S. (2000). Legislation and the use of Amazonian floodplains. Pages 505-534 in W.J. Junk, J.J. Ohly, M.T.F. Piedade, M.G.M. Soares, editors. *The central Amazon floodplain: actual use and options for a sustainable management*. Backhuys Publishers, Lieben.

Ward, J.V. & Stanford, JA. (1979). *The ecology of regulated streams*. Springer-Verlag, New York.

Ward, J.V. (1989). The four-dimensional nature of lotic ecosystems. *J. N. Am. Benthol. Soc.*, **8**, 2-8.

Welcomme, R.L. (1999). A review of a model for qualitative evaluation of exploitation levels in multi-species fisheries. *Fish. Manage. Ecol.*, **6**, 1-19.

Williams, M.R., Fisher, T.R. & Melack, J.M. (1997). Solute dynamics in soil water and groundwater in a central Amazon catchment undergoing deforestation. *Biogeochemistry*, **3**, 303-335.

Wishart, M. & Davies, B. (2003). Beyond catchment considerations in the conservation of lotic biodiversity. *Aquat. Conserv.*, **5**, 429-437.

