12-31-2018

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Recommended Citation

Muirhead, Charles A., "An Acoustic Monitoring Method for Assessing River Dolphin Presence and Changes in the Context of Anthropogenic Development" (2018). *Graduate Masters Theses*. 542.
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AN ACOUSTIC MONITORING METHOD FOR ASSESSING RIVER DOPHIN PRESENCE AND CHANGES IN THE CONTEXT OF ANTHROPOGENIC DEVELOPMENT

A Thesis Presented

by

CHARLES A. MUIRHEAD

Submitted to the Office of Graduate Studies,
University of Massachusetts Boston,
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

December 2018

Environmental Sciences Program

AN ACOUSTIC MONITORING METHOD FOR ASSESSING RIVER DOPHIN PRESENCE AND CHANGES IN THE CONTEXT OF ANTHROPOGENIC DEVELOPMENT

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ABSTRACT

AN ACOUSTIC MONITORING METHOD FOR ASSESSING RIVER DOPHIN PRESENCE AND CHANGES IN THE CONTEXT OF ANTHROPOGENIC DEVELOPMENT

December 2018

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Populations of river dolphins throughout Asia are in decline as a direct result of intensified anthropogenic activity along river systems. Water development projects, land use change, contamination, and intensified fishing practices are known factors contributing to the probable extinction of the Yangtze river dolphin (*Lipotes vexillifer*) and declining populations of the South Asian river dolphin (*Platanista gangetica spp.*), Irrawady dolphin (*Orcaella brevirostris*), and finless porpoise (*Neophocaena a. asiaeorientalis*). Although not yet as extensive, river system development in South America is following a similar path as that of Asia, with impacts on dolphin species likely to follow. Currently, the Amazon river dolphin (*Inia geoffrensis spp.*), Tucuxi (*Sotalia fluviatilis*), and Guiana dolphin (*Sotalia guianensis*) of South America remain listed as data deficient. There is limited information regarding potential changes in their population sizes, distributions, and habitat suitability.

Broad scale population monitoring is needed in order to prioritize, direct, and evaluate conservation efforts. To be effective, monitoring methods should be relatively easy to implement, standardized, reliable, cost effective, sustainable over large spacial and temporal scales, and provide timely turnaround of data results. This thesis describes and demonstrates one such method for monitoring shifts in river dolphin distribution relative to anthropogenic development. Shifts is distribution offer an early indication of degraded habitat suitability, which is a precursor to population decline.

I conducted a passive acoustic survey of dolphin presence in two areas of the Amazon River subject to different degrees of human use; the inland port city Iquitos and the Pacaya-Samiria National Reserve (PSNR). Surveys were based on acoustic monitoring of biosonar activity. Recorders were distributed at 17 sites along 61 linear km of river habitat for durations of 46 to 148 hr. Dolphin presence was 45% lower near the city than in the reserve. This pilot study demonstrates the efficacy of acoustic monitoring as a method for testing dolphin redistribution and/or decline hypotheses in the context of anthropogenic development. I make recommendations for applying passive acoustic surveys to basin-wide monitoring of river dolphin populations. The methods are readily scalable and are applicable to continuous future monitoring and status assessment of river dolphins in South America as well as in Asia.

ACKNOWLEDGEMENTS

This thesis is dedicated to Owen J. Muirhead for his help in initiating this project.

I extend my deepest thanks to…

The New England Aquarium
Scott Kraus for his advice and mentorship throughout my degree program

The Bioacoustics Research Program at Cornell University
Peter Wrege for providing recording equipment
Dean Hawthorn for assisting with spectrogram calibration
The Raven Team for providing an indispensable sound analysis program
and
Christopher Clark for many years of mentorship

My Friends and Field Guides in Perú
Louis Guimaraes Sandoval, Orlando Cueva, and Aladino for their invaluable field support and guidance, and without whom this project would not be possible.

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CHAPTER 1

INTRODUCTION

Biology of River Dolphins

The group of cetaceans, collectively referred to in this thesis as “river dolphins”, is composed of eight species sharing the defining characteristic that they all occupy river habitat and directly depend upon river systems for survival. This group however, is taxonomically diverse and extends beyond dolphins to include one species of porpoise. The term river *dolphin* therefore is not a perfect descriptor of the group’s taxonomical makeup. Here, emphasis should be placed on *river,* as the grouping is better defined by its ecological niche than shared phylogeny. Nonetheless, the term ‘river dolphin’ is in common usage throughout the literature and is retained here for convenience to describe both dolphins and porpoises that inhabit river systems.

The eight species that make up the river dolphin group include the 1) Yangtze river dolphin (*Lipotes vexilifer*)[1] and 2) Yangtze finless porpoise (*Neophocaena asiaeorientalis*) of China’s Yangtze River, 3) South Asian river dolphin (*Platanista gangetica*) of south Asia’s Indus, Ganges, and Brahmaputra river systems, 4) Irrawaddy dolphin (*Orcaella brevirostris*) which ranges from western Indonesia to India’s east

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[1] Although the Yangtze river dolphin is most likely extinct, it has not yet been classified as such by the IUCN. It is therefore retained in this thesis. Literature pertaining to its monitoring and conservation has been published as recently as 2007. The likely loss of this species relates closely to the conservation of all other river dolphin species discussed.

coast, 5) Guiana dolphin (*Sotalia guianensis*) of South America's east coast and Orinoco River, 6) Tucuxi (*Sotalia fluviatilis*) of South America's Amazon river system, 7) Amazon river dolphin (*Inia geoffrensis*) of South America's Amazon and Orinoco river systems, and 8) La Plata river dolphin (*Pontoporia blainvillei*) of South America's east coast and La Plata River estuary.

The extent to which these species depend on river habitat varies from the obligate river dolphins that exist only in freshwater river systems and appended lakes, to the facultative river dolphins that occupy both freshwater and marine environments. It should be noted that the often referenced 'true' river dolphins (i.e. Yangtze, South Asian, La Plata, and Amazon river dolphins) are a group defined by anatomical characteristics and the term should not be confused with 'obligate' river dolphin. True river dolphins have long rostrums, broad flippers, and unfused cervical vertebrae; adaptations specific to hunting and maneuvering among structurally complex, shallow environments characterized by highly variable currents. The La Plata river dolphin for example, even though considered a true river dolphin, is a facultative river dolphin found in estuaries, brackish coastal waters, and marine environments. The Tucuxi on the other hand, shares an almost identical morphology to its largely marine counterpart the Guiana dolphin and is not considered to be a true river dolphin, yet exists exclusively within the Amazon river system and is therefore an obligate river dolphin. While the distinction between obligate and facultative use of rivers has important implications relating to habitat connectivity, isolation of stocks, and species vulnerability, this thesis focuses primarily on those aspects associated with river habitat dependence common to all eight species.

The conservation status of marine stocks of facultative river dolphin species are noted but are not examined extensively.

All river dolphins share a highly developed capability for echolocation, an ideal adaptation for navigating and hunting in turbid river habitats. The extent of reliance on sound rather than light for interpreting their environment has led to diminished vision in most river dolphin species; and most notably the South Asian river dolphin, also referred to as the "Blind river dolphin". This loss of vision however has little effect on the capacity of river dolphins to hunt and navigate successfully. Indeed, they are top predators in their habitats, consuming a large array of fish and crustaceans, captured among structurally complex flooded forests, estuaries, and vegetated river banks using biosonar to "see" in the dark.[2]

As apex predators, river dolphins are dependent upon intact communities of lower trophic species and have been identified as indicators of ecosystem health (Gómez-Salazar et al., 2012b; Turvey et al., 2012). They are k-strategists, long lived and slow to reproduce, reaching sexual maturity at five to ten years of age and calving roughly every two to three years thereafter (depending on the species). Populations therefore require relatively long periods of time to recover from declines and depend upon the temporal continuity of undisturbed habitat and stable ecosystems.

All river dolphins have an affinity to shallow water environments. The degree to which this is the case varies among species from the Amazon river dolphin (which emigrates from rivers into flooded forests as shallow as 1.5m (McGuire & Alaiga-Rossel,

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[2,3] The nearly continuous emission of biosonar by river dolphins and their small size have important implications for monitoring the species, which are discussed in later sections.

2010) to the Fransiscana that primarily occupies coastal marine habitats ranging in depth from 5 to 35m (Danilewicz et al., 2009). The ability to master shallow water habitat is made possible in part by the species' relatively small sizes.[3] The largest of the species (the Amazon river dolphin) grows to an average 2.3 m, while the smallest (the Tucuxi) reaches an average length of only 1.5m. Their mastery of shallow water environments however, places the species in a vulnerable position. River dolphins are highly dependent upon water levels and river connectivity. Accessible habitat expands and contracts and is easily fragmented with only a few meters of change in water level. Moreover, an affinity to shallow water places river dolphins in close proximity to human activities that threaten their survival.

The specialization of river dolphins to riverine and estuarine habitats over past millennia has allowed the species to evade predation and access resources unavailable in marine environments. The move to this niche occurred independently on different continents and proved successful since the Middle Miocene (Hamilton et al., 2001). This use of rivers however now places the species in direct competition with humans. Presently, the world's rivers are undergoing rapid change as a result of human development which poses significant threats to river dolphin populations. Unlike the open ocean, rivers are restricted by their banks which channel all aspects of human use (e.g. shipping, fishing, and contamination) into high concentration. Under these circumstances, river dolphins must compete for resources in limited and confined environments which are of direct necessity to human settlement.

Anthropogenic Development of River Systems

Access to palatable, fresh water is imperative to human settlement. For purposes of irrigation, transportation, and resource exploitation, human settlement has centered on rivers and lakes since the dawn of civilization. At present, roughly 90% of the world population lives within 10km of a freshwater body and over 50% live within 3km (Kummu et al., 2011). Rivers are therefore conduits of both water and human civilization, and where interior wilderness awaits human settlement, rivers and lakes tend to be the first and most heavily settled part of the environment. This use of rivers and adjacent lands for settlement, transportation, fishing, agriculture, and industry by a growing human population has led to large-scale riverine habitat degradation across the globe (Nilsson & Berggren, 2000; Vörösmarty et al., 2010). Consequently, species that rely solely on river habitats face various levels of depletion and vulnerability to extinction.

Asia

Populations of river dolphins throughout Asia are in decline as a direct result of intensified anthropogenic activity along and within river systems. These population declines come in the wake of human population growth and industrial and agricultural development of China, India, Pakistan, and Bangladesh; the 1st, 2nd, 5th, and 8th most populous nations in the world respectively (U.N., 2017). The primary river systems of these countries, the Yangtze of China, the Ganges-Brahmaputru-Meghna of India and Bangladesh, and the Indus of Pakistan and India, have an estimated 400 million, 630 million, and 237 million people living within their respective watersheds (Frontier

Economics, 2016; Laghari et al., 2012; U.N., 2011); cumulatively 17% of the world population (Figure 1).

These three river systems are also those to which Asia's obligate river dolphins are endemic. These species (the likely extinct Yangtze river dolphin, the Yangtze finless porpoise, and the South Asian river dolphin) are currently classified as either Endangered or Critically Endangered by the International Union for Conservation of Nature (IUCN) (Reeves et al., 2000; Wang et al., 2013), while Asia's only facultative river dolphin, the Irrawaddy dolphin, is classified as Vulnerable (Reeves et al., 2008) with some freshwater populations likely to be extirpated in the near future (Beasley et al., 2013).

China, the range state of the Yangtze river dolphin and Yangtze finless porpoise has the largest human population of all countries containing river dolphins. It's economy, which is heavily based in manufacturing, grew from a GDP of 60billion USD in 1960 to 11trillion USD in 2016 (The World Bank, 2018). The Yangtze River, an important region for settlements and agriculture throughout China's history, has been used extensively since the mid 20th century (i.e. during China's rapid economic expansion) for development of hydroelectric power, industrial sites, and shipping from the country's interior to the East China Sea (Turvey, 2009). Heavy ship traffic, untreated industrial and human wastes, commercial fishing, and water diversion/extraction now characterize the entirety of the former range of the Yangtze river dolphin and Yangtze finless porpoise from the Three Gorges Region (near Yichang) to the East China Sea (Turvey, 2009). As of 2010, the Yangtze river basin was settled by 6% of the world population and supported 3% of global GDP (Frontier Economics, 2016).

In India and Bangladesh, the combined Ganges-Brahmaputra-Meghna (GBM) river basin supports an estimated 10% of the world population, including 40% of the world's impoverished population (Bernholz, 2004). Each day, roughly 1.3 billion liters of untreated human sewage enter the Ganges River alone (Singh & Singh, 2007). The economy in this region has traditionally and continues to be largely based in agriculture. But while traditional methods of farming revolved around floods brought by the monsoon and left water levels unregulated and rivers free flowing, modernization and mechanization have shifted agricultural practices toward designed irrigation and artificial regulation of stream flows through impoundments and canals, and toward dependence on synthetic fertilizers and pesticides. The basin is now heavily fragmented by dams and impoundments (Smith et al., 1998; Smith & Reeves, 1997) and carries a heavy load of agricultural pollutants (Kannan et al., 2005; Kannan et al., 1997; Singh & Singh, 2007; Smith et al., 1998). Like China, economic growth in India and Bangladesh has gone far beyond agriculture and now relies heavily on the manufacturing sector. The economic output of the Ganges river basin reached 690billion USD in 2010 (Frontier Economics, 2016). The combined GBM river basin is now heavily developed by industrial sites and urban centers, with much of the waste of these sites discharged into rivers untreated, leading to the accumulation of persistent organic pollutants and heavy metals throughout the river system (Kannan et al., 2005; Kannan et al., 1993; Kannan et al., 1997; Singh & Singh, 2007; Smith et al., 1998).

In the Indus river basin of Pakistan and India, the most notable impacts on river habitat stem from the heavy demands for water extraction to support agriculture, urbanization, and industrialization in an otherwise arid land. The Indus Basin Irrigation

System of Pakistan is the largest irrigation system in the world and extracts 75% of the Indus Rivers' water (Sharma et al., 2010). The system irrigates over 180,000km^2 of arid and semi-arid agricultural land (Braulik, 2006). The basin is therefore strewn with hydroelectric dams, impoundments, embankments, and canals, all of which alter flow regimes and disrupt the interconnectivity of water, sediments, nutrients, and organisms throughout the river system. As urbanization, industrialization, and agricultural intensification continue, the basin is becoming increasingly vulnerable to closure (i.e. when water commitments are not met and flows fall short of supporting ecosystem functions and services) (Laghari et al., 2012).

South America

River dolphins in South America have not yet exhibited severe declines such as those observed among Asiatic species. South American economies, human population densities, and river system development have lagged behind those of Asia, where the most severe habitat degradation has occurred (Figure 2). Nonetheless, economic growth and development throughout South America is occurring and driving the major river systems into a similar pattern of environmental degradation as that which has taken place throughout Asia (Castello et al., 2013; Castello & Macedo, 2016; Davidson et al., 2012; Soares-Filho et al., 2006).

Population growth and migration, and capital investments fueled by the global commodities market are driving urban growth in the Amazon where resource extraction occurs (Browder & Godfrey, 1997; Richards & VanWey, 2015). Cities are by nature, focal points of high ecological impact as they are characterized by large human populations and industry. With high resource consumption and high waste production, cities have profound impacts on their immediate and surrounding environments.

The largest cities of the Brazilian, Venezuelan, and Peruvian interiors (range states of South American river dolphins) are located along the main channels of the Amazon and Orinoco rivers. These rivers provide vital (and in some cases the only) shipping routes from South America's northern interior to the Atlantic Ocean and abroad. Urban conglomerations and cities (populations > 15,000) located on these rivers and within the ranges of South American river dolphins are listed in Table 1. In the Amazon of Brazil alone, the human population grew from 6 to 25 million between 1960 and 2010 (Davidson et al., 2012).

Much as the Amazon and Orinoco river systems are depended upon as vital shipping and transportation corridors for interior cities, they are also heavily and increasingly used for hydroelectric power. Finer and Jenkins (2012) documented 48 dams (>2 MW) in the Andean Amazon and plans for an additional 151 to be constructed (see Figure 1 in Finer and Jenkins, 2012) during the two decades following their publication; an increase of more than 300%. They concluded that 47% of newly constructed dams would have "high impact" on Andes-Amazon connectivity, which is a vital component of lowland Amazonian ecosystem health. Similarly, Castello and Macedo (2016) reported proliferation of hydroelectric projects throughout the southern Amazon from the Andes to eastern Brazil. They documented 154 dams (operating), 21 (under construction), and 277 (planned), (see Figure 2 in Castello and Macedo, 2016) all within the Amazon basin. The authors also note the numerous small-scale agricultural stream impoundments for irrigation, road construction, and power generation, which number in 10's of thousands located in smaller stream reaches of the basin which may have significant cumulative impacts on river ecosystems.

Growth of the global economy and increased demand for internationally traded commodities in the fossil fuel, mineral, and agricultural markets are also driving major environmental transformations of the Amazon basin (Davidson et al., 2012; Finer et al., 2008; Macedo, 2012; Richards & VanWey, 2015; Soares-Filho et al., 2006; Swenson et al., 2011). This demand extends beyond that of human population growth in the region. In the southern and eastern regions of the basin (i.e. the agricultural frontier) current growth rates of soy and beef production for export are predicted to result in the loss of 40% of Amazon forests by 2050 (Soares-Filho et al., 2006). In the western Amazon, approximately 688,000 km^2 of lowland habitat (i.e. directly overlapping river dolphin range) have been opened to multinational companies for oil and natural gas extraction (Finer et al., 2008). Exploration and drilling concessions already cover 72% and 65% of the Peruvian and Ecuadorian Amazon respectively and the extent of concessions is expected to increase (Finer et al., 2008).

Lowland river habitat of the western Amazon is also facing increasing exploitation by unregulated artisanal goldminers in response to market prices (Swenson et al., 2011). Both fossil fuel drilling and gold mining pose significant threats to the environment through the construction of new roads that penetrate virgin forests and promote settlement and subsequent deforestation/habitat fragmentation, and through chemical contamination from oil spills and leeched mercury.

Of greatest direct consequence to river dolphin populations are the growing commercial and artisanal fisheries of the Amazon basin (Trujillo et al., 2010). Due to the growth of cities, increased consumer demand, and construction of fish processing plants supporting a shift from local to regional/export markets, commercial fishing effort throughout the Amazon is intensifying, with increasing geographic coverage radiating from urban centers (Almeida et al., 2001; McGrath et al., 2004). In sampling seven major cities along the Amazon River, Almeida et al. (2004) found a positive linear relationship between urban population and the number of fish landings, and estimated there being over 48,000 fishers working the commercial fleet of the Brazilian Amazon, landing approximately 84,000 tons annually.

While the commercial fishery is geographically linked to urban centers (Petrere Jr., 1989), the rural artisanal fishery spreads throughout the entire Amazon basin. There are an estimated 112,000 fishers within Brazil's borders (Almeida et al., 2004). In the lower Amazon, fishing is cited as the most important source of income to households, with one person per family on average working in the fishery (Isaac, 2008). Total effort in the artisan fishery is increasing (Isaac, 2008) and poses a significant monitoring and management challenge because fishing effort is spread over vast and remote areas.

The geographic distribution of environmental impacts resulting from anthropogenic development is not homogenous throughout the Amazon basin. Fossil fuel and gold mining are occurring primarily in the western Amazon (Swenson et al., 2011), ranching and soy production permeates the south and south-east 'agricultural frontier' (Soares-Filho et al., 2006), damming coincides with areas of greater geographic relief in the far west (Finer & Jenkins, 2012), south, and east (Castello & Macedo, 2016), and fishing occurs throughout the mainstream, tributaries, and floodplain of the upper, central, and lower Amazon (Almeida et al., 2001; Alves et al., 2012; Iriarte &

Marmontel, 2013; Isaac, 2008; Loch et al., 2009; Zappes et al., 2013). Areas of exploitation are determined by resource availability, accessibility, and proximity to processing and export corridors (Richards & VanWey, 2015). As such, the spatial pattern of continued development of the Amazon basin will coincide to some extent with pre-existing infrastructure (i.e. river channels, roads, cities) leaving partially developed areas vulnerable to rapid expansion and delaying impacts to remote untouched areas (e.g. population growth pattern in Figure 2).

The developmental time lag between South America and Asia provides an opportunity to anticipate threats to river dolphins in South America, by evaluating how they were adversely affected in Asia by anthropogenic growth. Currently, the obligate river dolphins of South America (the Amazon river dolphin and Tucuxi) remain listed as Data Deficient by the IUCN (Reeves et al., 2011; Secchi, 2012). There is limited information regarding changes in their population sizes, distributions, and habitat suitability. Recent studies however, have begun to indicate that declines and redistributions of populations related to anthropogenic activity are occurring in specific locations of the Amazon and Orinoco river systems due to pressures described in the following section (Araújo & Wang, 2014; Dias et al., 2014; Gómez-Salazar et al., 2012b; Pavanato et al., 2016).

Effects of Anthropogenic Growth on River Dolphins

Water Development

Water development projects initiated for irrigation, flood control, transportation, and hydroelectric power result in large-scale fundamental changes to the habitats and ecosystems of rivers inhabited by dolphins (Dudgeon, 2000; Nilsson & Berggren, 2000; Smith & Reeves, 1997). Dams and irrigation barrages directly impact dolphins by blocking movement along stream channels, effectively fragmenting habitat and isolating meta-populations into small subgroups. Small isolated populations face reduced resilience to environmental and demographic disturbances, are at greater risk of inbreeding depression, and may be restricted from accessing preferred habitats and associated prey (Beasley et al., 2013; Braulik et al., 2014; Braulik 2006). These effects can reach hundreds of kilometers downstream of dams and barrages where artificially controlled flow regimes result in waters too shallow for dolphins to traverse, thereby causing additional fragmentation of habitat (Choudhary et al., 2012). Additional pressures arise through adverse effects on prey species in lower trophic levels. Alteration of stream biogeochemistry and inhibited fish migration cause declines in the prey species which river dolphins directly depend upon (Smith et al., 1998).

Fisheries Interactions

Mortality resulting from fisheries interactions is also having a pronounced impact. It is cited as one of the most critical anthropogenic pressures faced by river dolphins in Asia (Reeves et al., 2000) and is now arising as a leading documented cause of human-induced mortality in South American species (Dias et al., 2014; Iriarte & Marmontel, 2013; Loch et al., 2009; Mintzer et al., 2015; Mintzer et al., 2013; Zappes et al., 2013). Fisheries-dolphin interactions occur through accidental bycatch, targeted hunting, and prey depletion through overfishing. In some cases, vessel-dolphin collisions or propeller injuries occur as a result of dolphins' attraction to fish netted near vessels (Zappes et al., 2013).

Bycatch of river dolphins occurs primarily through seine net and floating or standing gillnet fishing practices (Mintzer et al., 2015), [although the Yangtze river dolphin fell victim largely to rolling hook and electrofishing practices (Turvey, 2009; Zhang et al., 2003)]. Dolphins either unknowingly collide with empty nets or actively seek entangled fish and in turn become entangled. This results in either death or injury, damaged fishing gear, or loss of fish catches. The latter has led to negative perceptions by fishers who consider river dolphins to be a competitor and liability (Mintzer et al., 2015), actively killing them as a result (Iriarte & Marmontel, 2013; Loch et al., 2009). In addition to targeted killing to protect fish catches, South American fishers actively hunt river dolphins to be used as bait in the catfish (*Calophysus macropterus*) fishery (Dias et al., 2014; Iriarte & Marmontel, 2014; Mintzer et al., 2013).

Contamination

Industrial waste and human sewage are affecting water quality in river dolphin habitats. Water and sediments in these areas carry elevated levels of persistent organic pollutants, heavy metals, and pathogenic bacteria. High concentrations of organic and heavy metal pollutants as well as fatal bacterial infections have been documented in Asiatic and South American river dolphins through biopsy and necropsy studies (Colborn & Smolen, 1996; Dove, 2009; Kannan, et al., 2005; Kannan et al., 1997; Kannan et al., 1993; Rosas & Lehti, 1996).

The extent to which populations are affected by contamination is difficult to quantify in situ. The myriad bacterial strains and synthetic chemicals that occur in polluted areas from industrial, agricultural, and human wastes affect dolphins in multiple ways, through multiple pathways, and may interact with one another as compound stressors (Colborn & Smolen, 1996). The effects may be acute and lethal, or they may be chronic and sublethal, leading to reduced fitness of populations with no single or easily identifiable source.

Through studies of similar species, organic pollutants and heavy metals are believed to negatively affect reproduction, early life stage development, and immune system function of river dolphins (Colborn & Smolen, 1996; Dove, 2009). As apex predators, dolphins are especially vulnerable to heavy metals and persistent organic pollutants that magnify up the food chain and accumulate in their bodies over time. Females transfer a portion of their contamination load to offspring during prenatal development and nursing, predisposing them to developmental affects and an increased accumulation load of their own which will be further increased over the course of their lives (Reeves et al., 2000).

Ultimately, while direct effects of contamination are difficult to quantify, the issue of these compound stressors working in unison to adversely impact river dolphin populations has been recognized in the literature and pollution is cited as a major threat to all river dolphin species (Reeves et al., 2000; Trujillo et al., 2010).

Climate Change

The effects of climate change on river dolphins are yet unknown. It is anticipated that precipitation patterns will change over time, increasing in some areas and decreasing in others with extreme weather events becoming more severe leading to flow regime changes in fresh water systems (Jiménez et al., 2014). The anthropogenic regulation of flow regimes and fragmentation of habitat through river development predisposes river dolphins to climate change threats, especially during dry season, low-water periods when habitat range is greatly restricted.

In highly developed and extensively fragmented river systems such as the Indus River, which flows primarily through arid lands, small isolated dolphin populations may be extirpated if sufficient water flow is not maintained (Choudhary et al., 2012; Reeves et al., 1991). Facing the potential of increased droughts however, the Indus river system will continue to be a vital resource to a growing human population and will likely be increasingly relied upon, primarily for irrigation. On the other end of the spectrum, in the várzea forest systems of South America, annual wet-season access to flooded forests will be restricted if precipitation declines. The threat of regional climate change in Amazonia leading to precipitation deficits (Malhi et al., 2009) is exacerbated by current deforestation and reduced evapotranspiration occurring throughout the Amazon River basin (Costa & Pires, 2010; D'Almeida et al., 2007). Annual flooding is fundamental to the health of várzea ecosystems. As such, these ecosystems are at great risk if flooding frequency, duration, or extent is significantly reduced (Hurd et al., 2016).

Generalized Habitat Degradation

Tracing the individual linkages between the many forms of habitat degradation and subsequent population effects, with the intent to quantify the impact of each stressor separately, presents a complex problem. While identifying stressors and their sources is necessary for the development and implementation of mitigation strategies, quantifying the effects of each stressor independently remains a challenge as multiple stressors from different sources augment one another and act cumulatively upon populations (National Academies of Sciences, 2017).

Generalized habitat degradation includes but is not limited to the aforementioned anthropogenic pressures. Land use change in watersheds, elevated noise, alterations in ecosystem and community structures, and changes in river biogeochemistry are among the many additional threats river dolphins face throughout their ranges (Nilsson & Berggren, 2000; Vörösmarty et al., 2010). These factors, among others, can be considered cumulatively as generalized habitat degradation and have been cited as factors contributing to the decline of river dolphin species (Huang et al., 2012; Reeves et al., 2000; Smith & Reeves, 2012; Trujillo et al., 2010)

Current Status of River Dolphin Species

This section provides a review of the current range and status of river dolphins throughout the world and highlights specific pressures that have contributed to the probable extinction of the Yangtze river dolphin, and declining populations of the South Asian river dolphin, La Plata river dolphin, Irrawady dolphin, and Yangtze finless porpoise. Literature is also reviewed for current threats to populations of the Amazon river dolphin, Tucuxi, and Giuana dolphin; species designated as ‘Data Deficient’ by the IUCN. In all of the reviewed species, documented declines resulted from growing human populations and associated development, modification, and resource exploitation along river systems.

Yangtze river dolphin (Lipotes vexillifer)

The Yangtze river dolphin, also referred to as the ‘Baiji’, was last documented in the wild in 2002 (Smith et al., 2017). While several unverified sightings have been reported since that time, the last known living individual, a specimen that survived in captivity for 22 years, died during the same year. This loss constituted the end of the verified existence of the Baiji, a species that originated approximately 20million years ago. In 2006, Turvey et al. (2007) surveyed the historical range of the Yangtze River for Baiji in in its entirety. No individuals were sighted. Although the IUCN notes that the Baiji may already be extinct, it currently remains classified as “Critically Endangered” (Smith et al., 2017).

The Baiji were an obligate river dolphin species that inhabited the middle and lower reaches of the Yangtze River, its tributaries, and appended lakes from its mouth in the East China Sea to the shallow rapids of the Three Gorges Region near present-day Yichang, China. A population also existed in the Qiantang River to the south. Their decline was the result of extensive development of the Yangtze and Qiantang watersheds (Smith et al., 2017; Turvey, 2009). Fisheries-dolphin interactions, hunting, dams and irrigation barrages, contamination, and generalized habitat degradation all contributed to the cumulative stress that drove this species to probable extinction (Reeves et al., 2000;

Smith et al., 2017; Turvey, 2009; Turvey et al., 2007; Zhang et al., 2003) Fisheries-dolphin interactions were noted as having the greatest observable impact on Baiji populations; including those arising from gillnets, rolling hooks, electrofishing, and dynamite fishing (Smith et al., 2017). Electrofishing in particular caused 40% of mortalities documented during the 1990s (Zhang et al., 2003).

Through the late 1970s and 1980s a number of published surveys were conducted throughout the Yangtze River in order to estimate the Baiji population size. Estimates ranged from 400 individuals in 1981 (Zhou, 1982) to less than 100 individuals in 1996 (Wang et al., 1998). Based on later surveys conducted in 1997, 1998, and 1999, Zhang et al. (2003) estimated a minimum population size of 13 individuals and annual population decrease of 10%. Finally, in 2006 Turvey et al. (2007) concluded that the species was most likely extinct after conducting their survey of the Baiji's entire historical range with no confirmed sightings.

During the latter stages of population decline, impact mitigation efforts to save the free-ranging population were recognized as necessary but inadequate, and a strategy of semi-captive breeding in an oxbow lake reserve was planned (Wang et al., 2006a; Wang et al., 2006b; Zhang et al., 1995). The effort to capture and relocate a viable stock of individuals however, was unsuccessful (Turvey, 2009).

Yangtze finless porpoise (Neophocaena asiaeorientalis ssp. asiaeorientalis)

The Yangtze finless porpoise, a subspecies of the Narrow-ridged finless porpoise, is comprised entirely of a freshwater population (Chen et al., 2010) living in the Yangtze River of China from upstream locations near Yichang to the river mouth at Shanghai

(Zhao et al., 2008). This range includes the two large inland lakes, Poyang and Dongting. The Yangtze finless porpoise was sympatric with the Yangtze river dolphin, and although the former has proved more resilient than the later, it is nonetheless in decline as a result of the same factors that led to the probable extinction of the Yangtze river dolphin (Turvey et al., 2013; Wang et al., 2013). The IUCN classifies the Yangtze finless porpoise as ‘Critically Endangered’ due a best estimated population of 1,800 individuals, down trending population size ($r = -6.4\% \text{ yr}^{-1}$), and diminishing habitat (Wang et al., 2013; Zhao et al., 2008). Zhao et al. (2008) estimate that the population declined by roughly half between the early 1990s and late 2000s. Based on current population trends, Mei et al. (2012) calculated an 86% probability that the Yangtze finless porpoise would go extinct within 100 years, while population modeling by Huang et al. (2017) predicted an average 37-49yr time to extinction.

During the 1990s, the attempts mentioned above to establish a breeding stock of Yangtze river dolphins in a semi-captive oxbow lake reserve coincided with efforts to do the same with the Yangtze finless porpoise. For the porpoise, efforts were successful and by 2005, a total of 27 individuals inhabited the lake with approximately two calves being born each year (Wang et al., 2005b). In 2005, a calf was born in complete captivity in the Baiji Dolphinarium at the Institute of Hydrology of the Chinese Academy of Sciences in Wuhan. Successful breeding and rearing programs raise the possibility for preserving the species and potentially increasing free-ranging stocks in the Yangtze River. For this to occur however, the Yangtze River ecosystem must be restored to a level of integrity capable of sustaining a viable finless porpoise population.

South Asian river dolphin (Platanista gangetica) subspecies

Indus river dolphin (Platanista gangetica ssp. minor)

The Indus river dolphin, also referred to as the ‘Bhulan’, is a subspecies of the South Asian river dolphin and an obligate river dolphin that inhabits the Indus River system in Pakistan and India (Braulik et al., 2014). The Bhulan is classified as “Endangered” by the IUCN (Braulik et al., 2012b). The species faces threats common to all river dolphins sharing habitats with growing human populations (Braulik et al., 2015; Reeves et al., 2000; Waqas et al., 2012). Most notable in the case of the Bhulan is the extensive fragmentation, depletion, and alteration of water flow throughout the Indus River resulting from large-scale development of river infrastructure. Because the Indus River flows through semiarid and arid environments, human populations settling along its banks have relied extensively on the Indus for irrigation of agricultural lands and for supplying water to cities and industry (Laghari et al., 2012; Sharma et al., 2010). Dams, canals, and irrigation barrages have effectively fragmented and reduced Bhulan habitat and split the metapopulation into isolated subpopulations, which are declining over time and some of which have been extirpated entirely (Braulik et al., 2014).

Historically, the Bhulan inhabited 3,500km of the Indus River system from its estuaries in the south to the upper reaches of its main tributaries (the Jhelum, Chenab, Ravi, and Sutlej rivers) in the north, where foothills of the Himalayas block further upstream movement (Braulik et al., 2015; Reeves et al., 1991). This range has since been fragmented into 17 sections by dams and irrigation barrages, ten of which are no longer occupied by dolphins, and the species now inhabits only 20% of its former range in the form of six[3] insular subpopulations amounting to a total population of ~1,450 individuals (Braulik et al., 2015). Three of these subpopulations, may be too small to sustain themselves, yet it is likely[4] that the largest is undergoing positive growth (Braulik et al., 2012).

In 1974, the Indus River section containing the largest subpopulation (that between the Guddu and Sukkur barrages in northern Sindh Province) was established as a protected reserve (the Indus Dolphin Reserve) to eliminate hunting (Waqas et al., 2012). The elimination of this threat most likely played a role in the subpopulation's growth noted above. However, the potential for one-way migration (i.e. downstream but not upstream) across barrages during high-water seasons may have contributed to increased numbers in that section of river, which occurs in the lower reaches of the Indus. Potential conservation actions discussed in the literature include the translocation of individuals from the Indus Dolphin Reserve population to sections with smaller subpopulations in order to reestablish genetic viability in those areas, and the creation of semi-natural reserves for captive breeding (as was attempted for the Yangtze river dolphin and has been accomplished for the Yangtze finless porpoise).

Ganges river dolphin (Platanista gangetica ssp. gangetica)

The Ganges river dolphin, also referred to as the 'Shushuk', is a subspecies of the South Asian river dolphin and an obligate river dolphin that inhabits the Karnaphuli-Sangu and Ganges-Brahmaputru-Meghna river systems of India and Bangladesh (Sinha

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[3] Presence in the 7th remaining section has not been confirmed (Braulik et al., 2015)

[4] Braulik et al., (2012) note statistical uncertainty among the varying studies and methodologies that were combined to determine the population trend.

& Kannan, 2014) with some few individuals (n<50) occupying the Karnali, Geruwa, Mohana, Bhada, Koshi and Narayani rivers system in Nepal (Jnawali et al., 2011). It has been suggested that Shushuks might move between lowland river systems via the Bay of Bengal when monsoon discharge increases fresh water plums at adjacent river mouths thereby creating low-salinity migratory corridors (Smith et al., 2001).

Similar to the Bhulan of Pakistan, the Shushuk faces threats associated with extensive water development projects throughout its range which have resulted in habitat deterioration, reduction, and fragmentation (Behera et al., 2013; Choudhary et al., 2012; Paudel et al., 2015; Smith et al., 1998). Indeed, the Ganges Basin together with the Indus Basin discussed above are inhabited by roughly one billion people, and as they are proximal to one another, they have been developed similarly, supporting the two largest irrigation systems in the world (Sharma et al., 2010). The Shushuk population therefore, much like the Bhulan, has been divided among a number of river stretches isolated by dams and irrigation barrages. The species has been extirpated from several sections of its former range and has declined overall from a population estimated between 4,000 and 5,000 during the 1980s to roughly 3,500 in 2014 (Sinha & Kannan, 2014). In Nepal (i.e. the upstream reaches of the Ganges basin) populations are expected to become regionally extinct by 2021 (Jnawali et al., 2011). Factors affecting the species decline include accidental entanglements in fishing gear, exposure to industrial, agricultural, and human wastes, declining prey abundance due to over fishing, restriction from preferred habitat, and inbreeding depression due to isolation (Behera et al., 2013; Choudhary et al., 2012; Reeves et al., 2000; Sinha & Kannan, 2014; Smith et al., 1998; Smith et al., 2012). Due to these threats as well as past and predicted population declines, the IUCN reclassified the Shushuk from ‘Vulnerable’ to ‘Endangered’ in 1996 (Smith et al., 2012).

Irrawaddy dolphin (Orcaella brevirostris)

The Irrawaddy dolphin is a facultative river dolphin that ranges from western Indonesia in the Makassar Strait through the Java Sea, Karmata Strait, Gulf of Thailand, and Andaman Sea, to the Indian coast of the Bay of Bengal (Minton et al., 2017). Occupancy of this range is not spatially continuous. The species occupies a conglomeration of coastal habitats, primarily in areas of brackish or fresh water, and a number of distinct subpopulations exist (Minton et al., 2017; Smith et al., 2007). Subpopulations that live entirely within freshwater systems have been identified in the Ayeyarwady, Mahakam, and Mekong rivers systems of Myanmar, Indonesia, Viet Nam, Lao PDR, and Cambodia and in the Chilika Lake of India and Songkhla Lake of Thailand (Beasley et al., 2013; Smith et al., 2007). While the species as a whole is classified as ‘Vulnerable’, four of the five freshwater subpopulations are classified as ‘Critically Endangered’ by the IUCN (Minton et al., 2017); not an unexpected state given the overlap of freshwater habitat and human populations.

Freshwater Irrawaddy dolphins face the same threats as obligate river dolphins where anthropogenic activity occurs along river systems (Minton et al., 2017; Smith et al., 2007). Habitat degradation due to urbanization and industrialization of river basins, mining, agriculture, and water development projects all contribute to current population declines. Fisheries-dolphin interactions, specifically gillnet entanglements, are reported to pose the greatest threat to their populations (Smith et al., 2007). In the Mekong and

Mahakam rivers for example, incidental mortality in gillnets was the cause of 87% and 66% of the respective documented yearly mean human-induced Irrawaddy dolphin deaths (Smith et al., 2007). Efforts to save these populations focus primarily on fisheries-dolphin interactions and have had some success in reducing mortality rates (Baird & Mounsouphom, 1994).

La Plata river dolphin (Pontoporia blainvillei)

The La Plata river dolphin is considered a ‘true river dolphin’, yet is found primarily in brackish and marine environments. Its range extends along the south Atlantic coast of Brazil, Uruguay, and Argentina where the species inhabits shallow, turbid nearshore waters and estuaries, most notably the La Plata River estuary (Danilewicz et al., 2009). Because of its lower dependency on confined freshwater river channels, the La Plata river dolphin has eluded some of the threats faced by other obligate river dolphin species (e.g. habitat fragmentation by dams and barrages). Its affinity to estuaries and shallow coastal waters however, makes it exceedingly vulnerable to fisheries-dolphin interactions, namely gillnet entanglements (Cappozzo et al., 2007). This is the primary threat to the species which has driven population declines resulting in its classification as ‘Vulnerable’ by the IUCN (Zerbini et al., 2017).

Guiana dolphin (Sotalia guianensis)

Like the La Plata river dolphin, the Guiana dolphin inhabits estuaries and shallow waters of near-shore marine habitats. Its range however, extends farther north from the south Atlantic Brazilian coast near Santa Catarina to the Caribbean coast of Honduras

(Fettuccia et al., 2009). The species also inhabits the Orinoco River of Venezuela (Aya et al., 2010). In marine habitats, the species is vulnerable to fishing gear entanglements (Monteiro-Neto et al., 2000; Zappes et al., 2013), while in the riverine habitat of the Orinoco the Guiana dolphin is placed in closer proximity to anthropogenic development and is susceptible to the same pressures faced by all other river dolphins (Trujillo et al., 2010). The Guiana dolphin is classified as 'Data Deficient' by the IUCN as there have been no range-wide abundance estimates for this species and no formal assessments of population trends have been made (Secchi, 2012).

Tucuxi (Sotalia fluviatilis)

The Tucuxi is an exclusively freshwater counterpart to the Guiana dolphin and inhabits the waters of the Amazon River basin of Brazil, Peru, Ecuador, and Columbia (Borobia et al., 1991; Fettuccia et al., 2009). The Tucuxi and Giana dolphin were previously considered subspecies (*Sotalia fluviatilis* ssp. *fluviatilis*) and (*Sotalia fluviatilis* ssp. *guianensis*) respectively, but have since been designated as two separate species (Caballero et al., 2006, 2007; Cunha et al., 2005). The Tucuxi is sympatric with the Amazon river dolphin throughout most of the Amazon basin (Gomez-Salazar et al., 2012a), but does not reach as far upstream in the river system's tributaries and does not disperse through the varzea as widely as the Amazon river dolphin during the flood season. Although Tucuxis utilize rising water levels to reach lakes and waterways otherwise inaccessible during the dry season, they display a preference for deep river channels (Faustino & Da Silva, 2006).

Due to the paucity of information regarding the overall population size and trend of Tucuxi, the IUCN has classified this species as ‘Data Deficient’ (Secchi, 2012). There are however a number of studies that document the negative impacts of fisheries-dolphin interactions (Dias et al., 2014; V. Iriarte & Marmontel, 2014; Iriarte & Marmontel, 2013; Loch et al., 2009) and threats of habitat degradation due to deforestation, boat traffic, mining, dams, and pollution (Trujillo et al., 2010).

Amazon river dolphin (Inia geoffrensis)

Three subspecies of the Amazon river dolphin or ‘Boto’ are currently recognized while a fourth has been proposed; (*I. g. geoffrensis*) of the Amazon river basin in Perú, Ecuador, Columbia, and Brazil, (*I. g. boliviensis*) of the Amazon river basin in Bolivia upstream of the Teotônio rapids bordering Brazil, (*I. g. humboldtiana*) of the Orinoco basin in Venezuela and Columbia, and the proposed (*I. g. araguaiaensis*) of the Araguaia–Tocantins watershed in Brazil (Best & Silva, 1993; Hrbek et al., 2014; Rice, 1998).

The Boto is classified as ‘Data Defficient’ by the IUCN (Reeves et al., 2011) due to insufficient data regarding overall trends in range and population size. However, threats common to all river dolphins sharing habitats with growing human populations have been identified for this species in all of its range states, including water development projects, pollution, boat traffic, fishing, and habitat degradation (Araújo & Wang, 2014; da Silva & Martin, 2000; IWC, 2000; Pavanato et al., 2016; Reeves et al., 2003; Trujillo et al., 2010). Mortality from fisheries interactions is of particular concern for this species throughout the literature (Alves et al., 2012; Dias et al., 2014; da Silva &

Best, 1996; Trujillo et al., 2010). Like other river dolphins, Botos are accidentally entangle in gillnets which are employed by fisheries throughout their range. This results in death or injury, and harassment or targeted killing by fishers who regard them as a direct competitor and nuisance species (Loch et al., 2009; Mintzer et al., 2015). Increasingly however, Boto are killed by fishers to be used as bait in the catfish or 'Mota' fishery which focuses on the scavenger fish (*Calophysus macropterus*) (Brum et al., 2015; Iriarte & Marmontel, 2014; Mintzer et al., 2013). The increase in use of Boto as bait is a result of the fishery's shift to Mota as a target species following the depletion of stocks of the more preferred 'Capaz' (*Pimelodus grosskopfii*) (Cunha et al., 2015). Dias et al. (2014) published the results of a 20-year study revealing population declines of Boto and Tucuxi within the Mamirauá Sustainable Development Reserve of Brazil and attributed this decline to fishery mortalities. In this area alone, an estimated 1500 dolphins are killed each year (Trujillo et al., 2010). Current efforts to mitigate impacts are having limited success due to the difficulty of monitoring fishers and enforcing laws throughout the expansive and remote geographic area covered by Amazonian fisheries.

Species Monitoring: Methods and Requirements

Ongoing, standardized monitoring of populations is a highly prioritized and integral component of management plans for river dolphins in Asia (Reeves et al., 2000) and South America (Trujillo et al., 2010). Indeed, species monitoring is a fundamental necessity to conservation. It serves four primary functions; 1) to establish baseline population states and identify change, 2) to identify and characterize the nature and magnitude of population threats, 3) to prioritize, and focus conservation actions to address population threats, and 4) to evaluate the effectiveness of conservation efforts and redirect/adapt those efforts as needed over time (Bowen & Depledge, 2006; Nichols & Williams, 2006).

Visual vs. Acoustic Monitoring

There are different advantages and disadvantages associated with visual and acoustic methods for monitoring dolphins. In many ways, the two complement one another; where one lacks efficacy the other excels. Visual surveys offer a relatively straightforward method for estimating the number of individuals in a population. In many cases, they also offer a means to characterize behavior, assess physical condition, and identify specific individuals. Such data are instrumental in determining habitat use, prevalence and causes of illness or injury, and movement patterns through the environment; key pieces of information in assessing conservation needs. The downsides to visual surveys are the relatively high cost and labor requirements, which limit their spatial and temporal scope. Visual detection of species is also highly dependent upon environmental conditions and is limited by weather, time of day, species' behavioral patterns, and surveyors' access to remote locations.

Passive acoustic surveys offer some remedy to the challenges of visual surveys. They are relatively cheaper when considered on a cost per spatiotemporal coverage basis. Once deployed, passive acoustic recorders operate autonomously and can be used to monitor large areas continuously, for extended periods of time. This is especially useful for monitoring remote locations, where maintaining visual observers is costly and logistically difficult. Moreover, acoustic surveys sample below the water's surface, and are thus unaffected by weather or daylight conditions that affect visibility during visual surveys.

Estimating the number of individuals in a population through acoustic surveys however, is not as straightforward as it is with visual surveys. It requires the ability to acoustically locate, track, and count individuals, or an accurate characterization of species call rates, transmission loss over distance, and probability of detection; all of which increase the complexity and cost of the survey. Acoustic surveys can successfully be used to determine density and abundance of populations, however the science requires further development before the methods become commonplace (Marques et al., 2013).

In short, the strength of visual surveys lies in abundance estimation, while acoustic surveys are ideal for characterizing presence and distribution. When both methods are used together, survey efficacy is greatly improved. Richman et al. (2014) and Kimura et al. (2009) combined visual and acoustic monitoring techniques during surveys of river dolphins and found that the addition of acoustic monitoring increased detection rates by 23% and 69% respectively. The utility of acoustic monitoring for increasing probability of detection was also demonstrated by Muirhead et al. (2014) through an acoustic survey that detected daily presence of marine cetaceans in Virginia's coastal waters three times as often as concurrent aerial surveys. While the acoustic components of these studies were shown to be more effective at detecting presence, visual surveys were necessary for estimating the number of individuals present.

In the marine realm, both visual and acoustic methods have been used extensively to monitor whale and dolphin populations to great success. However, the vast majority of riverine dolphin monitoring has been conducted through visual efforts alone with few incorporating an acoustic component. This may be due to a lack of funding facing researchers in developing countries (i.e. most range states of river dolphins) and a misconception that acoustic methods require state-of-the-art equipment and extensive expertise. While historically, acoustic methods have been cost-prohibitive to many researchers, advancements in recording equipment and analysis software have and continue to drive down both the cost and training necessary to conduct acoustic surveys (Sousa-Lima et al., 2013), making them a practical choice for monitoring-projects with tight funding constraints.

The limited use of acoustic methods in river systems may also be due to the fact that visual surveying is a much older methodology and has long been established by field researchers studying terrestrial and aquatic animals throughout the world. Present-day publications still reference visual sighting notes of river dolphins by naturalists and explorers dating back to the 1800s (see Braulik et al., 2014 and Turvey, 2009). Acoustic surveying of marine species on the other hand, was not employed until the later part of the 20th century and would not find common usage among marine mammal researchers until the late 1990s and early 2000s (Sousa-Lima et al., 2013). Its late-stage development and dissemination would therefor leave acoustic monitoring secondary to visual monitoring as a standard monitoring practice in many parts of the world for years to come.

Early development of passive[5] acoustic monitoring (PAM) networks was conducted in the mid-1900s by militaries for underwater surveillance of vessel movements through vast expanses of ocean. Once employed however, PAM not only detected the sounds of ships and submarines but also myriad sounds from fish and marine mammals. It became an obvious methodology for researchers hoping to determine the movements and distribution of whales and dolphins throughout the oceans, a daunting task that could not be completed by visual surveys alone. Throughout the 1980s, 1990s, and 2000s, the use of PAM to determine the range, seasonal movements, and behaviors of marine mammals over large temporal and spatial scales was refined and disseminated among marine researchers throughout the world.

That key value of monitoring very large and sometimes inaccessible areas for continuous extended periods of time, for animals that spend the majority of their lives below the surface and out of the view of observers, made PAM indispensable to the conservation of marine mammals. Monitoring projects have spanned months to years and covered 100's of square kilometers (Davis et al., 2017; Parijs et al., 2009), revealed expanded ranges (Mellinger et al., 2011), seasonal distribution patterns (Morano et al., 2012; Muirhead et al., 2018; Risch et al., 2014), exposure to anthropogenic threats (Hodge et al., 2015; Rice et al., 2014b; Salisbury et al., 2016), and population trends (Gerrodette et al., 2011) that could not be determined with visual surveys alone. With a higher probability of detecting focal species (Mellinger et al., 2007), PAM became

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[5] Passive Acoustic Monitoring involves passively listening for signals produced by the subject of interest (as opposed to Active Acoustic Monitoring which involves actively emitting a signal and monitoring for the echoes of that signal reflected off the subject of interest).

especially useful for surveying areas with low density populations such as infrequently used habitat corridors, areas at the limits of species' ranges, and the habitats of endangered species (Jaramillo-Legorreta et al., 2017; Rayment et al., 2011).

Riverine researchers however, have not yet employed the use of PAM to its full potential. Perhaps, in addition to the perceived costs and relatively short history of PAM, visual surveying appeared to be adequate for the confined space of river channels. Of the very few river dolphin surveys that have employed PAM to date, none have fully exploited the potential of acoustics for large-scale monitoring (although, Kimura et al., (2010) conducted a long-term PAM project spanning 466 days at a single location in the Yangtze River). PAM projects covering larger spatial scales than the Kimura study have been confined to the role of supplementing visual transect surveys (i.e. recording along a moving survey vessel to increase the probability of detection of the visual survey), thereby limiting the time recorded in any given area. There have been no concurrently long-term and wide-ranging studies of river dolphins using PAM to date (Table 2). This underutilization of acoustic monitoring leaves large gaps in our understanding of river dolphin ecology. As noted in Reeves et al., (2011) for example, the designated status of Boto and Tucuxi as 'Data Deficient' by the IUCN is justified in part by the fact that the current body of literature is based on study areas representing a small fraction of the species' overall ranges and lacks information on temporal trends.

The nature of basin-wide environmental change calls for a broad-scale understanding of river dolphin response in abundance and distribution. Smith and Reeves (2012) note that the vulnerability of river dolphins does not become apparent until studied as sufficient scale. The Amazon and Orinoco River basins cover approximately

1million km^2 and 6million km^2 respectively (Milliman & Meade, 1983), and river dolphins inhabit a majority of the main river channels in these basins (Trujillo et al., 2010). While monitoring these areas in their entirety is not practical, extending monitoring coverage across key areas, beyond which can be accomplished through visual surveying, will provide important insights to the responses of dolphins to the ecological changes they face (Gomez-Salazar et al., 2012; Parijs et al., 2009).

River dolphins are mobile, opportunistic predators. Their use and occupancy of habitats changes dynamically with factors such as prey availability, precipitation, breeding status, and habitat quality. A high-resolution understanding of this time-varying distribution is hard to achieve through visual surveys alone, as it requires continuous monitoring rather than temporally isolated surveys. Continuous acoustic monitoring can however achieve this and provide information on varying habitat preference, population behavior, and response to environmental change. If baseline distribution patterns are characterized, changes and aberrations can be used to identify areas where potential stressors and or habitat alterations have occurred (e.g. reduced prey abundance, deteriorated habitat, harassment, loss of corridors etc.). Early identification of such areas (i.e. before a population decline) is critical to develop effective mitigation and management strategies. Acoustic monitoring provides a means to greatly expand monitoring coverage to better characterize baseline states and changes in distribution throughout species' ranges.

While anticipating river dolphin decline in South America under the stresses of anthropogenic growth, there is a need for large-scale (i.e. river system wide) population monitoring in order to prioritize, direct, and evaluate conservation efforts. For such monitoring to be feasible and effective, it must be relatively easy to implement, standardized, reliable, low-cost, sustainable over large spacial and temporal scales, and provide timely turnaround of data results. The goal of this thesis is to describe and demonstrate a PAM method with these qualifications for monitoring the effects of anthropogenic pressure on river dolphins. Shifts in dolphin presence relative to anthropogenic activity offer an early indication of degraded habitat suitability; a precursor to population decline. Here, emphasis is placed on monitoring for early indicators of change, with the ability to scale efforts over large areas for extended uninterrupted periods of time in an efficient manner. The method presented in the following section requires limited expertise and relies on low-cost equipment, key factors in its dissemination to researchers interested in the conservation of river dolphins.

CHAPTER 2

PROOF OF CONCEPT STUDY

PASSIVE ACOUSTIC MONITORING OF RIVER DOLPHIN (*Inia g. geoffrensis* & *Sotalia fluviatilis*) PRESENCE; A COMPARISON BETWEEN WATERS NEAR THE CITY OF IQUITOS AND WITHIN THE PACAYA-SAMIRIA NATIONAL RESERVE

Introduction

The intention of this field study is to demonstrate a cost-effective, and logistically feasible survey method that can be scaled to large areas over long periods of time in order to monitor early shifts in Boto and Tucuxi distribution relative to anthropogenic change throughout the Amazon and Orinoco River systems. I conducted a passive acoustic survey of dolphin presence in two areas of the Amazon watershed of northern Peru (Figure 3). One area, the inland port city Iquitos, is characterized by a high degree of anthropogenic presence (e.g. vessel traffic, standing gillnets, and urban waste) while the other, the Pacaya-Samiria National Reserve (PSNR), is characterized by a low degree of anthropogenic presence.

I chose Iquitos and the PSNR as study areas because they are representative of urban and rural river habitats of the Amazon Basin. In general terms, Iquitos is an area of pronounced human activity and development while the PSNR is a pristine area where a baseline reference of dolphin populations in their natural state can be obtained. The study areas share similar physical geography and are located in the same meso-level ecosystem. Moreover, there are no physical obstructions to dolphin movement between Iquitos and the PSNR. With human population being the primary difference between study areas, Iquitos and the PSNR provide a simple case study for acoustically monitoring river dolphin presence in the context of human development of the Amazon River.

The City of Iquitos and its contiguous metropolitan districts Belén, Punchana, and San Juan Bautista, referred to here simply as Iquitos, comprise an urbanized area of approximately 360km^2 with a human population of more than 471,000 (INEI 2009). The city is located on the main channel of the Amazon River and is bordered by the Nanay River to the north-west, and Itaya River to the south-east (Figure 7a). It is an important port for shipping and transportation between South America's interior and the Atlantic Ocean, and a major center of commerce for the petroleum, natural gas, timber, fishing, and tourism industries.

Conversely, the PSNR is a protected area of 20,800km^2 with a human population of 24,000 dispersed among 92 separate villages (SERNANP, 2009). It is bordered by the Marañón River to the north and Ucayali River - Puinahua Canal to the south, which join to form the Amazon River. The economy is comprised of limited floodplain agriculture, subsistence hunting, fishing, and forest product gathering (Barham et al., 1999; Coomes et al., 2004), with ecotourism as a growing contributor to local livelihoods (Monteferri & Carpio, 2007).

Both Iquitos and the PSNR lie within the ranges of Boto and Tucuxi (Gomez-Salazar et al., 2012; McGuire & Alaiga-Rossel, 2010; Trujillo et al., 2010). Boto are an obligate river dolphin species, are included in the 'true' river dolphin group, and are characterized by their narrow, elongated jaws, broad pectoral fins, and unfused cervical vertebrae; adaptations that allow for maneuvering among obstacles in shallow water and capturing prey in confined spaces. During the wet season, they may disperse among flooded forests, small tributaries, and otherwise isolated lakes depending on calving status and/or prey availability (Martin & da Silva, 2004). They return to main channels in the dry season as receding water levels necessitate. Tucuxi, only recently identified as a separate species from their marine counterparts *S. guianensis* (Caballero et al., 2007), are also obligate river dolphins. They are found primarily in mainstream channels and lakes of sufficient year-round volume. Not considered 'true' river dolphins, they are characterized by shorter jaws, a streamlined conformation, and fused cervical vertebrae; adaptations more similar to those seen in oceanic delphinids for speed rather than obstacle negotiation. While Boto are known to travel farther from mainstream channels than Tucuxi (Martin et al., 2004), the two species are sympatric in the waters surveyed in this study (Gomez-Salazar et al., 2012). Moreover, this acoustic survey was conducted during the dry, low water season when Boto retreat from peripheral areas to reside in main channels alongside Tucuxi where prey density is high.

Methods

The Iquitos study area consisted of nine survey sites stationed within the main waterways surrounding the city (Figure 7a). Site Iquitos-1 (I-1) was located at the confluence of the Nanay and Amazon Rivers, while sites I-2 through I-4 were located upstream in the Nanay River at the confluences of smaller tributaries. Site I-5 was located at the confluence of the Itaya and Amazon Rivers. During the survey, the recorder at this site was accidentally retrieved by a local gillnet fisherman. We subsequently relocated the recorder to Site I-6 where the Itaya River mainstream broadens to a lake before passing the Iquitos port terminal and entering the Amazon. Sites I-7 through I-9 were located upstream in the Itaya River at the confluences of smaller tributaries. Stream depth at the recording sites ranged from 3.5m to 7.0m and varied by <0.5m during the survey. Stream width ranged from 60m to 339m. Spacing between adjacent recording sites ranged from 1.9km to 7.7km. We deployed recorders on 20 August 2014 and retrieved them on 25 August 2014, yielding recordings that ranged in length from 46h 12m to 119hr 20m. The recorder at Site I-5 was relocated to Site I-6 on 23 August (Table 3).

The PSNR study area consisted of eight survey sites in waterways comparable to the Nanay and Itaya Rivers in width and depth. These sites were clustered within the northeast region of the reserve, 170km upstream from Iquitos (Figures 3 and 8a). Site Pacaya-Samiria-1 (PS-1) was located at the confluence of the Yanayacu-Pucate River and Marañón River. Site PS-2 was located at the confluence of the Yanayacu and Pucate Rivers. Sites PS-3 through PS-5 were located upstream in the Pucate River at the confluences of smaller tributaries. Sites PS-6 and PS-8 were located upstream in the Yanayacu River at the confluences of smaller tributaries, while site PS-7 was located between sites PS-6 and PS-8 but not near a confluence. Stream depth at the recording sites ranged from 3.3m to 8.0m and varied by <0.5m during the survey. Stream width ranged from 61m to 240m. Spacing between adjacent recording sites ranged from 3.4km to 6.0km. We deployed recorders on 27, 28, 29, and 31 August 2014 and retrieved them on 2 and 3 September 2014, yielding recordings that ranged in length from 72h 37m to 148h 2m (Table 3).

We placed recorders at river confluences in order to increase the probability of dolphin detection. The affinity of river dolphins to confluences is well documented by a number of studies showing higher density and abundance in such areas (Araújo & Da Silva, 2014; Braulik et al., 2012a; Gomez-Salazar et al., 2012a; Kreb & Budiono, 2005; Martin et al., 2004; Smith et al., 2009; Vidal et al., 1997). Spacing between recorders in the Iquitos study area was largely dependent upon confluence location, but was also intended to provide evenly spaced coverage surrounding the city with a limited (n=8) number of recorders. Recording sites in the PSNR study area were intended to match those near Iquitos in spacing, proximity to tributaries, and in river depth and width.

We conducted acoustic surveys using shore-based Song Meter SM2 digital recording units (Wildlife Acoustics, Inc.) attached to HTI-96-min hydrophones (High Tech, Inc.) via 20m cables. The HTI-96-min hydrophones had a sensitivity of -164.3dB (re: 1V/μPa) and flat frequency response (± 2.2dB) from 2Hz to 30kHz. Sensitivity decreased to -184dB and varied by ± 3.7dB between 30kHz and 48kHz (Figure 4). We set all units to record at a sample rate of 96kHz, gain of 24dB, and bit depth of 16. At these settings, the complete system had a sensitivity of -140.3dB (± 2.2dB from 2Hz-30kHz) and -160.0dB (± 3.7dB from 30-48kHz), dynamic range of 96dB, and Nyquist frequency of 48kHz. Although the HTI-96-min hydrophone frequency response is not flat above 30kHz, all units shared the same frequency response curve. Therefore, no sensitivity bias was introduced between recording sites.

I analyzed the recordings visually and aurally using Raven Pro v1.5 (Bioacoustics (Research Program, 2015). Spectrograms were set to span 16-48kHz with a 1024-point FFT, Hann window, and 50% overlap (frequency resolution of 93.8 Hz, time resolution of 5.3 ms). The full duration of each recording was divided into 1min time slices. Each time slice was then assessed for the presence of echolocation signals (hereafter referred to as biosonar) characteristic of Boto and Tucuxi (Kamminga et al., 1993) (Figure 5). I assigned a binary value of 1 (if present) or 0 (if absent) without differentiating between the two species. I then plotted the results using time series graphs displaying the number of 1min samples during each hour of recording that contained biosonar at each survey site (Figures 7b and 8b). I also calculated the percent of 1min samples that contained biosonar during the full recording period at each survey site (Table 3, column 9).

I conducted a nonparametric Wilcoxon rank-sum test using MATLAB 2016a statistical toolbox (MathWorks Inc., 2016) to compare presence between the Iquitos and PSNR study areas. The Wilcoxon rank-sum test is an appropriate alternative to the Independent Samples t-Test when analyzing data sets that are small in sample size and lack normality in their distribution (Larsen & Marx, 2006). The comparison was based on the percent of 1min samples that contained biosonar during the full recording period at each of the 17 survey sites (Table 3, column 9). Using these same data points, I investigated the relationship between presence and river depth, river width, and upstream distance from the Marañon and Amazon main river channels. This was done through simple linear regression analyses. River measurement values are displayed in Table 3.

Because ambient noise from rain, boat motors, and non-target species varies across time and space, potential detection bias due to acoustic masking (Clark et al., 2009) of biosonar may have been introduced between survey areas (Figure 6). To address this, I determined the equivalent continuous sound level - Leq (dB re 1µPa) within the 16kHz to 48kHz frequency band for each 1min sample using Raven Pro v1.5 signal calibration and waveform measurement tools (*Raven Pro 1.4 User's Manual*, 2010). I then categorized all 1min samples by Leq in 1dB increments and compared biosonar detections between Iquitos and the PSNR at each Leq value. I plotted the results for both survey areas in a histogram displaying the percent of 1min samples that contained biosonar at each Leq value (Figure 11). I used the same method to plot data pertaining only to individual sites I-5 and PS-9 (Figure 12) in order to demonstrate the negative relationship between ambient noise and biosonar detection; a trend that is obscured when plotting data cumulatively from sites with markedly different levels of dolphin presence.

Results

There was great heterogeneity in dolphin presence across recording sites. Presence ranged from 0% (upstream in the Itaya River proximal to Iquitos) to 99% (at the confluence of the Marañon River in the PSNR). In both the Iquitos and PSNR study areas, the confluences of the largest river channels were most heavily occupied by dolphins, while in all four tributaries studied (Nanay, Itaya, Yanayacu, and Pucate), presence was lower at upstream recording sites than at their downstream outlets.

Biosonar detections in the Iquitos survey area occurred only at sites located in the Amazon and Nanay Rivers (Figure 7a,b). No biosonar was detected in the Itaya River upstream from its confluence with the Amazon River (Site I-5). Biosonar detection rate decreased significantly (from 57% to 2%) in the Nanay River upstream from its confluence with the Amazon River (Site I-1).

Biosonar was detected at all recording sites along the Yanayacu, Pucate, and Marañón rivers of the PSNR survey area (Figure 8a,b). Highest detection rates occurred at the Marañón River confluence (Site PS-1, 99%) and where the Yanayacu and Pucate rivers merge to create the Yanayacu-Pucate River (Site PS-2, 93%). Detection rate decreased upstream from these sites (to as low as 29%), but the decrease was not as extensive as that observed in the Nanay River of Iquitos.

Overall, dolphin presence was greater in the PSNR than near Iquitos. Recorders detected biosonar in 40,952 (69%) of the cumulative 59,387 1min samples recorded in the PSNR survey area and 7,693 (17%) of the cumulative 45,687 1min samples recorded in the Iquitos survey area. When excluding recording sites in the Itaya River upstream of site I-5 where no detections occurred, cumulative presence in the Iquitos survey area was 7,693 (24%) of 31,670 samples.

The difference in presence between the Iquitos and PSNR study areas was statistically significant (Wilcoxon rank-sum test; $p = 0.0073$, $\alpha = 0.05$) (Figure 9). The negative correlation between presence and upstream distance from river main channels was linear and statistically significant in the PSNR study area ($\beta_1 = -0.03$ Presence km^{-1}, 95% CI = [-0.06 -0.00], $p = 0.036$) (Figure 10a). In the Iquitos study area, the correlation was nonlinear with presence dropping off precipitously as distance from the Amazon main channel increased (Figure 10b). No correlation was found between presence and river depth or river width in either study area (Figure 10 c,d,e,f).

Leq of 1min samples ranged from 75 to 110dB at the PSNR recording sites and from 75 to 114dB at the Iquitos recording sites. This resulted in 36 Leq levels at which I compared biosonar presence between the two survey areas. The percent of 1min samples containing biosonar detections was higher in the PSNR at all of the Leq levels measured except for 110dB and 106dB (Figure 11). In looking at individual sites I-5 and PS-9, biosonar detection was negatively related to ambient noise level. The percent of 1min samples containing biosonar detections was higher at site PS-9 at all of the Leq levels measured except for 111dB (Figure 12).

Discussion

Findings

Overall, dolphin presence was lower in the Iquitos study area than in the PSNR study area. Although these results were statistically significant, the duration of this pilot study was limited by available travel time for the project and was therefore too short to make general conclusions about the effect of Iquitos on dolphin presence. Longer recordings are needed to examine seasonality of presence and to compare change over time in each study area. This study does however demonstrate the efficacy of acoustic monitoring as a method for testing dolphin redistribution and/or decline hypotheses in the context of human development. One of the many advantages of acoustic monitoring is that studies can easily be scaled up with limited additional effort. In this case, leaving recorders deployed for a longer duration would effectively increase the temporal scale of the project (with little or no additional field work) allowing for an examination of relative change over time and increasing the statistical strength of the results.

The negative relationship between anthropogenic activity and dolphin presence has been observed through visual surveys of river dolphins in other areas of the Amazon and Orinoco river basins (Dias et al., 2014; Gómez-Salazar et al., 2012b). And though this study was conducted on a limited scale which greatly reduced its statistical power, the results nonetheless agree with previous studies and should be considered in the context of known effects of anthropogenic presence on dolphin populations discussed in Chapter 1.

The complete absence of biosonar upstream in the Itaya River coincided with the densest human presence among study sites. The majority (6.5 of 9.5km) of the west bank of the Itaya River, from its mouth at site I-5 to 1.9km upstream of site I-7, is comprised of urban infrastructure including the Iquitos Port Terminal, lumber mills, and the densely populated district of Belén. This section of river also experiences the most boat traffic of all recording sites in the study. High ambient noise levels in this area may have prevented the detection of infrequent biosonar signals if they occurred. Yet the comparison of this section of river to others at equal noise levels reveals a relative minimum in dolphin presence along the Itaya River. Moreover, there was an absence of biosonar at sites farther upstream in the Itaya River (i.e. I-8 and I-9) where noise levels were reduced and probability of detection was not diminished.

It is unclear however, if the physical geography of the lake situated between sites I-5 and I-6 affected the presence of dolphins upstream of site I-5. The use of lakes by Boto and Tucuxi has been documented extensively. Mcguire and Aliaga-Rossel (2010) documented both species in lakes as shallow as 1.5m in the PSNR. During the study period, the center-of-channel depths of the lake inlet (site I-6) and lake outlet (site I-5) were 4.5m and 5.7m respectively. Stream depth and width upstream of the lake at sites I-7, I-8, and I-9 were similar to those in the PSNR at sites PS-6, PS-7, and PS-8, where dolphins were present.

Dolphins were in fact present upstream in the Nanay River on the north side of Iquitos, although their occurrence was infrequent and dispersed. The detection of dolphins occupying this river in particular demonstrates the value of continuous acoustic monitoring in areas with transient and/or low-density populations. During daylight hours between sunrise (06:10:00 PET) and sunset (18:10:00 PET), dolphin presence at sites I-2, I-3, and I-4, amounted to 4%, 1%, and 1% respectively. It would not be unlikely for a daytime visual survey (conducted at boat speeds set to outpace dolphins in order prevent double counts) to entirely miss the presence of dolphins in this area.

Dolphin presence decreased with upstream distance from main river channels in both study areas. This decrease however, was more pronounced in the Iquitos study area (Figure 10 a,b) indicating a diminished preference for habitat in tributaries bordering the city. Dolphins appear to have approached Iquitos via the Amazon main stream but rarely ventured nearer than the Nanay and Itaya confluences (Figure 7 a,b). Stream width and depth at the survey sites were not significantly correlated with dolphin presence. Based on documented habitat preferences of the species, I expect that trends would arise if the survey sites covered a broader range of width and depth values.

When comparing study areas at equal ambient noise levels, presence was greater in the PSNR than in Iquitos. This demonstrates that the reduced presence observed in Iquitos was not due simply to masking of biosonar or behavioral change in response to anthropogenic noise or varying levels of rain. The negative relationship between ambient noise and biosonar detection is clearly visible when looking at individual recording sites (Figure 12). This trend is obscured however, when plotting data for multiple sites cumulatively (Figure 11) because some sites (i.e. those farther from the larger main river channels) were inherently quieter, yet frequented by dolphins less often than those sites nearer main channels where both dolphins and boat traffic occurred most. Combining data across these conditions leads to a leveling out of the negative relationship that is apparent at each site individually.

The comparison of biosonar detection between study areas at equal ambient noise levels was included in the methods to eliminate potential bias stemming from uneven variations of noise throughout the surveys. Acoustic masking is a known factor contributing to the negative relationship between noise and biosonar detection rate. However, unknown factors such as changes in biosonar emission rate and movement patterns in response to elevated noise levels may also have played a role. Further research is needed to determine if and to what extent these potential factors are occurring.

Optimizing Recording Parameters

In this study, I set recorders to a sample rate of 96 kHz for an effective[6] recording frequency of 48 kHz. This was the highest sample rate capability of the SM2 recorders, and was sufficient to capture the lower frequency component of Boto and Tucuxi biosonar. However, the peak frequencies (i.e. the frequencies of maximum power) of biosonar from Boto and Tucuxi fall within the 47 to 125 kHz and 47 to 137 kHz bandwidths respectively (Yamamoto et al., 2015). Note in Figures 5 and 6, the biosonar signals are more visible at higher frequencies and less at lower ones, diminishing into background noise at the bottom of the spectrograms. These signals would be more visible still at the dolphins' peak frequencies above 48 kHz. Ideally, recorders in this study would have sample rates high enough to capture the frequencies at which biosonar has

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[6] In digital recording, the acquired recordings have a maximum frequency that is one half the sample rate of a recorder. This is called the Nyquist Frequency, and is the highest frequency at which aliasing (i.e. false signal artifacts) will not occur in the sound.

the greatest power. This would increase the distance over which dolphins could be detected.

The advantage of recording at higher sample rates is two-fold. While dolphin biosonar is has greater power at higher frequencies, noise from passing boats has less at higher frequencies. Note in Figure 6 the dark band of boat noise is concentrated in the lower half of the spectrogram. Thus, at higher frequencies biosonar becomes distinctly visible while boat noise is diminished, greatly improving the signal to noise ratio and increasing the probability of dolphin detection and distance over which they can be detected.

However, recording at higher sample rates draws more power and requires more storage space. This necessarily reduces the time that the recorders can operate autonomously in the field (as they require more frequent battery and data-drive changes). The tradeoff between recorder deployment time and sample rate should be considered carefully when designing an acoustic monitoring study. If the recorders are readily accessible and attended regularly enough to keep up with data storage and power demands, then taking advantage of a high sample rate will provide biosonar recordings with the highest signal to noise ratio. If however, the advantage of acoustic monitoring to cover large (sometimes remote) areas for long periods of time is to be fully exploited, then recorders may need to be left in the field unattended for as long as possible. In such a case, a sample rate of 96 kHz (effective recording frequency of 48kHz) is sufficient to capture Boto and Tucuxi biosonar, as demonstrated here.

Ongoing developments in technology continue to improve recording systems through higher capacity data storage, reduced power consumption, programmable recording schedules, and higher efficiency battery and/or solar power configurations. With these improvements, the frequency/duration tradeoff is becoming less and less of a limiting factor in study design. The SM4 For example, the latest Song Meter (SM4) to be released since the SM2, can now record continuously at a sample rate of 96 kHz for 60 days using an external 12V battery. Here, the limiting factor is data storage capacity which relies on two 512GB SD cards. If for example, the recorder is programmed to record every other minute rather than continuously, deployment time can be extended to 120days. Or, if higher capacity SD cards are used, the deployment time can be extended accordingly.

The detection range of recorders was not tested in this study. Previous studies have detected Ganges river dolphins and Yangtze finless porpoises in river environments at distances of 80m (Sasaki-Yamamoto et al., 2013), 275m (Akamatsu et al., 2001), 300m (Akamatsu et al., 2008), and 478m (Li et al., 2009). Detection distance is affected by biosonar source level, background noise level, recording frequency, and hydrophone sensitivity. River depth, substrate, and meanders also influence sound propagation and can therefore have an impact on detection distance. Although the exact detection range in this study is unknown, factors affecting detection range were controlled at all recording sites. All recorders had the same gain setting, hydrophone sensitivity, and recording frequency, and were deployed in locations of similar river depth. Background noise was accounted for as described above.

I chose the location and spacing between survey sites in the Iquitos and PSNR study areas to maximize the probability of detecting dolphins. River dolphins prefer stream confluences, where prey density is high and where they can conserve energy by avoiding swift downstream currents in the confluences eddies. Confluences were relatively evenly spaced around the City of Iquitos and given only eight recorders to work with, Sites I-1 through I-9 were the best suited to encircle Iquitos. In the PSNR study area, confluence sites of similar spacing, depth, and width were chosen for comparative purposes.

This pilot study demonstrates the feasibility of passive acoustic monitoring in river environments to investigate the distribution of river dolphins relative to anthropogenic presence. While the location and the duration of surveys in future studies will vary according to research objectives, the methods presented here illustrate in general terms the fundamentals of passive acoustic monitoring and key considerations for increasing the probability of dolphin detection. These methods are readily scalable and are applicable to continuous future monitoring and status assessment of river dolphins in South America as well as in Asia.

CHAPTER 3

APPLICATION OF ACOUSTIC MONITORING TO RIVER DOLPHIN CONSERVATION

Continuous monitoring is necessary in adaptive management in order to assess the effectiveness of mitigation efforts as the state of river dolphin populations and anthropogenic stressors change. It serves to 1) establish baseline population statuses and identify change, 2) identify and characterize the nature and magnitude of population threats, 3) prioritize, and focus conservation actions in order to address observed population threats, and 4) evaluate the effectiveness of conservation efforts and redirect/adapt those efforts as needed over time. Population characteristics that are commonly monitored to inform mitigation and conservation efforts include abundance, distribution, and habitat use. Changes in distribution and habitat use specifically, may provide an early indication of habitat degradation; a causal factor in abundance declines of river dolphins throughout Asia.

Acoustic surveys provide an efficient method for broad-scale continuous monitoring of changes in distribution and habitat use in response to anthropogenic pressures. Dolphins use biosonar almost continuously in river habitats, which are characterized by high turbidity and structural complexity. Acoustic detection of biosonar presence therefore provides an ideal metric for river dolphin occupancy. However, much like variable visibility during visual surveys can affect probability of detection, so too does variable ambient noise level affect acoustic detection. The normalization of survey results can be accomplished by analyzing recording samples that share the same ambient noise levels (i.e. masking potentials) as discussed in chapter 2.

Although the scope of fieldwork in the Iquitos/PSNR case study was spatiotemporally limited, the methods described herein are readily scalable. Recording units can operate continuously for months without servicing or maintenance and advancements in hardware technology (e.g. battery power and data storage capacity) continue to improve the duration and sampling frequency at which recorders can run. This reduces labor requirements while increasing the range and scope of coverage that are feasible through acoustic surveys. Moreover, recorder operation is easily standardized and made consistent over time and space to address the sampling effort issues commonly faced in cross-sectional and longitudinal meta-analyses of visual surveys. Lastly, shore-based recording units are comprised of simple, compact, lightweight hardware, making them low in cost yet reliable. Their operation is relatively straightforward and they are easily transported and set up. These characteristics are ideal for implementing large-scale monitoring projects in areas where funding and scientific expertise are limited and where environmental conditions and remoteness make ongoing field access logistically difficult and sometimes dangerous.

Recommendations for Future Acoustic Monitoring

Acoustic monitoring should be integrated with current and ongoing efforts to determine trends in river dolphin populations. Current assessment strategies rely almost entirely on visual surveys. While visual surveys play a necessary and invaluable role in population assessment, it is not feasible to achieve the spatial and temporal coverage necessary for basin-wide assessment through visual efforts alone. Acoustic monitoring provides a practical means to augment current efforts by greatly increasing the scale of population assessments and by revealing trends that may appear only with continuous monitoring rather than intermittent surveys. Acoustic monitoring should therefore be employed not as a replacement of, but rather, in addition to visual surveys in order to better determine trends in population size and distribution and better isolate the primary pressures that affect populations.

Current Assessment Efforts

The South American River Dolphin Protected Area Network (SARDPAN) was initiated by an internationally based team of researchers and conservation organizations and is comprised of 47 protected areas consisting of national parks, reserves, wildlife refuges, and ecological research stations spread across the Amazon and Orinoco river basins. Two major initiatives of SARDPAN are to 1) conserve habitat to sustain river dolphin populations, and 2) estimate abundance to assess the status of populations.

Standardized visual surveys have been implemented within and proximal to SARDPAN areas through the Abundance Estimation Program of South American River Dolphins. Although the geographic area covered by this program is extensive, surveys to date have only been conducted once in each area of interest. Assessing the performance of these protected areas however, requires repeated surveys over time. In the Mamirauá Sustainable Development Reserve of Brazil for example, Dias et al. (2014) conducted repeated visual surveys over a 20-year period, revealing drastic reductions in local populations of Boto and Tucuxi; evidence that the reserve is failing at protecting these two species.

Temporal coverage of the Mamirauá surveys was extensive, and they revealed an important trend regarding the efficacy of conservation efforts in the area. However, the geographic coverage of this effort was limited to approximately 36 linear kilometers of lake and channel waters in the southeast corner of the reserve. Information on the geographic extent of this decline is therefore lacking and there is no dataset upon which spatial extrapolations can be based.

In contrast, over the shorter period of 15 months, Gomez-Salazar et al. (2012a) covered the largest geographical area through a single series of standardized visual surveys for Boto and Tucuxi to date. They surveyed a total of 2,704 linear kilometers in an attempt to estimate population sizes and densities and identify critical habitat. Yet even at this extensive level of effort, the authors note the small fraction of potential dolphin habitat covered (0.04% and 0.3% of the Amazon and Orinoco river basins respectively). They recommend that future research efforts develop methods for extrapolating visual survey results to un-surveyed areas as a means to estimate overall abundance; specifically noting the need to account for heterogeneity of dolphin distribution throughout their ranges. Although this effort covered a larger area than the Mamirauá study, the authors surveyed each area for but a very brief period of time, thereby providing only a snapshot of dolphin abundance and distribution. To determine trends in abundance, the immense effort of these surveys will have to be repeated.

As illustrated by these examples, the resources and logistical effort required to conduct visual surveys results in a necessary compromise; limiting either temporal or spatial coverage. However, by overlapping continuous acoustic monitoring with intermittent visual surveys, both spatial and temporal coverage can be extended. Correlating acoustic and visual detections during concurrent survey efforts may offer a baseline from which inferences can be made about datasets from ongoing acoustic monitoring. Although exact numbers can't be derived from the acoustic monitoring methods described in this thesis, relative abundance and occupancy can. Increasing, decreasing, or steady-state trends can be elucidated from acoustic monitoring, during periods when visual surveys are not feasible. Ultimately, acoustic monitoring at larger spatiotemporal scales (inclusive of visual survey efforts) will aid in determining where and when extrapolating visual survey results is appropriate.

River Basin-based Monitoring

The anthropogenic pressures that dolphins face vary across South America in both form and magnitude. Note for example the difference in human population density between the eastern and western Amazon mainstream in Figure 2. It is therefore unlikely that the health of Boto and Tucuxi populations is consistent throughout their ranges. Populations in some areas may remain stable, while in others they may decline. To establish an accurate understanding of overall species status, assessments must account for both the large geographic extent of river dolphin ranges in South America and the heterogeneity of population densities and habitat suitability that occur there within.

Assessing the status of species with ranges that cover roughly half of the South American continent is a daunting task indeed. A systematic and ecosystem-based incremental approach is needed to accomplish this. River basins and sub-basins provide natural subunits of river dolphin ranges by dividing the landscape into quasi-independent regions. Delineated by separate drainages, sub-basins isolate dolphin movements to various extent, and have within themselves aquatic ecosystems of greater connectivity than with those of other sub-basins. As such, the status of dolphin populations within sub-basins is likely more consistent than would be found across sub-basins. Treating river dolphins that inhabit separate sub-basins as separate stocks has been suggested in the literature (Gomez-Salazar et al., 2012a). Indeed, the emergence of basins that have become entirely isolated from one another has led to the speciation of Botos discussed in Chapter 1 (Best & da Silva, 1993; Hrbek et al., 2014; Rice, 1998).

Sub-basins however share some degree of connectivity (albeit limited) within their parent basin, namely, at their outlets to a shared mainstream. This provides a dispersion corridor through which we would expect migration/mixing to occur between dolphin stocks. Gomez-Salazar et al. (2012a) note however that river dolphins tend to display strong site fidelity to areas where they were born and not migrate over large distances. Similar findings are reported by McGuire and Henningsen (2007) and Shostell and Ruiz (2010). So, while sub-basins provide a level of isolation that warrants their individual attention for ecosystem health and dolphin stock assessments, they are nonetheless integrated within the broader river system hierarchy that makes up river dolphin ranges.

The Boto and Tucuxi of South America occur in both the Amazon and the Orinoco basins. Among these basins speciation has occurred; *I. g. humboldtiana* and *Sotalia araguaiensis* occupying the Orinoco basin, and *I. g. geoffrensis* and *Sotalia fluviatilis* occupying the Amazon basin with *I. g. boliviensis* isolated upstream of the Teotônio rapids bordering Brazil and Bolivia. The Amazon basin itself can be further divided into seventeen sub-basins (Figure 13), sixteen of which share a direct connection with the Amazon main stream while one, the Araguaia–Tocantins sub-basin, has a limited connection with the Amazon River along its lowermost reaches but primarily empties directly into the Atlantic through Marajó Bay. Each of these sub-basins requires focused monitoring for stock assessment and management, as differences in vulnerability and resilience may be present due to unequal baseline population abundances, physical geographies, habitat capacities, and anthropogenic pressures. Extirpation of river dolphins from geographic areas isolated by natural and manmade barriers has been documented in all Asiatic species due to these very factors (Beasley et al., 2013; Braulik et al., 2014; Smith et al., 2001; Zhao et al., 2008).

The Araguaia-Tocantins Sub-Basin Example

The Araguaia–Tocantins sub-basin provides an illustrative example of a watershed facing elevated anthropogenic pressures that is inhabited by river dolphins which are largely isolated from the broader Amazon. Located in the southeastern region of the Amazon, this sub-basin is heavily exploited for timber, agriculture, mining, and hydroelectric power. The uppermost (southern) reaches of the basin border Brazil's capital Brasília and neighboring city Goiânia. From there, the watershed drains northward through its two primary stems, the Araguaia River to the east and Tocantins River to the west. These two rivers flow more or less in parallel with one another and merge before emptying into the Atlantic Ocean. Below their confluence, in the lowermost (northern) section of the basin, waters partially mingle with the Amazon main channel west of Majaró Island, before emptying through the Pará River and Majaró Bay (Figures 13 and 14).

Upstream of their confluence, the Araguaia River is free flowing with no major river obstructions or dams, while the Tocantins River has six dams currently in operation and three additional dams under consideration for development (see Figure 2 in Araújo & Wang, 2014). Downstream of the confluence, there is one dam in operation and another planned for construction. Fragmentation of the Tocantins River is liken to that of the Indus River (see Figure 1 in Braulik et al., 2014), where *Platanista gangetica minor* has been extirpated from multiple fragmented river sections over the past six decades.

Figure 14 illustrates an uneven distribution of anthropogenic pressures occurring throughout the basin. Human settlement is primarily in the north and far south, while deforestation has occurred in the north, mining in the northwest and eastern midsection, and fragmentation of the Tocantins River in the east. To date, visual surveys have investigated river dolphin distribution in limited sections of the basin in the south (Araujo & Wang, 2012; Araújo & da Silva, 2014) and north (Pivari et al., 2017). No comprehensive survey has been conducted spanning the geographic extent of the basin nor have surveys spanned the different forms and various intensities of anthropogenic pressures occurring throughout the basin. Therefore, the overall health of the Araguaia-

Tocantins sub-basin river dolphin stock and the impacts of these pressures have not been quantified.

The arrangement of recording sites proposed in Figure 14 would facilitate cross-sectional and longitudinal analyses of basin-wide river dolphin distribution and response to human pressures. These recording sites have a relatively even distribution across the basin and span areas of high and low anthropogenic pressure. Proposed sites are located at river confluences where an extensive number of studies (Araújo & Da Silva, 2014; Braulik et al., 2012a; Gomez-Salazar et al., 2012a; Kreb & Budiono, 2005; Martin et al., 2004; Smith et al., 2009; Vidal et al., 1997) have shown river dolphin abundance to be greatest. In the Tocantins River, there is at least one recording site within in each isolated river section.

Continuous monitoring of Araguaia-Tocantins sub-basin through acoustic surveying can provide an ongoing dataset of river fragment occupancy across seasons and as anthropogenic change continues to occur. Insights on how dolphins use their remaining fragmented habitats is instrumental in managing isolated populations with limited ranges. Acoustic surveying will prove especially useful for determining the presence and distribution of low-density populations, which may otherwise elude visual surveys. All other sub-basins can be monitored in this manner, with a similar arrangement of recording sites located at river confluences, evenly distributed, and spanning areas of high and low anthropogenic impact.

The Amazon Main Stem

The Amazon main channel is the primary corridor along which all Amazonian sub-basins are connected. It is also the main conduit of human settlement and development through South America's interior. Here, the largest cities, densest shipping, and most intense fishing occur. The main channel therefor requires monitoring much in the same way as individual sub-basins, as it provides an expanse of habitat in which resident dolphin populations exist across varying levels of anthropogenic pressure. Unlike semi-isolated sub-basins however, where river dolphin populations can be viewed as separate stocks, the main channel is a vital dispersion corridor; the connection that all sub-basin stocks depend upon for a link to conspecifics.

Management of the Amazon main stem requires an ongoing assessment of its function in connecting river dolphin habitats, as isolated populations are inherently more vulnerable. Even without obvious physical obstructions such as hydroelectric dams, dolphin movement can be disrupted by anthropogenic activity. Zhao et al. (2008) for example, discovered through visual surveys of the Yangtze main channel, a region void of Yangtze finless porpoise between Shishou and Yueyang separating upstream stocks from downstream stocks. There were however no physical obstructions such as dams, barrages or low water levels in this section to account for the lack of presence. It is probable that porpoises are avoiding areas with severe habitat degradation, intense anthropogenic activity, and a lack of prey. It is currently unknown to what extent pressures such as boat noise or standing gill nets in heavily trafficked and fished areas hinder the movements of river dolphins in the Amazon main channel, nor whether urbanization and other forms of habitat degradation are fragmenting the main channel habitat.

Acoustic monitoring provides a means to assess habitat connectivity and identify areas where fragmentation is occurring that may go unnoticed by single-pass visual line transect surveys. Continuous, rather than intermittent, monitoring is needed to assess the effects of inconspicuous potential habitat barriers (i.e. areas avoided by dolphins). In such areas where movement is partially rather than absolutely restricted, continuous time series data sets will reveal occupancy patterns on a continuum and can identify areas where habitat connectivity is diminishing long before complete absence occurs.

Acoustic surveys to monitor the effect of major urban centers on dolphin movement along the Amazon main stem can be conducted as described in the Iquitos/PSNR case study. Recording sites should be distributed in a manner that allows for the analysis of impacts by spanning areas of high and low anthropogenic presence. Ongoing monitoring of Iquitos as well as investigations of other growing cities should be conducted in parallel with nearby nonurban reference sites sharing similar physical geographies and habitat types. A list of urbanized areas (populations > 15,000) located on rivers within the ranges of Boto and Tucuxi is provided in Table 1.

A particular advantage of acoustically monitoring urbanized areas is the ability to quantify noise exposure from vessel traffic. Although anthropogenic noise has been cited as a threat to river dolphins (Sinha & Kannan, 2014; Smith et al., 2007; Turvey 2009; Zhao et al., 2008), exposure levels, impacts, and outcomes have yet to be quantified. Research in this area has primarily focused on marine species (Nowacek et al., 2007), and assumptions regarding the potential affects of noise exposure on river dolphins are mainly translated from their marine counterparts. The physical features of river habitats differ greatly from the marine environment however, and it is yet unclear to what extent noise permeates river habitats or how dolphins are affected in the vertically and horizontally restricted spaces of river channels. Dolphins may avoid boat traffic and areas with consistently higher levels of traffic and noise may hinder dolphin movements through otherwise natural corridors.

When integrating acoustic monitoring with current assessment efforts, regardless of whether the focus is in the main channel or a specific sub-basin, the appropriate number, location, and spacing of recording sites, as well as recording duration will all depend upon the research questions under investigation. Funding and resource constraints will necessarily play a role in determining the number of recorders available. In the Iquitos/PSNR pilot study, survey design was constrained by both number of available recording units and available travel time. Within these limits, decisions were made to come up with the most appropriate arrangement to examine differences in dolphin presence in the context of human development. The design goal was to compare dolphin presence between an urbanized developed area and a rural undeveloped area. As such, recorders were placed where they were thought to have the highest probability of detecting dolphins near the city of Iquitos while spaced evenly and widely enough to cover the area of interest. Recorders were deployed with similar spacing in areas of similar physical geography in the PSNR for purposes of comparison.

Recorders in the proposed Araguaia-Tocantins sub-basin study were spaced much farther apart with the intention to analyze distribution on a much larger scale, while evenly sampling the basin and the various regions of anthropogenic pressures that are occurring throughout. Here too, proposed recording sites were located at river confluences where the probability of dolphin detection is greatest. Future investigations will inevitably differ from these examples and corresponding design considerations will need to be made for optimal use of recording resources. Accounting for factors such as hydrology and ambient noise will be necessary as demonstrated in the Iquitos/PSNR case study.

Closing Remarks

This thesis demonstrates a viable method for detecting early indications of change occurring in the distribution and/or size of river dolphin populations. Population declines due to habitat degradation are often detected only after ecosystems have reached critical levels of degradation, at which point the feasibility and likely success of conservation efforts are greatly diminished (Huang et al., 2012). Huang et al. (2012) note that this is especially true for long-lived, slowly reproducing species such as river dolphins, which may experience a time lag between environmental change and subsequent population effects. From the Iquitos/PSNR case study, we cannot determine whether the observed differences between the Iquitos study area and the PSNR study area are due to decreased numbers of individuals or a redistribution of individuals. However, the reduced presence observed in the Iquitos area is an indication of diminished habitat suitability; a potential precursor and driver of population decline.

This thesis also demonstrates the practicality of acoustic surveys for monitoring river dolphin habitat use over large areas, continuously, and for long periods of time. This allows for the acquisition of baseline data, identification of locations of high conservation priority, and the determination of whether ecosystem function at such locations is changing. It is during the early stages of environmental change, before population decline, that observation and mitigation efforts should be implemented to increase the likelihood of conservation success.

Human population and economic growth in South America have lagged behind that of Asia. However, the declines in river dolphin populations that occurred in Asia as a result of anthropogenic growth will most likely occur in South America as the same patterns of river exploitation are followed. In anticipation of these threats, early indicators of change and informed direction for mitigation are essential to conservation. The methods developed herein provide a valuable tool for continuous future monitoring and status assessment of river dolphins in both South America and Asia.

FIGURES

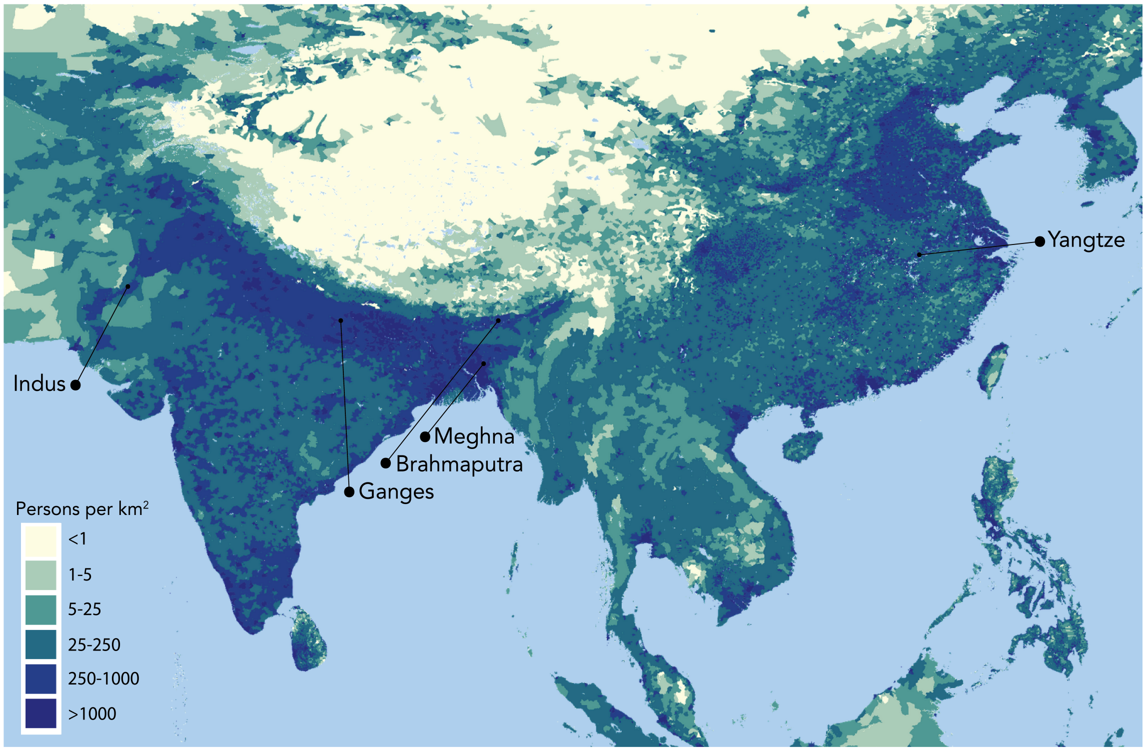


Figure 1: 2015 UN-Adjusted Population Density of Asia. Major river systems of Asia (home to the South Asian and Yangtze river dolphin, Irrawaddy dolphin, and Yangtze Finless porpoise) are among the most heavily human-populated areas in this region of the world. From left to right, the Indus, Ganges-Brahmaputra-Meghna, and Yangtze river basins can be distinguished by high human density clusters. Raster data were downloaded from the National Aeronautics and Space Administration (NASA) Socioeconomic Data and Applications Center (SEDAC) hosted by the Center for International Earth Science Information Network (CIESIN) at the Columbia University Earth Institute.

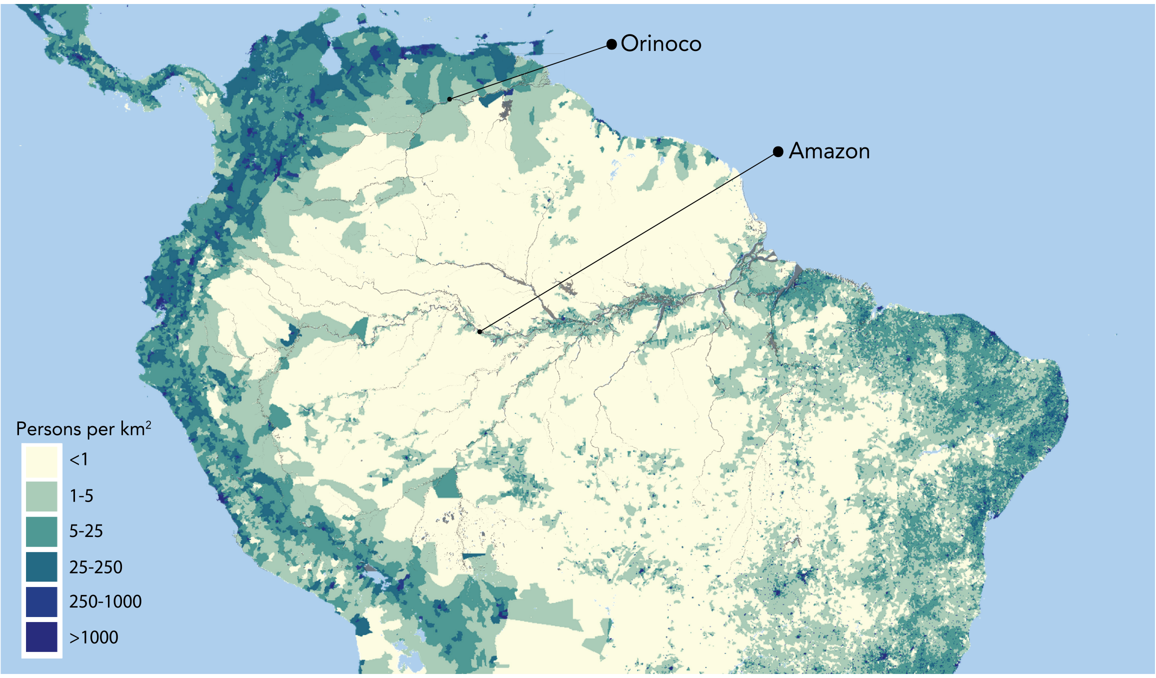


Figure 2: 2015 UN-Adjusted Population Density of South America. Major river systems of south America (home to the Amazon river dolphin, Tucuxi, and Guiana dolphin) are not as densely populated by humans as in south Asia. Nonetheless, the Amazon River main channel can be distinguished by the elevated human density cluster stretching from the Atlantic westward to the Andes Mountains, demonstrating the River's role as a conduit of human development through the continent's interior. Raster data were downloaded from the National Aeronautics and Space Administration (NASA) Socioeconomic Data and Applications Center (SEDAC) hosted by the Center for International Earth Science Information Network (CIESIN) at the Columbia University Earth Institute.

Table 1: Growth of cities (population >15,000) along the Amazon River from 1991 to 2010. *Growth beginning in 2000 is calculated for cities lacking 1991 census data.

State	City	1991	2000	2010	Growth
AMZ	Manaus	1,006,585	1,396,768	1,792,881	78%
PAR	Belém	849,187	1,272,354	1,381,475	63%
PAR	Ananindeua	...	392,627	470,819	20%
LOR	Iquitos	274,759	370,962	410,800	50%
RON	Porto Velho	229,788	273,709	390,733	70%
AMP	Macapá	154,063	270,628	381,214	147%
ROR	Boa Vista	120,157	197,098	277,799	131%
PAR	Santarém	180,018	186,297	215,790	20%
PAR	Marabá	102,435	134,373	186,270	82%
PAR	Castanhal	92,852	121,249	153,378	65%
PAR	Parauapebas	27,443	59,260	138,690	405%
PAR	Marituba	...	64,884	107,123	65%
AMP	Santana (Porto Santana)	45,800	75,849	99,111	116%
PAR	Tucuruí	46,014	60,918	92,442	101%
PAR	Altamira	50,145	62,285	84,092	68%
PAR	Abaetetuba	56,389	70,843	82,998	47%
PAR	Paragominas	40,054	58,240	76,511	91%
PAR	Bragança	49,600	56,572	72,621	46%
PAR	Itaituba	62,186	64,486	70,682	14%
PAR	Redenção	44,944	59,613	70,065	56%
AMZ	Parintins	41,591	58,125	69,890	68%
AMZ	Manacapuru	36,019	47,662	60,174	67%
PAR	Tailândia	9,657	28,128	58,713	508%
AMZ	Itacoatiara	37,380	46,465	58,157	56%
PAR	Cametá	30,278	40,417	52,838	75%
PAR	Capanema	39,825	46,329	50,732	27%
AMZ	Tefé	39,057	47,698	50,069	28%
AMZ	Coari	21,081	39,504	49,651	136%
PAR	Breves	28,719	40,285	46,560	62%
PAR	Jacundá	22,081	34,518	45,683	107%
PAR	São Félix do Xingu	8,198	12,530	45,113	450%
PAR	Santa Isabel do Pará	23,728	33,078	43,000	81%
PAR	Oriximiná	21,163	29,181	40,147	90%
AMP	Laranjal do Jari	14,301	26,792	37,904	165%
AMZ	Tabatinga	19,822	26,637	36,355	83%
PAR	Barcarena	21,629	27,767	36,297	68%
PAR	Rondon do Pará	26,400	30,061	34,696	31%
PAR	Salinópolis	19,317	30,417	33,391	73%
PAR	Dom Eliseu	11,806	23,801	32,516	175%
PAR	Conceição do Araguaia	29,851	29,370	32,464	9%
PAR	Vigia	25,166	28,006	32,353	29%

AMZ - Amazonas; AMP = Amapá; PAR = Pará; LOR = Loreto; RON = Rondónia; ROR = Roraima

Continued...

State	City	1991	2000	2010	Growth
PAR	São Miguel do Guamá	18,123	24,457	31,884	76%
PAR	Tomé-Açu	16,206	27,314	31,563	95%
PAR	Xinguara	27,378	26,264	31,492	15%
AMZ	Humaitá	18,700	23,991	30,501	63%
PAR	Santana do Araguaia	8,521	17,326	29,663	248%
PAR	Breu Branco	...	15,952	29,308	84%
AMZ	Iranduba	6,403	9,940	28,979	353%
PAR	Benevides	8,361	20,912	28,912	246%
PAR	Ulianópolis	...	11,909	28,525	140%
PAR	Novo Repartimento	...	15,524	27,950	80%
PAR	Alenquer	21,958	25,160	27,722	26%
PAR	Tucumã	12,441	16,496	26,907	116%
PAR	Igarapé-Miri	19,797	24,983	26,205	32%
AMZ	Maués	16,658	21,179	25,832	55%
PAR	Óbidos	20,147	22,978	25,466	26%
PAR	Moju	9,748	17,626	25,162	158%
PAR	Portel	11,852	17,325	24,852	110%
PAR	Monte Alegre	16,987	20,921	24,565	45%
PAR	Uruará	5,767	13,166	24,430	324%
LOR	Requena	14,954	22,055	24,300	62%
AMZ	Lábrea	15,444	19,276	24,207	57%
PAR	Mãe do Rio	19,140	18,738	23,052	20%
AMZ	Eirunepé	13,442	16,781	22,166	65%
PAR	Capitão Poço	14,557	21,121	21,441	47%
PAR	Igarapé-Açu	12,610	19,489	21,207	68%
PAR	Goianésia do Pará	...	14,878	21,082	42%
PAR	Soure	14,500	17,303	21,015	45%
PAR	Canaã dos Carajás	...	3,924	20,727	428%
PAR	Itupiranga	8,431	14,754	20,490	143%
AMZ	Manicoré	14,373	15,339	20,349	42%
AMZ	Benjamin Constant	11,539	14,171	20,138	75%
PAR	Almeirim	16,342	18,916	19,965	22%
PAR	Ourilândia do Norte	...	9,689	19,913	106%
AMZ	Carauari	11,498	16,876	19,744	72%
AMZ	Boca do Acre	11,296	14,614	19,348	71%
AMZ	São Gabriel da Cachoeira	6,835	12,373	19,054	179%
PAR	Baião	7,877	10,865	18,555	136%
PAR	Mocajuba	11,756	14,561	18,279	55%
PAR	Augusto Corrêa	8,683	13,356	18,240	110%
LOR	Nauta	8,579	16,230	17,300	102%

AMZ - Amazonas; AMP = Amapá; PAR = Pará; LOR = Loreto; RON = Rondónia; ROR = Roraima

Table 2: River dolphin surveys with an acoustic component. Literature review was conducted through the Cornell University Library scientific article search engine, Duke University Library scientific article search engine, and Google Scholar search engine, using key words *acoustic monitoring, acoustic survey, acoustic detection, river dolphin,* and *freshwater cetacean*

Year	Author	Species	Method	Time	Space	Recorder	Findings
2001	Akamatsu et al.	Yangtze finless porpoise	Moving Vessel	30.5 hours during November, 1998	774 linear km along the Yangtze River from Wuhan to Poyang Lake, China	Sony PCHB 244	Detecting presence
2005	Wang et al.	Yangtze finless porpoise	Stationary	42 hours from 20 to 22 October, 2003 and from 17 to 19 October, 2004	1 location in the Tian-e-zhou Oxbow reserve of the Yangtze River, China	Pulse Event Data Logger	Detecting presence
2008	Li et al.	Yangtze finless porpoise	Moving Vessel	120 hours between 6 November and 13 December, 2006	1669 linear km along Yangtze River from Yichang to Shanghai, China	A-tag	Evaluating boat avoidance by individuals
2008	Akamatsu et al.						Detecting presence and counting individuals
2009	Le it al.						Localizing, and tracking individuals
2009	Kimura et al.	Yangtze finless porpoise	Moving Vessel	from 11 to 16 May, 2007	120 linear km along the confluence of the Yangtze River and Poyang Lake, China	A-tag	Detecting presence, counting individuals
2009	Kimura et al.	Yangtze finless porpoise	Stationary	120 hours from 27 to 29 April, 2006 and from 9 to 10 May, 2007	3 locations spaced 1 to 2 km apart at the confluence of the Yangtze River and Poyang Lake, China	A-tag	Detecting presence
2010	Kimura et al.	Yangtze finless porpoise	Stationary	466 days from June, 2007 to May, 2009	1 location at the confluence of the Yangtze River and Poyang Lake, China	A-tag	Density estimation
2012	Kimura et al.	Yangtze finless porpoise	Moving Vessel	12 repeated surveys from May 2007 to August, 2010	77 linear km along the confluence of the Yangtze River and Poyang Lake, China	A-tag	Seasonal distribution patterns and correlation to fish presence
2012	Sasaki-Yamamoto	South Asian river dolphin	Stationary	252 hours from 6 to 8 February, 2007; from 17 to 21 February, 2008; and from 11 to 16 November, 2008	5 locations spaced 0.15 to 0.525 km apart in the upper Ganges River, India	A-tag	Detecting presence and direction of travel

Continued…

Year	Author	Species	Method	Time	Space	Recorder	Findings
2014	Richman et al.	South Asian river dolphin	Moving Vessel	during January and February, 2012	169 linear km along the Halda, Sangu, and Karnaphuli rivers and Shikalbaha-Chandkhali canal, Bangladesh	A-tag	Detecting presence
2014	Wang et al.	Yangtze finless porpoise	Stationary	from 11:00 on 8 June to 07:20 on 23 June, 2013	1 location in the lower Yangtze River, China	A-tag	Detecting presence and feeding behavior
2015	Wang et al.	Yangtze finless porpoise	Stationary	from 17:00 to 07:00 each night from 15 to 23 December, 2012	9 locations spaced 27 to 157 km apart in the middle and lower Yangtze River, China	A-tag	Detecting presence and feeding behavior
2015	Yamamoto et al.	Amazon river dolphin	Stationary	from 9 February to 1 March, 2011; and from 12 to 27 February, 2012	5 locations spaced 1 to 13 km apart in the Mamirauá Sustainable Development Reserve, Brazil	A-tag	Detecting presence, direction of travel, and feeding behavior
2017	Campbell et al.	Amazon river dolphin & Tucuxi	Stationary	8 recording sessions between June, 2013 and January, 2015	2 locations spaced 7 km apart in the Yarinacocha Lagoon, Perú	C-POD	Detecting presence

Figure 3: Iquitos and Pacaya-Samiria study areas in northern Perú. Iquitos is located on the Amazon River 170km down stream from the Pacaya-Samiria study area.

Table 3: Recording site locations, hydrology, period, and percent time during which biosonar was present.

	Site	Latitude	Longitude	Stream Depth (m)	Stream Width (m)	Distance from Main Channel (m)	Survey Start	Survey End	Duration	Biosonar Presence
Iquitos	I-1	-3.70208	-73.24634	7.0	325	0	8/20/2014 12:21:50	8/25/2014 10:55:50	118h 34m	57%
	I-2	-3.70904	-73.27507	3.9	339	4,700	8/20/2014 11:23:53	8/24/2014 23:49:53	108h 26m	5%
	I-3	-3.74462	-73.28220	5.8	230	9,700	8/20/2014 10:46:37	8/25/2014 10:06:37	119h 20m	2%
	I-4	-3.74770	-73.31180	5.3	212	17,300	8/20/2014 09:20:02	8/24/2014 23:45:02	110h 25m	2%
	I-5	-3.71260	-73.23178	5.7	134	0	8/20/2014 12:59:52	8/23/2014 12:08:52	71h 9m	71%
	I-6	-3.76698	-73.23189	4.5	107	6,200	8/23/2014 15:37:24	8/25/2014 13:49:24	46h 12m	0%
	I-7	-3.76612	-73.25086	5.2	87	8,400	8/20/2014 16:35:38	8/25/2014 13:24:38	116h 49m	0%
	I-8	-3.78821	-73.25014	3.5	90	13,000	8/20/2014 14:50:32	8/25/2014 12:59:32	118h 9m	0%
	I-9	-3.79980	-73.28262	5.7	60	16,900	8/20/2014 15:44:54	8/25/2014 12:32:54	116h 48m	0%
Pacaya-Samiria	PS-1	-4.64780	-73.78764	8.0	240	700	8/28/2014 14:19:10	9/3/2014 02:55:10	132h 36m	99%
	PS-2	-4.65179	-73.83723	12.2	108	6,700	8/28/2014 09:34:51	9/3/2014 02:53:51	137h 19m	93%
	PS-3	-4.68724	-73.84813	11.0	71	11,000	8/27/2014 16:14:36	9/1/2014 16:24:36	120h 10m	57%
	PS-4	-4.71801	-73.85957	5.5	79	15,000	8/27/2014 16:51:04	9/1/2014 17:00:04	120h 9m	56%
	PS-5	-4.75276	-73.87727	8.8	62	20,800	8/27/2014 17:30:45	9/2/2014 21:32:45	148h 2m	29%
	PS-6	-4.62673	-73.84930	3.5	77	10,100	8/29/2014 09:25:33	9/3/2014 09:56:33	120h 31m	80%
	PS-7	-4.63320	-73.88091	3.3	69	13,800	8/31/2014 14:51:04	9/3/2014 15:28:04	72h 37m	44%
	PS-8	-4.60984	-73.90617	5.5	61	17,900	8/28/2014 10:57:49	9/3/2014 06:00:49	139h 3m	84%

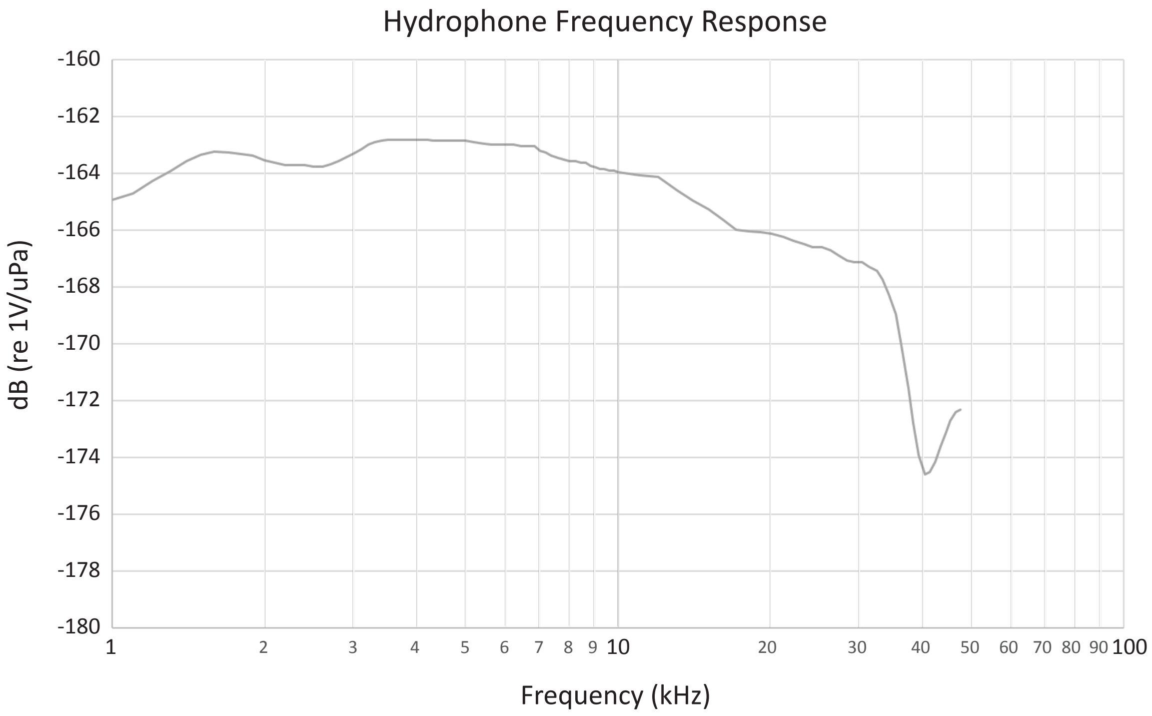


Figure 4: Hydrophone sensitivity represented as a frequency response curve from 1 to 48kHz. The hydrophone's sensitivity varies with frequency of recorded signal. Note the higher variability above 30kHz.

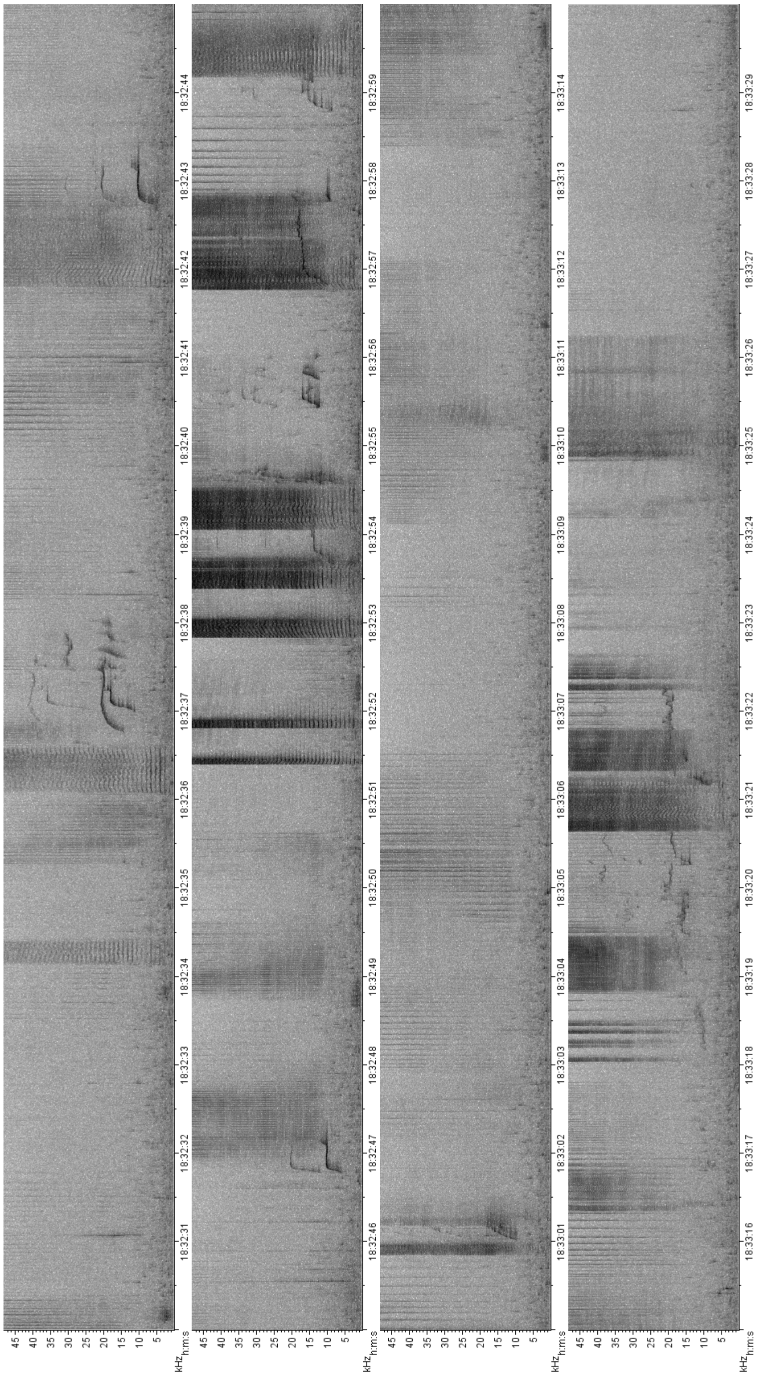


Figure 5: Spectrogram of 1min sample containing biosonar. Sample duration is broken into four contiguous 15sec plots. Frequency (0-48kHz) is represented by the y-axes. Time (08-28-2014 18:32:30 to 08-28-2014 18:33:30) is represented by the x-axes. Amplitude is represented by the grey-scale with louder signals appearing darker than quieter signals. The vertical, broadband impulsive signals are biosonar "clicks" and "buzzes". The tonal, narrowband frequency modulating signals are whistles. Note the diminished signal strength of biosonar below 16kHz.

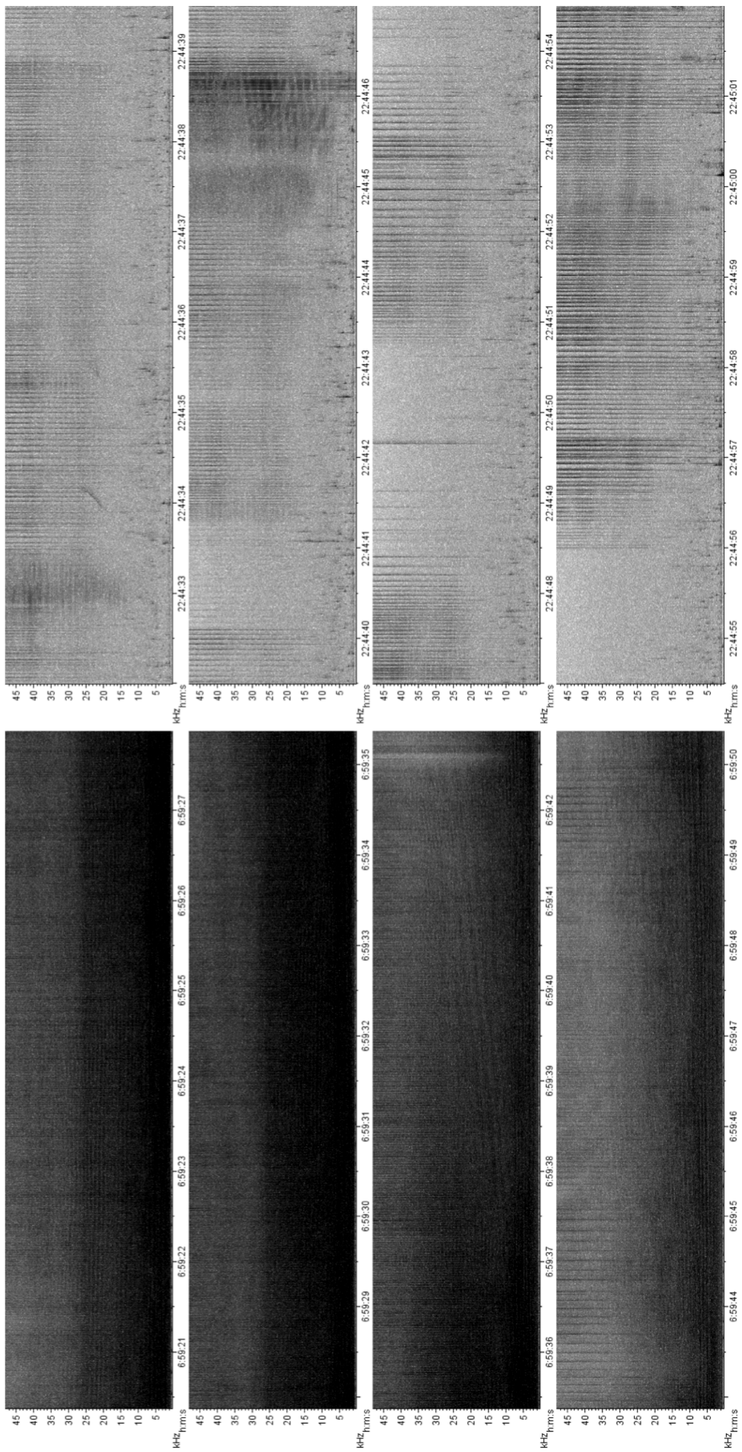


Figure 6: Comparison of spectrograms with high and low noise. Biosonar is present in both high noise (left) and low noise (right) samples. The high noise sample has an Leq of 110db (re 1 uPa), while the low noise sample has an Leq of 90db (re 1 uPa). The masking effect of anthropogenic noise (in this case, a passing boat) can clearly be seen in the high noise sample.

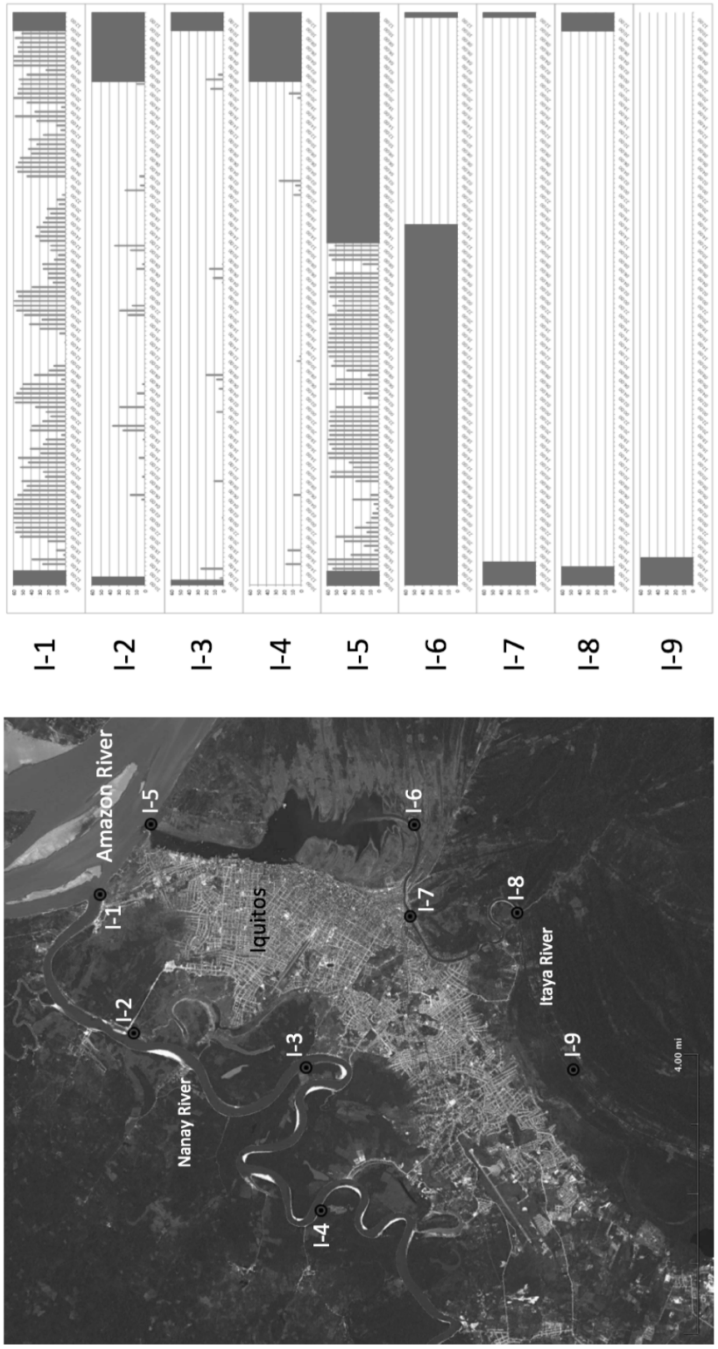


Figure 7: (a) Recording sites situated around the City of Iquitos. Sites *Iquitos-1* (I-1) through I-4 were located in the Nanay River to the north west of the city. Sites I-5 through I-9 were located in the Itaya River to the south east of the city. The large river to the north east is the Amazon main channel. **(b)** Number of 1min samples containing echolocation clicks during each hour of recording at each site in the Iquitos study area. The vertical axis represents 60 minutes. The horizontal axis represents 123 hours. Dark grey blocks represent periods with no recorded audio data. The change of recording location from site I-5 to I-6 occurred midway through the survey.

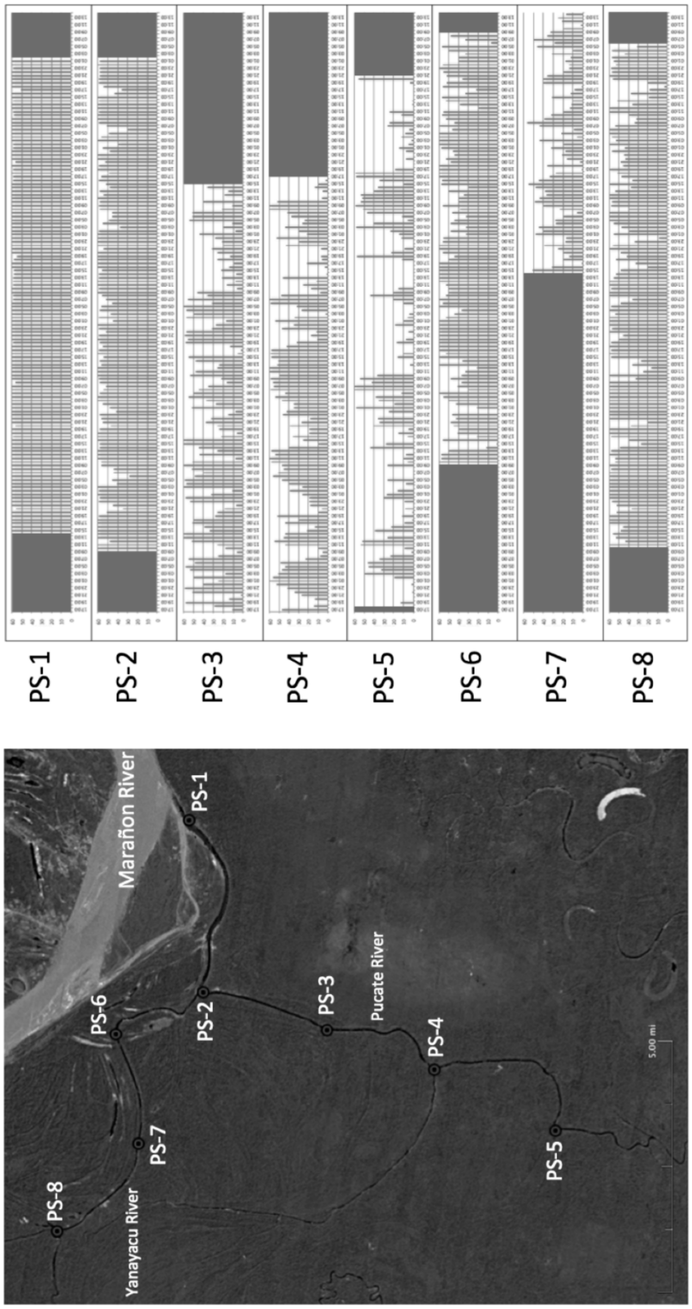


Figure 8: (a) Recording sites situated in the Pacaya-Samiria National Reserve (PSNR), 140km upstream from Iquitos. Sites *Pacaya-Samiria 1* (PS-1) and PS-2 were located in the Yanayacu-Pucate River. Sites PS-3 through PS-5 were located in the Pucate River. Sites PS-6 through PS-8 were located in the Yanayacu River. All recording sites except PS-7 were located at the confluences of smaller tributaries. The large river to the north east is the Marañón main channel. **(b)** Number of 1min samples containing echolocation clicks during each hour of recording at each site in the PSNR study area. The vertical axis represents 60 minutes. The horizontal axis represents 158 hours. Dark grey blocks represent periods with no recorded audio data.

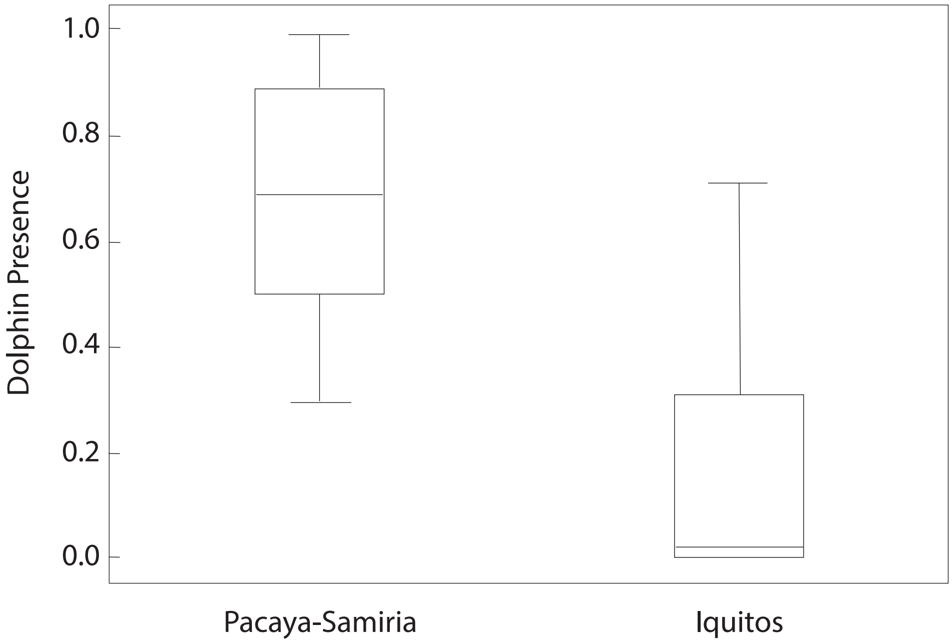
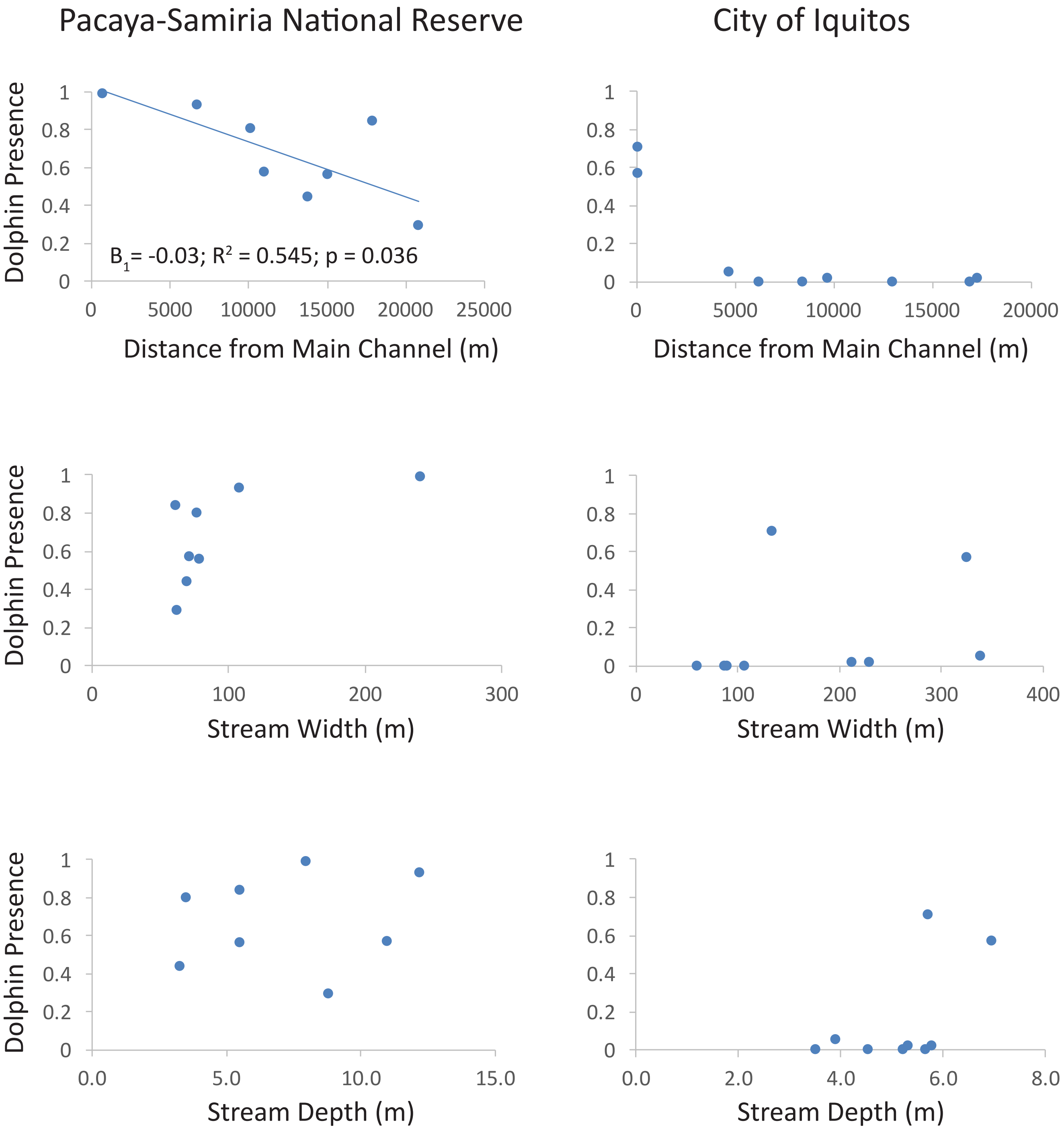


Figure 9: Boxplots of dolphin presence in the PSNR and Iquitos study areas based on portion of time biosonar was detected at each of the 17 survey sites.



Pacaya-Samiria National Reserve

City of Iquitos

Figure 10: Linear regression plots of dolphin presence at each survey site vs hydrological measures in the PSNR study area (left) and Iquitos study area (right). Y-axes represent the portion of 1min samples that contained biosonar during the survey. X-axes represent distance from main river channels, stream width, and stream depth in meters. Best-fit lines, and values for β_1, R^2, and p are given for plots in which β_1 differed from 0 with statistical significance ($\alpha = 0.05$).

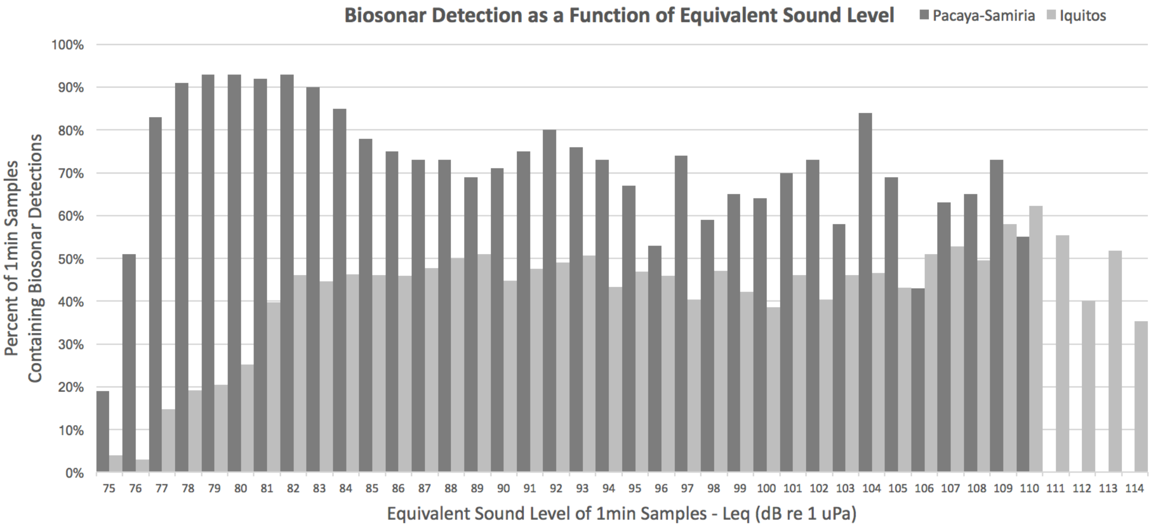


Figure 11: Percent of 1min samples containing biosonar for each noise level measured in the PSNR and Iquitos study areas cumulatively. Presence was greater in the PSNR at all but two noise levels (106dB and 110dB).

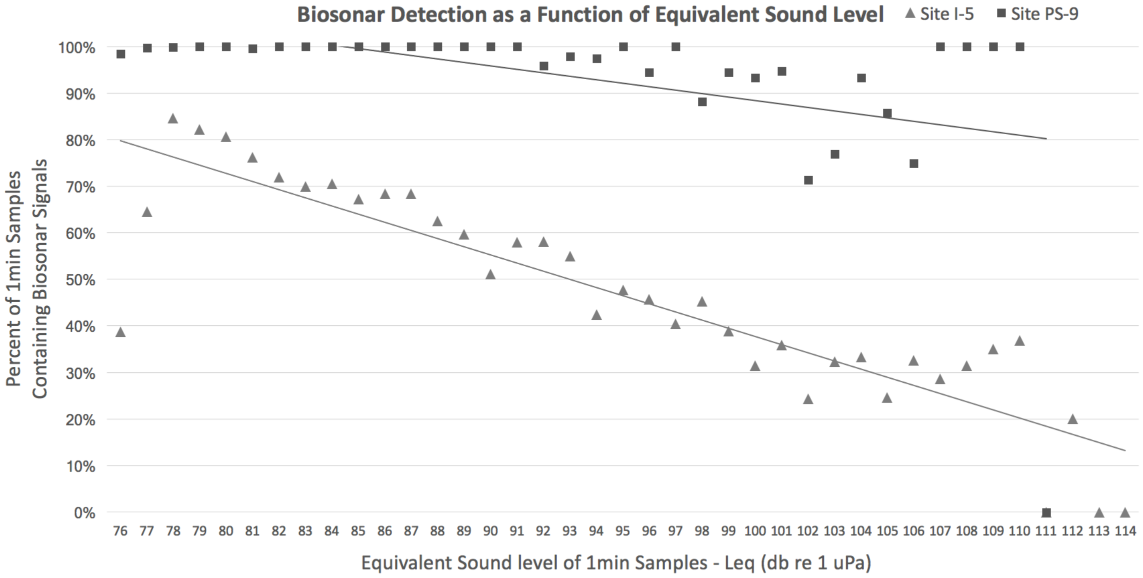


Figure 12: Percent of 1min samples containing biosonar for each noise level measured at site I-5 and site PS-9. As ambient noise increased, biosonar detection decreased. Percent presence was greater at site PS-9 at all noise levels except 111dB.

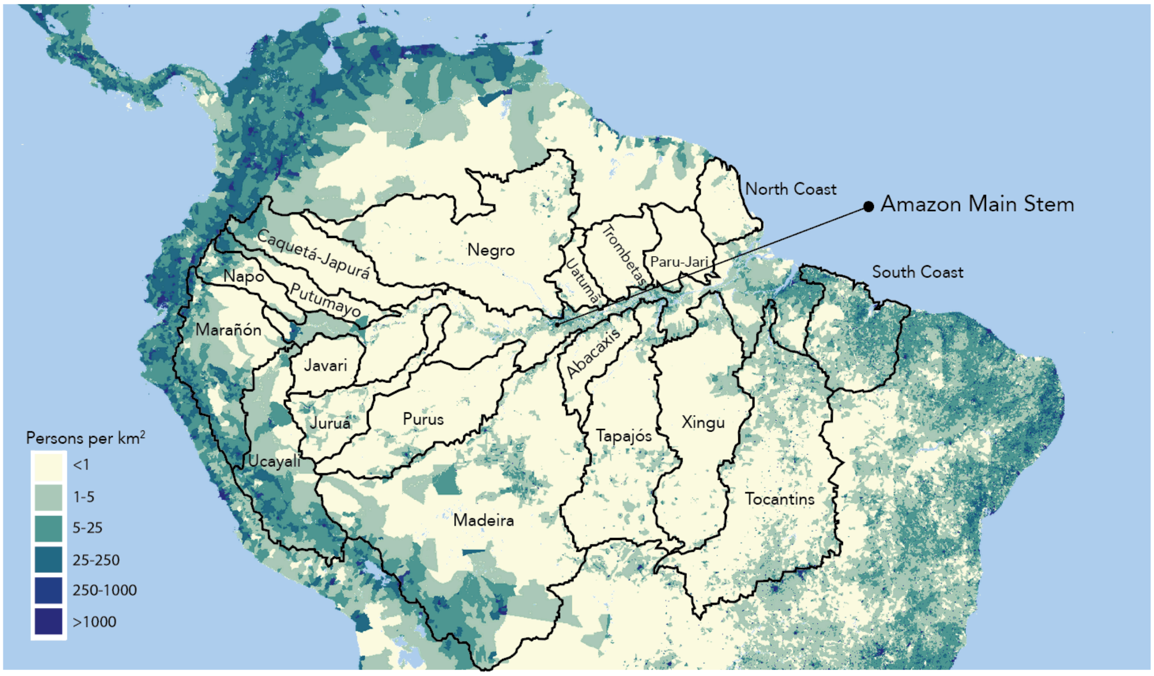
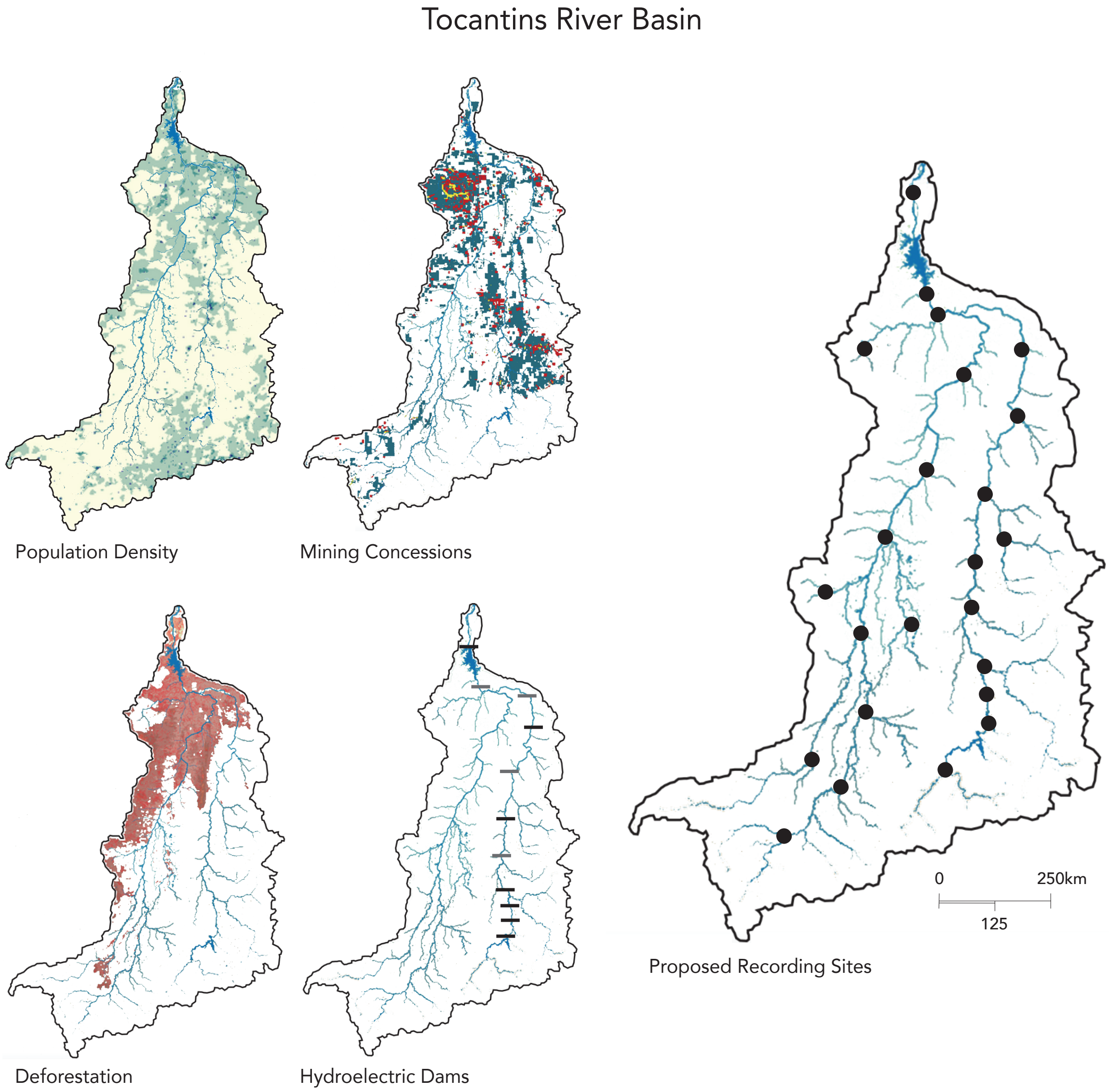


Figure 13: Major sub-basins of the Amazon Basin. River basin delineation was downloaded from the ESRI geodatabase *Amazon GIS-Based River Basin Framework* developed by Venticinque et al., (2016). Population raster data were downloaded from the National Aeronautics and Space Administration (NASA) Socioeconomic Data and Applications Center (SEDAC) hosted by the Center for International Earth Science Information Network (CIESIN) at the Columbia University Earth Institute.



Tocantins River Basin

Population Density

Mining Concessions

Deforestation

Hydroelectric Dams

Proposed Recording Sites

Figure 14: Distribution of anthropogenic pressures and proposed recording site locations for a large-scale acoustic survey in the Tocantins River Basin. River basin delineation was downloaded from the ESRI geodatabase *Amazon GIS-Based River Basin Framework* developed by Venticinque et al., (2016). Population raster data were downloaded from the National Aeronautics and Space Administration (NASA) Socioeconomic Data and Applications Center (SEDAC) hosted by the Center for International Earth Science Information Network (CIESIN) at the Columbia University Earth Institute. Mining concession and deforestation raster data were downloaded from the Wildlife Conservation Society (WCS) Amazon Waters Initiative. Hydroelectric dam locations are those reported in Araújo and Wang (2014).

REFERENCE LIST

Akamatsu, T., Wang, D., Wang, K., Li, S., Dong, S., Zhao, X., … Richlen, M. (2008). Estimation of the detection probability for Yangtze finless porpoises (*Neophocaena phocaenoides asiaeorientalis*) with a passive acoustic method. *The Journal of the Acoustical Society of America*, *123*(6), 4403–4411. http://doi.org/10.1121/1.2912449

Akamatsu, T., Wang, D., Wang, K., & Wei, Z. (2001). Comparison between visual and passive acoustic detection of finless porpoises in the Yangtze River, China. *The Journal of the Acoustical Society of America*, *109*(4), 1723–1727. http://doi.org/10.1121/1.1356705

Almeida, O. T., Lorenzen, K., & McGrath, D. (2004). Commercial fishing sector in the regional economy of the Brazilian Amazon. *Proceedings of the Second International Symposium on the Management of Large Rivers for Fisheries*, *1*, 15–24. Retrieved from https://www.researchgate.net/profile/Angela_Arthington/publication/29453558_Environmental_flow_assessment_with_emphasis_on_holostic_methodologies/links/0fcfd50b6bb0e993a1000000.pdf#page=23

Almeida, O. T., McGrath, D. G., & Ruffino, M. L. (2001). The commercial fisheries of the lower Amazon: an economic analysis. *Fisheries Management and Ecology*, *8*(3), 253–269. http://doi.org/10.1046/j.1365-2400.2001.00234.x

Alves, L. C. P. de S., Zappes, C. A., & Andriolo, A. (2012). Conflicts between river dolphins (Cetacea: Odontoceti) and fisheries in the Central Amazon: a path toward tragedy? *Zoologia (Curitiba)*, *29*(5), 420–429. http://doi.org/10.1590/S1984-46702012000500005

Araújo, C. C., & Da Silva, V. M. F. (2014). Spatial distribution of river dolphins, Inia geoffrensis (Iniidae), in the Araguaia River (central Brazil). *Mammalia*, *78*(4). http://doi.org/10.1515/mammalia-2013-0112

Araujo, C. C., & Wang, J. Y. (2012). Botos (Inia geoffrensis) in the Upper Reaches of the Tocantins River (Central Brazil) with Observations of Unusual Behavior, Including Object Carrying. *Aquatic Mammals*, *38*(4), 435–440. http://doi.org/10.1578/AM.38.4.2012.435

Araújo, C. C., & Wang, J. Y. (2014). The dammed river dolphins of Brazil: impacts and conservation. *Fauna and Flora International, Oryx*, *49*(1). http://doi.org/10.1017/S0030605314000362

Aya, M. P., Ferrer, A., Lasso, C. A., Ruiz-García, M., Bolaños-Jiménez, J., & Caballero, S. (2010). Status, distribution and conservation of the river dolphins Inia geoffrensis and Sotalia spp. in Venezuela. In F. Trujillo, E. Crespo, P. A. Van Damme, & J. S. Usma (Eds.), *The Action Plan for South American River Dolphins 2010-2010* (pp. 17–28). Bogotá, D.C., Colombia: WWF, Fundación Omacha, WDS, WDCS, Solamac.

Baird, I. G., & Mounsouphom, B. (1994). Irrawaddy dolphins (Orcaella brevirostris) in southern Lao PDR and northeastern Cambodia. *Natural History Bulletin of the Siam Society*, *42*(2), 59–175.

Barham, B., Coomes, O., & Takasaki, K. (1999). Rain forest livelihoods: income generation, household wealth and forest use. *Society and Natural Resources*, *14*(4), 34–42.

Beasley, I., Pollock, K., Jefferson, T. A., Arnold, P., Morse, L., Yim, S., … Marsh, H. (2013). Likely future extirpation of another Asian river dolphin: The critically endangered population of the Irrawaddy dolphin in the Mekong River is small and declining. *Marine Mammal Science*, *29*(3), E226–E252. http://doi.org/10.1111/j.1748-7692.2012.00614.x

Behera, S. K., Singh, H., & Sagar, V. (2013). Status of Ganges River Dolphin (Platanista gangetica gangetica) in the Ganga River basin, India. *Journal of the Aquatic Ecosystem Health and Management Society*, *16*(4). http://doi.org/10.1080/14634988.2013.845069

Bernholz, C. D. (2004). Sustainable Development of the Ganges-Brahmaputra-Meghna Basins: edited by Asit K. Biswas and Juha I. Uitto. Tokyo: United Nations University Press, 2001. 202 pp. ISBN 92-808-1041-3 (paper). *Journal of Government Information*, *30*(1), 110–112. http://doi.org/10.1016/J.JGI.2004.03.004

Best, R. C., & Silva, V. M. da. (1993). Inia geoffrensis. *Mammalian Species*, *426*, 1–8.

Bioacoustics Research Program (2015) Raven Pro: interactive sound analysis software. Version 1.5. (n.d.).

Borobia, M., Siciliano, S., Lodi, L., & Hoek, W. (1991). Distribution of the South American dolphin *Sotalia fluviatilis*. *Canadian Journal of Zoology*, *69*(4), 1025–1039. http://doi.org/10.1139/z91-148

Bowen, R., & Depledge, M. (2006). Rapid Assessment of Marine Pollution (RAMP). *Marine Pollution Bulletin*, *53*(10–12), 631–639. http://doi.org/10.1016/J.MARPOLBUL.2006.09.002

Braulik, G., Bhatti, Z., Ehsan, T., Hussain, B., Khan, A., Khan, A., … Garstang, R. (2012). Robust abundance estimate for endangered river dolphin subspecies in South Asia. *Endangered Species Research*, *17*(3), 201–215. http://doi.org/10.3354/esr00425

Braulik, G. T. (2006). Status assessment of the Indus River dolphin, Platanista gangetica minor, March–April 2001. *Biological Conservation*. http://doi.org/10.1016/j.biocon.2005.11.026

Braulik, G. T., Arshad, M., Noureen, U., Northridge, S. P., & Gilbert, T. (2014). Habitat Fragmentation and Species Extirpation in Freshwater Ecosystems; Causes of Range Decline of the Indus River Dolphin (Platanista gangetica minor). http://doi.org/10.1371/journal.pone.0101657

Braulik, G. T., Noureen, U., Arshad, M., & Reeves, R. R. (2015). Review of status, threats, and conservation management options for the endangered Indus River blind dolphin. *Biological Conservation*. http://doi.org/10.1016/j.biocon.2015.09.008

Braulik, G. T., Reichert, A. P., Ehsan, T., Khan, S., Northridge, S. P., Alexander, J. S., & Garstang, R. (2012). Habitat use by a freshwater dolphin in the low-water season. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *22*(4), 533–546. http://doi.org/10.1002/aqc.2246

Braulik, G. T., Smith, B. D., & Chaudhry, S. (2012). Platanista gangetica ssp. minor. *The IUCN Red List of Threatened Species 2012: e.T41757A17628296.*

Browder, J. O., & Godfrey, B. J. (1997). *Rainforest cities: Urbanization, development, and globalization of the Brazilian Amazon.* Columbia University Press.

Brum, S. M., da Silva, V. M. F., Rossoni, F., & Castello, L. (2015). Use of dolphins and caimans as bait for *Calophysus macropterus* (Lichtenstein, 1819) (Siluriforme: Pimelodidae) in the Amazon. *Journal of Applied Ichthyology*, *31*(4), 675–680. http://doi.org/10.1111/jai.12772

Caballero, S., Trujillo, F., Vianna, J. A., Barrios-Garrido, H., Montiel, M. G., Beltrán-Pedreros, S., … Baker, C. S. (2007). TAXONOMIC STATUS OF THE GENUS SOTALIA: SPECIES LEVEL RANKING FOR "TUCUXI" (SOTALIA FLUVIATILIS) AND "COSTERO" (SOTALIA GUIANENSIS) DOLPHINS. *Marine Mammal Science*, *23*(2), 358–386. http://doi.org/10.1111/j.1748-7692.2007.00110.x

Caballero, S., Trujillo, F., Vianna, J. A., Barrios-Garrido, H., Trujillo, F., Vianna, J. A., … Santos, M. C. O. (2006). *Phylogeography of the South American riverine and coastal dolphins Sotalia fluviatilis and Sotalia guianensis*.

Cappozzo, H. L., Negri, M. F., Pérez, F. H., Albareda, D., Monzón, F., & Corcuera, J. F. (2007). Incidental mortality of franciscana dolphin (Pontoporia blainvillei) in Argentina. *Latin American Journal of Aquatic Mammals*, *6*(2), 127–137. http://doi.org/10.5597/lajam00118

Castello, L., & Macedo, M. N. (2016). Large-scale degradation of Amazonian freshwater ecosystems. *Global Change Biology*, *22*(3), 990–1007. http://doi.org/10.1111/gcb.13173

Castello, L., McGrath, D. G., Hess, L. L., Coe, M. T., Lefebvre, P. A., Petry, P., … Arantes, C. C. (2013). The vulnerability of Amazon freshwater ecosystems. *Conservation Letters*, *6*(4), 217–229. http://doi.org/10.1111/conl.12008

Chen, L., Bruford, M. W., Xu, S., Zhou, K., & Yang, G. (2010). Microsatellite variation and significant population genetic structure of endangered finless porpoises (Neophocaena phocaenoides) in Chinese coastal waters and the Yangtze River. *Marine Biology*, *157*(7), 1453–1462. http://doi.org/10.1007/s00227-010-1420-x

Choudhary, S., Dey, S., Dey, S., Sagar, V., Nair, T., & Kelkar, N. (2012). River dolphin distribution in regulated river systems: implications for dry-season flow regimes in the Gangetic basin. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *22*(1), 11–25. http://doi.org/10.1002/aqc.1240

Clark, C. W., Ellison, W. T., Southall, B. L., Hatch, L., Van Parijs, S. M., Frankel, A., & Ponirakis, D. (2009). Acoustic masking in marine ecosystems: intuitions, analysis, and implication. *Ecology Progress Series*, *395*, 201–222.

Colborn, T., & Smolen, M. J. (1996). Epidemiological analysis of persistent organochlorine contaminants in cetaceans. In *Reviews of environmental contamination and toxicology* (pp. 91–172).

Coomes, O., Barham, B., & Takasaki, K. (2004). Targeting conservation–development initiatives in tropical forests: insights from analyses of rain forest use and economic reliance among Amazonian peasants. *Ecological Economics*, *51*(1–2), 47–64. http://doi.org/10.1016/J.ECOLECON.2004.04.004

Costa, M. H., & Pires, G. F. (2010). Effects of Amazon and Central Brazil deforestation scenarios on the duration of the dry season in the arc of deforestation. *International Journal of Climatology*, *30*(13), 1970–1979.

Cunha, H. A., da Silva, V. M. F., Lailson-Brito, J., Santos, M. C. O., Flores, P. A. C., Martin, A. R., … Solé-Cava, A. M. (2005). Riverine and marine ecotypes of Sotalia dolphins are different species. *Marine Biology*, *148*(2), 449–457. http://doi.org/10.1007/s00227-005-0078-2

Cunha, H. A., Da Silva, V. M. F., Santos, T. E. C., Moreira, S. M., Do Carmo, N. A. S., & Solé-Cava, A. M. (2015). When You Get What You Haven't Paid for: Molecular Identification of "douradinha" Fish Fillets Can Help End the Illegal Use of River Dolphins as Bait in Brazil. In *Journal of Heredity* (Vol. 106). http://doi.org/10.1093/jhered/esv040

D'Almeida, C., Vörösmarty, C. J., Hurtt, G. C., Marengo, J. A., Dingman, S. L., & Keim, B. D. (2007). The effects of deforestation on the hydrological cycle in Amazonia: a review on scale and resolution. *International Journal of Climatology*, *27*(5), 633–647. http://doi.org/10.1002/joc.1475

Da Silva, V., & Martin, A. (2000). *The Status of the Boto or Amazon River Dolphin Inia geoffrensis (de Blainville, 1817): A Review of Available Information.* Cambridge, UK.

Danilewicz, D., Secchi, E. R., Ott, P. H., Moreno, I. B., Bassoi, M., & Borges-Martins, M. (2009). Habitat use patterns of franciscana dolphins (Pontoporia blainvillei) off southern Brazil in relation to water depth. *Journal of the Marine Biological Association of the United Kingdom*, *89*(5), 943. http://doi.org/10.1017/S002531540900054X

Davidson, E. A., de Araújo, A. C., Artaxo, P., Balch, J. K., Brown, I. F., C. Bustamante, M. M., … Wofsy, S. C. (2012). The Amazon basin in transition. *Nature*, *481*(7381), 321–328. http://doi.org/10.1038/nature10717

Davis, G. E., Baumgartner, M. F., Bonnell, J. M., Bell, J., Berchok, C., Bort Thornton, J., … Van Parijs, S. M. (2017). Long-term passive acoustic recordings track the changing distribution of North Atlantic right whales (Eubalaena glacialis) from 2004 to 2014. *Scientific Reports*, *7*(1), 13460. http://doi.org/10.1038/s41598-017-13359-3

Dias, R., Da Silva, V. M. F., & Martin, A. R. (2014). Monitoring of Botos and Tucuxis (Mammalia, Cetacea) over the last twenty years in Brazilian Amazon shows drastic populational decrease. In *XVI Reunião de Trabalho de Especialistas em Mamíferos Aquáticos da América do Sul (XVI RT) e X Congresso da Sociedade Latino Americana de Especialistas em Mamíferos Aquáticos (SOLAMAC), At Cartagena, Colômbia*.

Dove, V. (2009). *Mortality investigation of the Mekong Irrawaddy River dolphin (Orcaella brevirostris) in Cambodia based on necropsy sample analysis.*

Dudgeon, D. (2000). Large-Scale Hydrological Changes in Tropical Asia: Prospects for Riverine Biodiversity. *http://dx.doi.org/10.1641/0006-3568(2000)050[0793:LSHCIT]2.0.CO;2*. http://doi.org/10.1641/0006-3568(2000)050[0793:LSHCIT]2.0.CO;2

Faustino, C., & Da Silva, V. M. F. (2006). Seasonal use of Amazon floodplains by the tucuxi Sotalia fluviatilis (Gervais 1853), in the central Amazon, Brazil. *Latin American Journal of Aquatic Mammals*, *5*(2), 95–104. http://doi.org/10.5597/lajam00100

Fettuccia, D., da Silva, V., & Simões-Lopes, P. (2009). Non-metric characters in two species of Sotalia (Gray, 1866) (Cetacea, Delphinidae). *Brazilian Journal of Biology*, *69*(3), 907–917. http://doi.org/10.1590/S1519-69842009000400020

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. http://doi.org/10.1371/journal.pone.0035126

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*, *3*(8), e2932. http://doi.org/10.1371/journal.pone.0002932

Frontier Economics HSBC. (2016). Economic output from top ten river basins. Retrieved February 17, 2017, from https://www.theguardian.com/news/datablog/2012/jun/11/water-river-basins-economic-growth#data

Gerrodette, T., Taylor, B. L., Swift, R., Rankin, S., Jaramillo-Legorreta, A. M., & Rojas-Bracho, L. (2011). A combined visual and acoustic estimate of 2008 abundance, and change in abundance since 1997, for the vaquita, Phocoena sinus. *Marine Mammal Science*, *27*(2), E79–E100. http://doi.org/10.1111/j.1748-7692.2010.00438.x

Gómez-Salazar, C. ., Coll, M. ., & Whitehead, H. (2012). River dolphins as indicators of ecosystem degradation in large tropical rivers. *Ecological Indicators*, *23*, 19–26. http://doi.org/10.1016/J.ECOLIND.2012.02.034

Gomez-Salazar, C., Trujillo, F., Portocarrero-Aya, M., & Whitehead, H. (2012). Population, density estimates, and conservation of river dolphins (Inia and Sotalia) in the Amazon and Orinoco river basins. *Marine Mammal Science*, *28*(1), 124–153. http://doi.org/10.1111/j.1748-7692.2011.00468.x

Hamilton, H., Caballero, S., Collins, A. G., & Brownell, R. L. (2001). Evolution of river dolphins. *Proceedings. Biological Sciences*, *268*(1466), 549–56. http://doi.org/10.1098/rspb.2000.1385

Hodge, K. B., Muirhead, C. A., Morano, J. L., Clark, C. W., & Rice, A. N. (2015). North Atlantic right whale occurrence near wind energy areas along the mid-Atlantic US coast: Implications for management. *Endangered Species Research*, *28*(3). http://doi.org/10.3354/esr00683

Hrbek, T., da Silva, V. M. F., Dutra, N., Gravena, W., Martin, A. R., & Farias, I. P. (2014). A New Species of River Dolphin from Brazil or: How Little Do We Know Our Biodiversity. *PLoS ONE*, *9*(1), e83623. http://doi.org/10.1371/journal.pone.0083623

Huang, S.-L., Mei, Z., Hao, Y., Zheng, J., Wang, K., & Wang, D. (2017). Saving the Yangtze finless porpoise: Time is rapidly running out. *Biological Conservation*, *210*, 40–46. http://doi.org/10.1016/J.BIOCON.2016.05.021

Huang, S. L., Hao, Y., Mei, Z., Turvey, S. T., & Wang, D. (2012). Common pattern of population decline for freshwater cetacean species in deteriorating habitats. *Freshwater Biology*, *57*(6), 1266–1276. http://doi.org/10.1111/j.1365-2427.2012.02772.x

Hurd, L. E., Sousa, R. G. C., Siqueira-Souza, F. K., Cooper, G. J., Kahn, J. R., & Freitas, C. E. C. (2016). Amazon floodplain fish communities: Habitat connectivity and conservation in a rapidly deteriorating environment. *Biological Conservation*, *195*, 118–127. http://doi.org/10.1016/J.BIOCON.2016.01.005

INEI (Instituto Nacional de Estadística e Informática). (2009). *Perú, Estimaciones y Proyecciones de población por sexo según departamento, provincia y distrito 2012-2015*. Lima Peru. Retrieved from https://www.scribd.com/doc/111455706/Peru-Estimaciones-y-Proyecciones-de-poblacion-por-sexo-segun-departamento-provincia-y-distrito-2012-2015-INEI

Iriarte, V., & Marmontel, M. (2013). River dolphin (inia geoffrensis, sotalia fluviatilis) mortality events attributed to artisanal fisheries in the western brazilian amazon. *Aquatic Mammals*, *39*(2). http://doi.org/10.1578/AM.39.2.2013.116

Iriarte, V., & Marmontel, M. (2014). Insights on the use of dolphins (boto, Inia geoffrensis and tucuxi, Sotalia fluviatilis) for bait in the piracatinga (Calophysus macropterus) fishery in the western Brazilian Amazon. *Journal of Cetacean Research and Management*, *13*(2).

Isaac, V. J. (2008). The artisanal fishery fleet of the lower Amazon. *Fisheries Management and Ecology*, *15*(3), 179–187. http://doi.org/10.1111/j.1365-2400.2008.00599.x

IWC. (2000). *Report of the Scientific Committee. 52nd Meeting of the International Whaling Commission*.

Jaramillo-Legorreta, A., Cardenas-Hinojosa, G., Nieto-Garcia, E., Rojas-Bracho, L., Ver Hoef, J., Moore, J., … Taylor, B. (2017). Passive acoustic monitoring of the decline of Mexico's critically endangered vaquita. *Conservation Biology*, *31*(1), 183–191. http://doi.org/10.1111/cobi.12789

Jiménez Cisneros, B. E., Oki, T., Arnell, N. W., Benito, G., Cogley, J. G., Doll, P., ..., & Mwakalila, S. S. (2014). Freshwater resources. In R. Pachauri & L. Meyer (Eds.), *Report of Working Group II to the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC).*

Jnawali, S. R., Baral, H. S., Lee, S., Acharya, K. P., Upadhyay, G. P., Pandey, M., … Khatiwada, A. P. (2011). The Status of Nepal Mammals: The National Red List Series, Department of National Parks and Wildlife Conservation Kathmandu, Nepal. *Preface by Simon M. Stuart Chair IUCN Species Survival Commission The Status of Nepal's Mammals: The National Red List Series*, *4*.

Kamminga, C., Van Hove, M. T., Englesma, F. J., & Terry, R. P. (1993). Investigations on cetacean sonar X: a comparative analysis of underwater echolocation clicks of Inia spp. and Sotalia spp. *Aquatic Mammals*, *19*, 31.

Kannan, K., Ramu, K., Kajiwara, N., Sinha, R. K., & Tanabe, S. (2005). Organochlorine Pesticides, Polychlorinated Biphenyls, and Polybrominated Diphenyl Ethers in Irrawaddy Dolphins from India. *Archives of Environmental Contamination and Toxicology*, *49*(3), 415–420.

Kannan, K., Senthilkumar, K., & Sinha, R. K. (1997). Sources and Accumulation of Butyltin Compounds in Ganges River Dolphin, Platanista gangetica. *Applied Organometallic Chemistry*, *11*, 223–230. Retrieved from https://s3.amazonaws.com/academia.edu.documents/46348097/Sources_and_Accumulation_of_Butyltin_Com20160608-24155-1njpezf.pdf?AWSAccessKeyId=AKIAIWOWYYGZ2Y53UL3A&Expires=1517601789&Signature=3t6Rsn4HwLlAtDRbGOu%2B%2BXbxQyU%3D&response-content-disposition=in

Kannan, K., Sinha, R. K., Tanabe, S., Ichihashi, H., & Tatsukawa, R. (1993). Heavy metals and organochlorine residues in Ganges River dolphins from India. *Marine Pollution Bulletin*, *26*(3), 159–162. http://doi.org/10.1016/0025-326X(93)90128-7

Kimura, S., Akamatsu, T., Li, S., Dong, S., Dong, L., Wang, K., … Arai, N. (2010). Density estimation of Yangtze finless porpoises using passive acoustic sensors and automated click train detection. *The Journal of the Acoustical Society of America*, *128*(3), 1435. http://doi.org/10.1121/1.3442574

Kimura, S., Akamatsu, T., Wang, K., Wang, D., Li, S., Dong, S., & Arai, N. (2009). Comparison of stationary acoustic monitoring and visual observation of finless porpoises. *The Journal of the Acoustical Society of America*, *125*(1), 547–553. http://doi.org/10.1121/1.3021302

Kreb, D., & Budiono. (2005). Conservation management of small core areas: key to survival of a Critically Endangered population of Irrawaddy river dolphins Orcaella brevirostris in Indonesia. *Oryx*, *39*(2), 178–188. http://doi.org/10.1017/S0030605305000426

Laghari, A. N., Vanham, D., & Rauch, W. (2012). The Indus basin in the framework of current and future water resources management. *Hydrol. Earth Syst. Sci*, *16*(4), 1063–1083. http://doi.org/10.5194/hess-16-1063-2012

Larsen, R. J., & Marx, M. L. (2006). *An Introduction to Mathematical Statistics and its Applications*. (S. Yagan, Ed.) (4th ed.). Upper Saddle River, New Jersey: Pearson Prentis Hall.

Li, S., Akamatsu, T., Wang, D., & Wang, K. (2009). Localization and tracking of phonating finless porpoises using towed stereo acoustic data-loggers. *The Journal of the Acoustical Society of America*, *126*(1), 468–475. http://doi.org/10.1121/1.3147507

Loch, C., Marmontel, M., & Simões-Lopes, P. C. (2009). Conflicts with fisheries and intentional killing of freshwater dolphins (Cetacea: Odontoceti) in the Western Brazilian Amazon. *Biodiversity and Conservation*, *18*(14), 3979–3988. http://doi.org/10.1007/s10531-009-9693-4

Macedo, M. N. (2012). *Seeing the forest for the streams: A multiscale study of land-use change and stream ecosystems in the Amazon's agricultural frontier*. Columbia University. Retrieved from https://doi.org/10.7916/D89039N6

Malhi, Y., Aragão, L. E. O. C., Galbraith, D., Huntingford, C., Fisher, R., Zelazowski, P., … Meir, P. (2009). Exploring the likelihood and mechanism of a climate-change-induced dieback of the Amazon rainforest. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(49), 20610–5. http://doi.org/10.1073/pnas.0804619106

Marques, T. A., Thomas, L., Martin, S. W., Mellinger, D. K., Ward, J. A., Moretti, D. J., … Tyack, P. L. (2013). Estimating animal population density using passive acoustics. *Biological Reviews*, *88*(2), 287–309. http://doi.org/10.1111/brv.12001

Martin, A. R., & da Silva, V. M. E. (2004). River dolphins and flooded forest: seasonal habitat use and sexual segregation of botos (Inia geoffrensis) in an extreme cetacean environment. *Journal of Zoology*, *263*, 295–305. http://doi.org/10.1017/S095283690400528X

Martin, A. R., Da Silva, V. M. F., & Salmon, D. L. (2004). Riverine habitat preferences of botos (Inia geoffrensis) and tucuxis (Sotalia fluviatilis) in the central Amazon. *Marine Mammal Science*, *20*(2), 189–200. http://doi.org/10.1111/j.1748-7692.2004.tb01150.x

MathWorks Inc. (n.d.). MATLAB and Statistics Toolbox Release 2016a. Natick, Massachusetts, United States.

McGrath, D. G., Cardoso, A., & Sá, E. P. (2004). COMMUNITY FISHERIES AND CO-MANAGEMENT ON THE LOWER AMAZON FLOODPLAIN OF BRAZIL. In R. L. Welcomme & T. Petr (Eds.), *THE SECOND INTERNATIONAL SYMPOSIUM ON THE MANAGEMENT OF LARGE RIVERS FOR FISHERIES.* (pp. 207–221). Retrieved from http://www.indiawaterportal.org/sites/indiawaterportal.org/files/Proceedings_IInd International Symposium_Management of Large Rivers for Fisheries_FAO %26 Mekong River Commission_2003_Volume II.pdf#page=215

McGuire, T. L., & Alaiga-Rossel, E. (2010). *Ecology and conservation status of river dolphins Inia and Sotalia in Peru: from The Action Plan for South American River Dolphins 2010 – 2020. WWF, Fundación Omacha, WDS, WDCS, Solamac*.

Mcguire, T. L., & Henningsen, T. (2007). Movement Patterns and Site Fidelity of River Dolphins (Inia geoffrensis (Inia geoffrensis (and Sotalia fluviatilis) in the Peruvian Amazon as Determined by Photo-Identification. *Aquatic Mammals*, *33*(3), 359–367. http://doi.org/10.1578/AM.33.3.2007.359

Mei, Z., Huang, S.-L., Hao, Y., Turvey, S. T., Gong, W., & Wang, D. (2012). Accelerating population decline of Yangtze finless porpoise (Neophocaena asiaeorientalis asiaeorientalis). *Biological Conservation*, *153*, 192–200. http://doi.org/10.1016/J.BIOCON.2012.04.029

Mellinger, D. K., Nieukirk, S. L., Klinck, K., Klinck, H., Dziak, R. P., Clapham, P. J., & Brandsdóttir, B. (2011). Confirmation of right whales near a nineteenth-century whaling ground east of southern Greenland. *Biology Letters*, *7*(3), 411–3. http://doi.org/10.1098/rsbl.2010.1191

Milliman, J. D., & Meade, R. H. (1983). World-Wide Delivery of River Sediment to the Oceans. *The Journal of Geology*, *91*(1), 1–21. http://doi.org/10.1086/628741

Minton, G., Smith, B. D., Braulik, G. T., Kreb, D., Sutaria, D., & Reeves, R. (2017). Orcaella brevirostris. *The IUCN Red List of Threatened Species*. Retrieved from http://dx.doi.org/10.2305/IUCN.UK.2017-3.RLTS.T15419A50367860.en

Mintzer, V. J. ., Martin, A. R. ., da Silva, V. M. ., Barbour, A. B. ., Lorenzen, K. ., & Frazer, T. K. (2013). Effect of illegal harvest on apparent survival of Amazon River dolphins (Inia geoffrensis). *Biological Conservation*, *158*, 280–286. http://doi.org/10.1016/J.BIOCON.2012.10.006

Mintzer, V. J., Schmink, M., Lorenzen, K., Frazer, T. K., Martin, A. R., & da Silva, V. M. F. (2015). Attitudes and behaviors toward Amazon River dolphins (Inia geoffrensis) in a sustainable use protected area. *Biodiversity and Conservation*, *24*(2). http://doi.org/10.1007/s10531-014-0805-4

Monteferri, B., & Carpio, C. (2007). *Oportunidades para el turismo en la Reserva Nacional Pacaya Samiria: Invirtiendo en conservación con responsabilidad*. Lima Peru. Retrieved from http://bibliotecavirtual.minam.gob.pe/biam/bitstream/handle/minam/758/BIV00220.pdf?sequence=1

Monteiro-Neto, C., Alves-Júnior, T. T., Avila, F. C., Campos, A. A., Costa, A. F., Silva, C. N., & Furtado-Neto, M. A. A. (2000). Impact of fisheries on the tucuxi (Sotalia fluviatilis) and rough-toothed dolphin (Steno bredanensis) populations off Ceará state, northeastern Brazil. *Aquatic Mammals*, *26*(1), 49–56.

Morano, J. L., Rice, A. N., Tielens, J. T., Estabrook, B. J., Murray, A., Roberts, B. L., & Clark, C. W. (2012). Acoustically Detected Year-Round Presence of Right Whales in an Urbanized Migration Corridor. *Conservation Biology*, *26*(4), 698–707. http://doi.org/10.1111/j.1523-1739.2012.01866.x

Muirhead, C. A., Salisbury, D. P., Diamond, C., & Rice, A. N. (2014). *Acoustic and Visual Surveys for Baleen Whales in Virginia's Coastal Waters*. Ithaca, NY.

Muirhead, C. A., Warde, A. M., Biedron, I. S., Nicole Mihnovets, A., Clark, C. W., & Rice, A. N. (2018). Seasonal acoustic occurrence of blue, fin, and North Atlantic right whales in the New York Bight. *Aquatic Conservation: Marine and Freshwater Ecosystems*. http://doi.org/10.1002/aqc.2874

National Academies of Sciences, Engineering, and M. (2017). *Approaches to Understanding the Cumulative Effects of Stressors on Marine Mammals*. Washington, D.C.: National Academies Press. http://doi.org/10.17226/23479

Nichols, J. D., & Williams, B. K. (2006). Monitoring for conservation. *Trends in Ecology & Evolution*, *21*(12), 668–673. http://doi.org/10.1016/J.TREE.2006.08.007

Nilsson, C., & Berggren, K. (2000). Alterations of Riparian Ecosystems Caused by River Regulation: Dam operations have caused global-scale ecological changes in riparian ecosystems. *BioScience*, *50*(9), 783–792.

NOWACEK, D. P., THORNE, L. H., JOHNSTON, D. W., & TYACK, P. L. (2007). Responses of cetaceans to anthropogenic noise. *Mammal Review*, *37*(2), 81–115. http://doi.org/10.1111/j.1365-2907.2007.00104.x

Parijs, S. M. Van, Clark, C. W., Sousa-Lima, R. S., Parks, S. E., Rankin, S., Risch, D., & Opzeeland, I. C. Van. (2009). Management and research applications of real-time and archival passive acoustic sensors over varying temporal and spatial scales. *Marine Ecology Progress Series*, *395*, 21–36. http://doi.org/10.2307/24874239

Paudel, S., Timilsina, Y. P., Lewis, J., Ingersoll, T., & Jnawali, S. R. (2015). Population status and habitat occupancy of endangered river dolphins in the Karnali River system of Nepal during low water season. *Marine Mammal Science*, *31*(2). http://doi.org/10.1111/mms.12192

Pavanato, H. J., Melo-Santos, G., Lima, D. S., Portocarrero-Aya, M., Paschoalini, M., Mosquera, F., … Maretti, C. (2016). Risks of dam construction for South American river dolphins: A case study of the Tapaj?s River. *Endangered Species Research*. http://doi.org/10.3354/esr00751

Petrere Jr., M. (1989). River fisheries in Brazil: A review. *Regulated Rivers: Research & Management*, *4*(1), 1–16. http://doi.org/10.1002/rrr.3450040102

Pivari, D., Pacca, H. M., De, T., & Sebrian, C. G. (2017). Occurrence of Boto-do-Araguaia (Inia araguaiaensis) in a Region of the Araguaia River, Brazil, Documented for an Environmental Impact Study for a Hydroelectric Dam. *Aquatic Mammals*, *4343*(105). http://doi.org/10.1578/AM.43.5.2017.530

Raven Pro 1.4 User's Manual. (2010). *Raven Pro 1.4 User's Manual*. Ithaca, NY: Cornell Lab of Ornithology.

Rayment, W., Dawson, S., Scali, S., & Slooten, L. (2011). Listening for a needle in a haystack: passive acoustic detection of dolphins at very low densities. *Endangered Species Research*, *14*(2), 149–156. http://doi.org/10.3354/esr00356

Reeves, R. R., Chaudhry, A. A., & Khalid, U. (1991). Competing for Water on the Indus Plain: Is There a Future for Pakistan's River Dolphins? *Environmental Conservation*, *18*(4), 341. http://doi.org/10.1017/S0376892900022591

Reeves, R. R., Jefferson, T. A., Karczmarski, L., Laidre, K., O'Corry-Crowe, G., Rojas-Bracho, L., … Zhou, K. (2008). *Orcaella brevirostris. The IUCN Red List of Threatened Species*. Retrieved from http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T15419A4579987.en

Reeves, R. R., Jefferson, T. A., Karczmarski, L., Laidre, K., O'Corry-Crowe, G., Rojas-Bracho, L., … Zhou, K. (2011). *Inia geoffrensis. The IUCN Red List of Threatened Species 2011*.

Reeves, R. R., Smith, B. D. (Brian D., Crespo, E. A., Notarbartolo di Sciara, G., & IUCN/SSC Cetacean Specialist Group. (2003). *Dolphins, whales, and porpoises : 2002-2010 conservation action plan for the world's cetaceans*. (IUCN/SSC Cetacean Specialist Group, Ed.). Gland, Switzerland and Cambridge, UK.: IUCN. Retrieved from https://portals.iucn.org/library/node/8201

Reeves, R. R., Smith, B. D., & Kasuya, T. (2000). *Biology and Conservation of Freshwater Cetaceans in Asia*. *IUCN*. Gland, Switzerland and Cambridge, UK.

Rice, A. N., Tielens, J. T., Estabrook, B. J., Muirhead, C. A., Rahaman, A., Guerra, M., & Clark, C. W. (2014). Variation of ocean acoustic environments along the western North Atlantic coast: A case study in context of the right whale migration route. *Ecological Informatics*, *21*. http://doi.org/10.1016/j.ecoinf.2014.01.005

Rice, D. W. (1998). *Marine mammals of the world : systematics and distribution*. Society for Marine Mammalogy.

Richards, P., & VanWey, L. (2015). Where Deforestation Leads to Urbanization: How Resource Extraction Is Leading to Urban Growth in the Brazilian Amazon. *Annals of the Association of American Geographers*, *105*(4), 806–823. http://doi.org/10.1080/00045608.2015.1052337

Richman, N. I., Gibbons, J. M., Turvey, S. T., Akamatsu, T., Ahmed, B., Mahabub, E., … Jones, J. P. G. (2014). To See or Not to See: Investigating Detectability of Ganges River Dolphins Using a Combined Visual-Acoustic Survey. *PloS One*, *9*(5), e96811.

Risch, D., Castellote, M., Clark, C. W., Davis, G. E., Dugan, P. J., Hodge, L. E., … Van Parijs, S. M. (2014). Seasonal migrations of North Atlantic minke whales: novel insights from large-scale passive acoustic monitoring networks. *Movement Ecology*, *2*(1), 24. http://doi.org/10.1186/s40462-014-0024-3

Rosas, F. C. W., & Lehti, K. K. (1996). Nutritional and mercury content of milk of the Amazon river dolphin, Inia geoffrensis. *Comparative Biochemistry and Physiology A-Physiology*, *115*(2), 117–119. http://doi.org/10.1016/0300-9629(96)00021-7

Salisbury, D. P., Clark, C. W., & Rice, A. N. (2016). Right whale occurrence in the coastal waters of Virginia, U.S.A.: Endangered species presence in a rapidly developing energy market. *Marine Mammal Science*, *32*(2), 508–519. http://doi.org/10.1111/mms.12276

Sasaki-Yamamoto, Y., Akamatsu, T., Ura, T., Sugimatsu, H., Kojima, J., Bahl, R., … Kohshima, S. (2013). Diel changes in the movement patterns of Ganges River dolphins monitored using stationed stereo acoustic data loggers. *Marine Mammal Science*, *29*(4), 589–605. http://doi.org/10.1111/j.1748-7692.2012.00590.x

Secchi, E. (2012). Sotalia fluviatilis. *The IUCN Red List of Threatened Species 2012: e.T190871A17583369*. Retrieved from http://dx.doi.org/10.2305/IUCN.UK.2012.RLTS.T190871A17583369.en

SERNANP (Servicio Nacional de Áreas Naturales Protegidas). (2009). *Plan maestro Reserva Nacional Pacaya Samiria para la conservación de la diversidad biológica y el desarrollo sostenible de la Reserva Nacional Pacaya Samiria y su zona de amortiguamiento 2009-2013*. Iquitos Peru. Retrieved from http://old.sernanp.gob.pe/sernanp/archivos/biblioteca/publicaciones/RN_Pacaya/Plan Maestro 2009-2014 RN Pacaya Samiria ver pub.pdf

Sharma, B., Amarasinghe, U., Xueliang, C., de Condappa, D., Shah, T., Mukherji, A., … Smakhtin, V. (2010). The Indus and the Ganges: river basins under extreme pressure. *Water International*, *35*(5), 493–521. http://doi.org/10.1080/02508060.2010.512996

Shostell, J. M., & Ruiz, M.-G. (2010). An Introduction to River Dolphin Species. In *Biology, Evolution and Conservation of River Dolphins within South America and Asia* (p. 504). UK: Nova Science Pub Inc. Retrieved from https://www.researchgate.net/profile/Manuel_Ruiz-Garcia/publication/230585067_An_introduction_to_River_Dolphin_species/links/0912f501b087e3cb0b000000/An-introduction-to-River-Dolphin-species.pdf

Silva, V. M. F., & Best, R. C. (1996). Freshwater dolphin/fisheries interaction in the Central Amazon(Brazil). *Amazoniana*, *14*(1), 165–175.

Singh, M., & Singh, A. K. (2007). Bibliography of Environmental Studies in Natural Characteristics and Anthropogenic Influences on the Ganga River. *Environmental Monitoring and Assessment*, *129*(1–3), 421–432. http://doi.org/10.1007/s10661-006-9374-7

Sinha, R. K., & Kannan, K. (2014). Ganges River Dolphin: An Overview of Biology, Ecology, and Conservation Status in India. *AMBIO*, *43*(8), 1029–1046. http://doi.org/10.1007/s13280-014-0534-7

Smith, B., Aminul, A., Shakhawat, H., & Khan, H. (1998). River Dolphins in Bangladesh: Conservation and the Effects of Water Development, *22*(3), 323–335. Retrieved from https://search-proquest-com.proxy.lib.duke.edu/docview/884865322?pq-origsite=summon&https://www.nclive.org/cgi-bin/nclsm?rsrc=328

Smith, B. D., Ahmed, B., Edrise Ali, M., & Braulik, G. (2001). Status of the Ganges river dolphin or shushuk Platanista gangetica in Kaptai Lake and the southern rivers of Bangladesh. *Oryx*, *35*(1). http://doi.org/10.1046/j.1365-3008.2001.00153.x

Smith, B. D., Braulik, G., Strindberg, S., Mansur, R., Diyan, M. A. A., & Ahmed, B. (2009). Habitat selection of freshwater-dependent cetaceans and the potential effects of declining freshwater flows and sea-level rise in waterways of the Sundarbans mangrove forest, Bangladesh. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *19*(2), 209–225. http://doi.org/10.1002/aqc.987

Smith, B. D., Braulik, G. T., & Sinha, R. (2012). Platanista gangetica ssp. gangetica. *The IUCN Red List of Threatened Species 2012: e.T41756A17627639*.

Smith, B. D., & Reeves, R. R. (1997). *Report of the Workshop on the Effects of Water Development on River Cetaceans*. Rajendrapur, Bangladesh.

Smith, B. D., & Reeves, R. R. (2012). River Cetaceans and Habitat Change: Generalist Resilience or Specialist Vulnerability? *Journal of Marine Biology*, *2012*, 1–11. http://doi.org/10.1155/2012/718935

Smith, B. D., Shore, R. G., & Lopez, A. (2007). *Status and Conservation of Freshwater Populations of Irrawaddy Dolphins* (No. 31). Retrieved from http://www.wcs.org/science

Smith, B. D., Wang, D., Braulik, G. T., Reeves, R., Zhou, K., Barlow, J., & Pitman, R. L. (2017). Lipotes vexillifer. *The IUCN Red List of Threatened Species 2017: e.T12119A50362206*.

Soares-Filho, B. S., Nepstad, D. C., Curran, L. M., Cerqueira, G. C., Garcia, R. A., Ramos, C. A., … Schlesinger, P. (2006). Modelling conservation in the Amazon basin. *Nature*, *440*(7083), 520–523. http://doi.org/10.1038/nature04389

Sousa-Lima, R. S., Norris, T. F., Oswald, J. N., & Fernandes, D. P. (2013). A Review and Inventory of Fixed Autonomous Recorders for Passive Acoustic Monitoring of Marine Mammals. *Aquatic Mammals*, *39*(1), 23–53. http://doi.org/10.1578/AM.39.1.2013.23

Swenson, J. J., Carter, C. E., Domec, J.-C., & Delgado, C. I. (2011). Gold Mining in the Peruvian Amazon: Global Prices, Deforestation, and Mercury Imports. *PLoS ONE*, *6*(4), e18875. http://doi.org/10.1371/journal.pone.0018875

The World Bank. (2018). World Bank national accounts data, and OECD National Accounts data files.

Trujillo, F. ., Crespo, E. ., Van Damme, P. A. ., & Usma, J. S. (2010). The Action Plan for South American River Dolphins: 2010-2020. In F. . Trujillo, E. . Crespo, P. A. . Van Damme, & J. S. Usma (Eds.), . Solamac. Bogotá, D.C., Colombia.: WWF, Fundación Omacha, WDS, WDCS.

Turvey, S. (2009). *Witness to extinction : how we failed to save the Yangtze River dolphin*. Oxford University Press.

Turvey, S. T., Pitman, R. L., Taylor, B. L., Barlow, J., Akamatsu, T., Barrett, L. A., … Wang, D. (2007). First human-caused extinction of a cetacean species? *Biology Letters*, *3*(5). Retrieved from http://rsbl.royalsocietypublishing.org/content/3/5/537.short

Turvey, S. T., Risley, C. L., Barrett, L. A., Yujiang, H., & Ding, W. (2012). River Dolphins Can Act as Population Trend Indicators in Degraded Freshwater Systems. *PLoS ONE*, *7*(5), e37902. http://doi.org/10.1371/journal.pone.0037902

Turvey, S. T., Risley, C. L., Moore, J. E., Barrett, L. A., Yujiang, H., Xiujiang, Z., … Ding, W. (2013). Can local ecological knowledge be used to assess status and extinction drivers in a threatened freshwater cetacean? *Biological Conservation*, *157*, 352–360. http://doi.org/10.1016/J.BIOCON.2012.07.016

U.N. (United Nations). (2011). *Ganges-Brahmaputra-Meghna river basin*. Retrieved from http://www.fao.org/nr/water/aquastat/basins/gbm/gbm-CP_eng.pdf

U.N. (United Nations). (2017). *World Population Prospects: The 2017 Revision*.

Vidal, O., Barlow, J., Hurtado, L. A., Torre, J., Cendon, P., & Ojeda, Z. (1997). Distribution and abundance of the Amazon river dolphin (Inia geoffrensis) and the tucuxi (Sotalia fluviatilis) in the Upper Amazon river. *Marine Mammal Science*, *13*(3), 427–445. http://doi.org/10.1111/j.1748-7692.1997.tb00650.x

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., & Davies, P. M. (2010). Global threats to human water security and river biodiversity. *Nature*, *467*(7135), 555.

Wang, D., Hao, Y., Wang, K., Zhao, Q., Chen, D., Wei, Z., & Zhang, X. (2005). Aquatic Resource Conservation. The first Yangtze finless porpoise successfully born in captivity. *Environmental Science and Pollution Research - International*, *12*(5), 247–250. http://doi.org/10.1065/espr2005.08.284

Wang, D., Turvey, S. T., Zhao, X., & Mei, Z. (2013). Neophocaena asiaeorientalis ssp. asiaeorientalis. *The IUCN Red List of Threatened Species 2013: e.T43205774A45893487*.

Wang, D., Zhang, X., & Liu, R. (1998). Conservation status and the future of baiji and finless porpoise in the Yangtze River of China. In Z. Huang, B. Fu, & Z. Yang (Eds.), *Ecology and environment protection in the large water conservancy projects of the Yangtze River* (pp. 218–226). Beijing, China: Environmental Science Press.

Wang, D., Zhang, X., Wang, K., Wei, Z., Würsig, B., Braulik, G. T., & Ellis, S. (2006). Conservation of the Baiji: No Simple Solution. *Conservation Biology*, *20*(3), 623–625. http://doi.org/10.2307/3879219

Wang, K., Wang, D., Zhang, X., Pfluger, A., & Barrett, L. (2006). Range-wide Yangtze freshwater dolphin expedition: The last chance to see Baiji? *Environmental Science and Pollution Research*, *13*(6), 418–424. http://doi.org/10.1065/espr2006.10.350

Waqas, U., Malik, M. I., & Khokhar, L. A. (2012). Conservation of Indus River Dolphin (Platanista gangetica minor) in the Indus River system, Pakistan: an overview. *Rec. Zool. Surv.*, *21*, 82–85.

Yamamoto, Y., Akamatsu, T., da Silva, V. M. F., Yoshida, Y., & Kohshima, S. (2015). Acoustic characteristics of biosonar sounds of free-ranging botos (Inia geoffrensis) and tucuxis (Sotalia fluviatilis) in the Negro River, Amazon, Brazil. *The Journal of the Acoustical Society of America*, *138*(2). http://doi.org/10.1121/1.4926440

Zappes, C. A., Alves, L. C. P. de S., Silva, C. V. da, Azevedo, A. de F., Di Beneditto, A. P. M., & Andriolo, A. (2013). Accidents between artisanal fisheries and cetaceans on the Brazilian coast and Central Amazon : Proposals for integrated management. *Ocean & Coastal Management*, *85*, 46–57. http://doi.org/10.1016/j.ocecoaman.2013.09.004

Zerbini, A. N., Secchi, E., Crespo, E., Danilewicz, & D. & Reeves, R. (2017). Pontoporia blainvillei. *The IUCN Red List of Threatened Species 2017: e.T17978A50371075*.

Zhang, X., Wang, D., Liu, R., W, Z., Hua, Y., Wang, Y., … Wang, L. (2003). The Yangtze River dolphin or baiji (Lipotes vexillifer): population status and conservation issues in the Yangtze River, China. *Aquatic Conservation: Marine and Freshwater Ecosystems*, *13*(1), 51–64. http://doi.org/10.1002/aqc.547

Zhang, X., Wei, Z., Wang, X., Yang, J., & Chen, P. (1995). Studies on the feasibility of establishment of a semi-natural reserve at Tian-e-zhou (Swan) Oxbow for baiji, Lipotes vexillifer. *Acta Hydrobiologica Sinica*, *19*(2), 110–122.

Zhao, X., Barlow, J., Taylor, B. L., Pitman, R. L., & Wang, K. (2008). Abundance and Conservation Status of the Yangtze Finless Porpoise in the Yangtze River, China. *Biological Conservation*, *141*(12), 3006–3018. Retrieved from http://digitalcommons.unl.edu/usdeptcommercepub

Zhou, K. (1982). On the conservation of the baiji, Lipotes vexillifer. *Nat. Sci.*, *4*, 71–74.