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Population, density estimates, and conservation of river dolphins (*Inia* and *Sotalia*) in the Amazon and Orinoco river basins

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ABSTRACT

This study is part of an on-going effort to evaluate and monitor river dolphin populations in South America. It comprises the largest initiative to estimate population size and densities of *Inia* and *Sotalia* dolphins using statistically robust and standardized methods. From May 2006 to August 2007, seven visual surveys were conducted in selected large rivers of Bolivia, Colombia, Brazil, Ecuador, Peru, and Venezuela in the Amazon and Orinoco river basins. Population sizes of *Inia* and *Sotalia* were estimated for different habitats (main river, tributary, lake, island, confluence, and channel). A total of 291 line and 890 strip transects were conducted, covering a distance of 2,704 linear kilometers. We observed 778 *Inia geoffrensis*, 1,323 *Inia boliviensis*, and 764 *Sotalia fluviatilis*. High-density areas were identified (within 200 m from the river banks, confluences, and lakes) and we propose that these constitute critical habitat for river dolphins. High densities of river dolphins seem to coincide with well-managed freshwater protected areas and should be considered as hot spots for river dolphins in South America.

Key words: pink river dolphin, boto, *Inia*, tucuxi, *Sotalia fluviatilis*, population size, density, Amazon and Orinoco river basins, conservation.

To manage and conserve any species effectively, a good understating of population density and habitat use are critical. Riverine cetaceans generally surface inconspicuously and are highly mobile. This complicates efforts to estimate abundance, and as a result, management efforts are delayed due to a lack of knowledge. Riverine dolphins, which inhabit major river systems in Asia and South America, include some of the most endangered cetaceans (Reeves and Leatherwood 1994, IWC 2000, Reeves 2000). As a result of their proximity to terrestrial habitat, major anthropogenic threats, such as the depletion of aquatic resources, water development projects, noise pollution, chemical pollution and direct capture of dolphins are likely to increase (Vidal 1993). Statistically robust and standardized density and population estimates are necessary to inform the conservation status and monitor trends of river dolphin populations worldwide (Reeves and Leatherwood 1994, IWC 2000, Reeves 2000).

Based on information obtained from rigorous surveys dedicated to estimating density and population sizes, the conservation status of many cetacean species that live close to land is of serious concern. The most dramatic case is that of the Yangtze River dolphin (*Lipotes vexillifer*) in China which is considered "Functionally Extinct" due to a lack of sightings or acoustic records during an intensive 6 wk multi-vessel survey using a line transect sampling design (Turvey *et al*. 2007). Similarly, the vaquita (*Phocoena sinus*) in the northern reaches of the Gulf of California in Mexico, categorized by the International Union for Conservation of Nature (IUCN) as Critically Endangered, is in serious danger of extinction due to their isolated and localized distribution, high levels of entanglements and small population size, which was assessed using line-transect surveys covering its entire distribution (Jaramillo-Legorreta *et al*. 1999, Rojas-Bracho *et al.* 2006, Gerrodette *et al.* 2011). The Ganges river dolphin (*Platanista gangetica*) and the Irrawaddy dolphin (*Orcaella brevirostris*), currently classified as Endangered and Vulnerable, respectively, have also been subjects of rigorous visual vessel-based surveys (Braulik 2006, Smith *et al*. 2006, Smith and Braulik 2008).

River dolphins in South America are widely distributed in the Amazon and Orinoco river basins. The boto, or pink river dolphin, of the family Iniidae had three recognized subspecies: *Inia geoffrensis geoffrensis* in the Amazon basin, *Inia geoffrensis humboldtiana* in the Orinoco basin, and *Inia geoffrensis boliviensis* in the Bolivian Amazon basin (Best and da Silva 1989*a*, *b*; Pilleri and Gihr 1977, Rice 1998). However, more recent studies have suggested that the genus *Inia* has two species: *Inia geoffrensis* in the Amazon and Orinoco basins (Brazil, Colombia, Ecuador, Peru, French Guiana, and Venezuela) and *Inia boliviensis* in the Amazon and Madeira upper basins (Bolivia) (da Silva 1994; Hamilton *et al*. 2001; Banguera-Hinestroza *et al*. 2002; Ruiz-Garcia *et al*. 2006, 2007, 2008; Ruiz-García 2010). We use this taxonomy. The tucuxi, *Sotalia fluviatilis*, of the family Delphinidae is sympatric with *Inia* in Brazil, Colombia, Ecuador, Peru, and French Guiana in the Amazon river basin (Borobia *et al*. 1991, Cunha *et al*. 2005, Caballero *et al*. 2007). In the

Orinoco river basin, *Sotalia* dolphins have been sighted along the entire Orinoco River in Venezuela below the Parguaza rapids. Further research is needed to decide whether these populations of *Sotalia* in the Orinoco are coastal transients making incursions into the river, or part of a riverine population that entered into the Amazon and from there made its way to the Orinoco (Borobia *et al*. 1991, Caballero *et al.* 2007).

The overall population size of river dolphins in the Amazon and Orinoco basins is currently unknown. *Inia geoffrensis* and *Sotalia fluviatilis* remain listed by the IUCN as Data Deficient (Reeves *et al*. 2008) and the status of *Inia boliviensis,* if considered as a separate species, has yet to be established. Population estimates comprise one of the five scientific criteria used by the IUCN to list species into categories of threat, which are designed to draw attention to species that may be at risk of extinction (IUCN 2010).

Population estimates for *Inia* and *Sotalia* in South America have been obtained sporadically from surveys conducted in small areas using varied methodologies. Previous data on river dolphins has mainly been expressed as encounter rates instead of population numbers (Layne 1958, Kasuya and Kajihara 1974, Pilleri and Gihr 1977, Meade and Koehnken 1991, da Silva 1994, Herman *et al.* 1996, Trujillo 2000). The first rigorous survey for South American river dolphins *Inia* and *Sotalia* using a standardized protocol of strip and line transects was conducted over 120 linear kilometers in the Amazon River, bordering Colombia, Peru, and Brazil (Vidal *et al*. 1997). Subsequently, these methods were used to estimate population parameters of river dolphins in the upper Peruvian Amazon basin (Leatherwood 1996), Ecuador (Utreras 1996), Peru (McGuire 2002), Bolivia (Aliaga-Rossel 2002), and Brazil (Martin and da Silva 2004, Martin *et al*. 2004). Results showed that *Inia* and *Sotalia* dolphins aggregate in productive environments with high fish densities and low current speeds. Densities appear to be generally higher at the river margins, confluences and lakes, and change with hydroclimatic seasons (Martin and da Silva 2004, Martin *et al*. 2004). The Amazon and Orinoco basins are strongly influenced by seasonal changes in hydrology. Within the same year, variations of 11–15 m may occur in the vertical level of a river, and hundreds of kilometers in the horizontal plane (Goulding *et al*. 1996). These changes affect dissolved oxygen, fish migrations, habitat availability and productivity, and consequently the distribution of river dolphins (Martin *et al*. 2004). During the low water period, the available aquatic habitat is considerably reduced, and dolphin populations are constrained. During the high water period, more habitats become available (*e.g.,* channels, shallow lakes, and flooded forest), and the aquatic fauna disperse. These changes are known to affect interactions between predators and their prey (Goulding 1980, Goulding 1989, Fernandes 1997).

This study comprises the largest regional initiative in South America designed to obtain detailed information on populations of river dolphins in order to evaluate their conservation status. We used standardized strip and line transect surveys in selected rivers across the Amazon and Orinoco basins in order to determine (1) what are the group sizes and densities of *Inia* and *Sotalia*, (2) which features of the environment are related to these density estimates and group sizes, and (3) what are the population sizes of river dolphins in different locations of South America. This study is part of an initiative to establish a network of Freshwater Protected Areas (FWPAs) by researchers, governments and local communities named SARDPAN (South American River Dolphin Protected Area Network).

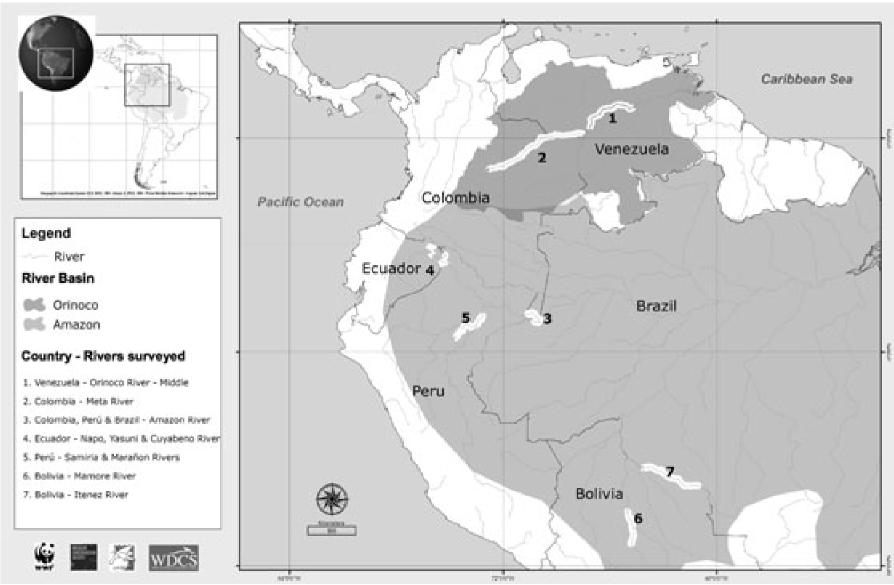

Figure 1. Map of the Amazon and Orinoco basins in South America showing the rivers surveyed for each country during the expeditions conducted from 2006 to 2007.

METHODS

Field Methods

Between May 2006 and August 2007, seven surveys were conducted in large rivers in six countries of the Amazon and Orinoco basins (Fig. 1, Table 1). Boats were chartered in each area in order to conduct visual surveys using standardized methods: a combination of transects running parallel (200 m strip-width transect) and at 45° (cross-channel line transects) to the shore (Vidal *et al*. 1997). Strip-width transects of 200 m were oriented parallel to the banks along the river margins of each river, maintaining an average distance of 100 m from the shore, as controlled by laser range finders. When the river margins were <200 m wide in some habitats such as tributaries and channels, the vessel navigated through the center of the waterway and the average strip-width was calculated by measuring distances to each shore with laser range finders (Vidal *et al*. 1997). Cross-channel line transect routes were conducted by selecting a starting point for the vessel to turn on a ~45° angle towards the other bank, where another 200 m strip-width transect was begun. These turns were made when at least one strip transect had been completed and in places where the captain considered it safe and convenient to cross the river in order to avoid obstacles such as rocks, islands, large floating objects, and shallow areas (Vidal *et al*. 1997).

Sighting protocols were the same for both transect types. Two platforms in constant communication were installed in each ship; one at the front with at least four observers (effort data recorder, sightings data recorder, and two observers) and one at the back, with at least two observers (sightings data recorder and observer) to record sightings that were missed by observers in the front. Sightings from the forward platform

Table 1. Countries, dates, and habitats surveyed: area, transect length, Ntrans (the number of transects performed per habitat type), and N*Inia* and N*Sotalia* (the number of dolphins seen on the surveys). *S* is 200 m strip-width transect and *L* is cross-channel line transect. Data were not estimated (N/A) or not available in the field (blank spaces) for some categories.

			Area (km^2)		Length (km)		Ntrans		N*Inia*		N*Sotalia*	
Country (river)	Date	Habitat	*S*	*L*	*S*	*L*	*S*	*L*	*S*	*L*	*S*	*L*
Amazon River Basin												
Bolivia (River	12–22 August	Channel	51.0		30.5		10		41			
Itenez)	2007	Lake	8.0		11.7		6		40			
		Confluence			2.1		1					
		Tributary	930.3	124.2	554.5		152		824			
			989.3						905			
		Total	1,113.5		598.8		173		905			
Bolivia	17–22 June	Tributary	389.0		365.9		146		418			
(River Mamore)	2007	Total	389.0		365.9		146		418			
Colombia (Rivers	21–29 February	Channel	61.0	N/A	59.6		19		39		72	
Amazon	2007	Confluence	N/A	N/A	7.2		4		23		34	
Loretoyacu		Island	54.0		66.1		23		38		46	
Javari)		Lake	9.6	N/A	12.5		8		32		36	
		Main River	67.5	347.6	120.7	46.8	46	37	52	6	126	11
		Tributary	52.8	N/A	2.4		1		5		2	
			245.0	347.6	268.3	46.8	101	37	189	6	316	11
		Total	592.6		315.2		138		195		327	
Ecuador (Rivers	17–22 July	Confluence	N/A		11.1		4		7		2	
Napo Cuyabeno	2006	Island	N/A		2.8		1					
Yasuni		Channel			1.0		1					
Lagartococha		Lake	7.0	N/A	16.5		15		5			
Aguarico)		Main River	95.5	N/A	25.6	13.1	12	10				
		Tributary	48.5		126.8		52		15		3	
			144.0		183.7	13.1	85	10	27		5	
		Total	144.0		196.9		95		27		5	

Peru (Rivers Samiria Marañon-Amazon)	8–11 September 2006	Channel	N/A		3.3		1		9		2	
		Confluence	N/A		6.0		3		16		36	
		Island	22.4	N/A	13.6		6				7	
		Main River	78.4	414.7	153.3	47.0	60	46	105	25	120	30
		Tributary	39.0		144.9		47		191		123	
			139.8	414.7	321.0	47.0	117	46	321	25	288	30
		Total	554.4		368.0		163		346		318	
Orinoco River Basin												
Colombia (River Meta)	24–29 August 2006	Channel	N/A	N/A	41.3		15		11			
		Confluence	N/A	N/A	10.0		5		16			
		Island	133.4	N/A	39.0		23		8			
		Main River	400.5	697.2	254.2	117.2	119	109	33	10		
			533.9	697.2	344.5	117.2	162	109	68	10		
		Total	1,231.1		461.7		271		78			
Venezuela (River Orinoco)	10–18 May 2006	Channel	20.0	N/A	21.5		7		1			
		Confluence	N/A	N/A	16.1		8		20		5	
		Island	126.0	N/A	45.1		17		11		2	
		Main River	276.2	1261.6	212.1	100.5	72	89	88	12	63	44
		Tributary	N/A	N/A	1.9		2					
			422.2	1, 261.6	296.7	100.5	106	89	120	12	70	44
		Total	1,683.8		397.2		195		132		114	
		All habitats	2,863.1	2,721.0	2,379	325	890	291	2,048	53	679	85
Total Surveys		All transects	5,708.3		2,704		1,181		2,101		764	

were not informed to the aft platform. Positions were rotated every 2 h. Data from both the forward and aft platforms were integrated into a single data sheet at the end of each survey to confirm the number of dolphins sighted and avoid repeats. All observers had previous experience with river dolphin research. They actively searched for individuals and identified species (*Inia* and *Sotalia*) by naked eye. Observation height ranged between 3 m and 7 m above the river surface. Small ships, with low observation platforms (3 m), were used when the location was characterized by narrow or shallow habitat types. When the location surveyed consisted principally of main rivers, large ships with higher observation platforms (maximum 7 m) were preferred. Time, position, species, and number of dolphins (group size) were recorded for each sighting by both the forward and aft platforms. Group size was the sum of the total number of dolphins seen at the surface at each sighting, and does not necessarily correspond to a social group. Sightings started the first time that a dolphin was seen at the surface and ended 1 min after the last time a dolphin was seen at the surface or when dolphins had passed out of the observers' area of view. Estimating group size of river dolphins is often difficult and therefore the most experienced observers took the lead by giving their best estimates to the data recorder (Vidal *et al*. 1997). Surveys did not stop when dolphins were sighted. A compass bearing relative to the heading of the boat was used to measure the angle from the observation platform to the location of the first sighting. The distance from the platform to the dolphin was estimated by naked eye (observers were trained before the surveys to estimate the distance to inanimate floating objects in the river whose distance was validated with a laser range finder). Only the most efficient and experienced observers estimated distances during the surveys and often validated estimates using a laser range finder.

Environmental data were recorded systematically every 10 min, as well as at every dolphin sighting, and when the searching effort began and ended. A Geographic Positioning System (GPS) recorder provided information on date, time, vessel position, vessel speed (5–19 km/h), vessel direction of travel, and number of kilometers surveyed per transect. Visibility sighting conditions were ranked by the observers, at the beginning and end of each transect and when dolphins were seen. Sun glare was coded as strong (3), medium (2), low (1), and none (0); river state was coded as calm (0), small ripples (1), medium and large ripples (2), and waves and turbulence (3). Overall sighting conditions were considered excellent when sun glare and river state were both 0, good when the highest of the two condition codes was 1, moderate when the maximum code was 2, and poor when either code was 3.

Five habitat types were delineated in the study areas through satellite images, and were later confirmed visually in the field (Table 2). Each survey was classified according to the annual flood cycle: low waters, high waters, and transitional periods (Goulding 1980, Sioli 1984, Junk *et al*. 1989). The survey in Ecuador was conducted during the high water season, in Peru during the low water season and all other surveys were conducted during the transitional water season.

Group Sizes and Density Estimates

Mean group size and standard error were calculated for each species and habitat type for each country surveyed. Density estimates were calculated independently for sightings obtained within cross-channel line transects and for 200 m strip-width transects. Data from all cross-channel transects were aggregated to estimate an overall density for each species using the software DISTANCE, version 5.0 (Buckland *et al*.

Table 2. Definition of habitat types surveyed during the 2006–2007 surveys in the Amazon and Orinoco river basins.

Habitat type	Definition	Areas surveyed
Main River	White water rivers of Andean and Guyanese shield origin, typically turbid, brown-yellow in color with low transparency, basic pH and sediment-rich (Sioli 1984). At least 400 m in width and classified as a basin or sub-basin.	Orinoco, Meta, Amazon–Marañón, Javari, Napo, Iténez, Mamoré Rivers
Confluences	Intersection areas of the main channel with other channels or rivers. Confluences maintain connection during all hydrologic periods and may or may not present a mix of white and black waters.	Meta–Orinoco, Samiria–Amazon, Amazon–Javari, Napo–Amazon
Tributaries	Small and medium size rivers no more than 400 m in width. Water in tributaries are usually black and clear, originate from the flooded forest plains and are relatively acidic and high in tannins (Sioli 1984).	Samiria, Iténez, Mamoré, Cuyabeno, Yasuni, Lagartococha, Aguarico, and Loretoyacu
Channels	Water courses no more than 300 m width generally associated with island and main river systems. Navigability is limited depending on rainy seasons.	
Islands	Waters adjacent to land bodies in the water course of main rivers with vegetation that may appear or disappear due to hydrologic dynamics.	

2001, Thomas *et al.* 2002, Thomas *et al.* 2010):

$$D = \frac{nE(i)f(0)}{2Lg(0)}$$

where n is the number of groups sighted, $E(i)$ is the estimated mean group size for the population in habitat type i, $f(0)$ is the sighting probability density at zero perpendicular distance (or the inverse of the effective half strip width [ESW]), L is the total transect length, and $g(0)$ the probability of seeing a group on the transect line.

Using the data from the two sighting platforms $g(0)$ was estimated as follows. The detection function fitted for both species has a shoulder approximately 50 m wide (Fig. 2). Hence, data within this segment can be used to estimate $g(0)$. If the probabilities of missing dolphin groups that are on the transect line (in practice within 50 m) are equal from the forward and aft platforms and independent (q), then $g(0) = (1 - q^2)$, and the probability of a group on the transect line being missed by the first platform given it was seen at the second platform is also q. Thus $g(0)$ can be estimated from $g(0) = (1 - (n_{01}/n_{.1})^2)$, where $n_{.1}$ is the number of groups sighted from the second platform within 50 m of the transect line, and n_{01} the number of these that were missed by the first platform. An estimate of the coefficient of variation

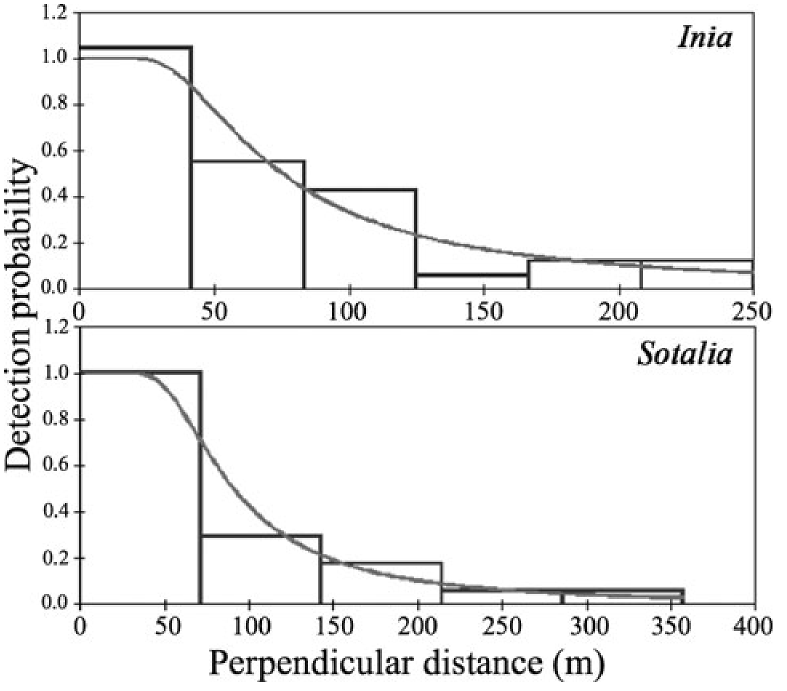

Figure 2. Detection probabilities for *Inia* and *Sotalia* with perpendicular distance from cross-channel line transect track line.

of this estimate is (from the delta method, checked using simulation):

$$CV_{g(0)} = 2(n_{01}/n_{.1})\sqrt{\frac{(n_{01}/n_{.1})}{n_{.1}(1-(n_{01}/n_{.1}))(1+(n_{01}/n_{.1}))^2}}$$

Three models were used to fit the detection function (the probability of sighting with perpendicular distance from the transect line): uniform, half-normal, and hazard-rate (Buckland *et al.* 2001). The best model was selected using the Akaike's Information Criterion (AIC) (Burnham and Anderson 2002).

From the 200 m strip-width transects we found that river dolphins are distributed according to a gradient with higher densities closer to the shore (Fig. 3). Thus, there is a systematic variation in perceived density perpendicular to the transect line where variation in density with distance from the bank is conflated with variation in the detection probability at different distances from the vessel. In the center of the river (where cross-channel line transect surveys are performed), there does not seem to be a gradient of density relative to the transect line. Therefore, we used the detection function fitted for the cross-channel line transects to correct for undetected clusters in the 200 m strip-width transects. To do this, we estimated the mean proportion of animals detected (P_k) for each 50 m width strip (k) parallel to the track line. Thus, two P_k values for each species were calculated from the the area under the detection

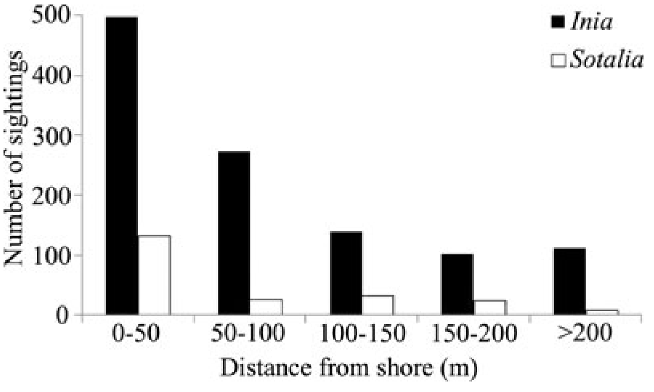

Figure 3. Number of sightings (*Inia* and *Sotalia*) within 50 m width strips parallel to the shore during strip transects with the vessel 100 m from the shore. Sightings observed outside the 200 m strip-width were excluded from further analysis.

function ($g(x)$): $P_{0-50}(P_1)$ for groups detected within 50 m from the track line:

$$P_{0-50} = \frac{\int_0^{50} g(x)}{50}$$

and P_{50-100} (P_2) for those between 50 and 100 m from the trackline:

$$P_{50-100} = \frac{\int_{50}^{100} g(x)}{50}$$

The detection probability $g(x)$ used the detection function model selected and the parameter estimates calculated from the cross-channel line transect surveys (Buckland *et al*. 2001). If on the 200 m strip-width transect, n_{0-50} is the number of groups counted between 0 and 50 m from the shore (50–100 m from the boat on the shoreward side of the track line), n_{50-100} is the number of groups counted between 50 and 100 m from the shore (0–50 m from the boat on the shoreward side of the track line), $n_{100-150}$ is the number of groups counted between 100 and 150 m from the shore (0–50 m from the boat on the riverward side of the track line), and $n_{150-200}$ is the number of groups counted between 150 and 200 m from the shore (50–100 m from the boat on the riverward side of the track line), the corrected number of animals sighted was:

$$E(i)\left[\frac{n_{0-50}}{P_2} + \frac{n_{50-100}}{P_1} + \frac{n_{100-150}}{P_1} + \frac{n_{150-200}}{P_2}\right]$$

where *E(i)* is the estimated group size for the population in habitat type *i*. Densities (D_i) for 200 m strip-width transects were then calculated independently for each habitat type (i) (Buckland *et al.* 2001):

$$D_i = \frac{E(i)\left[\dfrac{n_{0-50}}{P_2} + \dfrac{n_{50-100}}{P_1} + \dfrac{n_{100-150}}{P_1} + \dfrac{n_{150-200}}{P_2}\right]}{W\,L_i\,g(0)}$$

where L_i is the total length of the strip transects conducted in that habitat, and W is the strip width (200 m). For areas less than 200 m wide we used the average strip-width: Bolivia, Iténez River, Channel = 166.78; Colombia, Meta River, Channel = 187.5; Ecuador, Tributaries = 64.04, Peru, Samiria River, Tributary = 105.97. Standard errors (SE) were estimated based on the coefficient of variation (CV) for the encounter rate, CV for the detection probability and the CV for $g(0)$:

$$\mathrm{SE}(D) = Dx\sqrt{(\mathrm{CV}_{\mathrm{encounter\_rate}})^2 + (\mathrm{CV}_{\mathrm{detection\_probability}})^2 + \mathrm{CV}(\mathrm{g}(0))^2}$$

CV (encounter rate) was obtained from 200 m strip-width transects surveys by calculating the standard deviation (SD) of the sighting rates of individuals within that habitat type (per km of transect; $s_k = z_k/l_k$), where z_k is the number of individuals sighted on transect k:

$$\mathrm{CV}_{\mathrm{encounter\_rate}} = \frac{\mathrm{SD}(s_k)}{\mathrm{Mean}(s_k)}$$

Based on the Jackknife procedure (Sokal and Rohlf 1981), P_k values were obtained from the detection curve by leaving out all dolphin sightings from one country (river), y, in turn ($P_{k,-y}$) and new density estimates were obtained:

$$D_{i,-y} = \frac{E(i)\left[\dfrac{n_{0-50}}{P_{2,-y}} + \dfrac{n_{50-100}}{P_{1,-y}} + \dfrac{n_{100-150}}{P_{1,-y}} + \dfrac{n_{150-200}}{P_{2,-y}}\right]}{W\,L_i\,g(0)}$$

Then "pseudo-values" (ϕ) (Sokal and Rohlf 1981) were calculated as:

$$\phi_y = mD_i - (m - 1)D_{i,-y}$$

where m is the number of rivers, and the approximate SE as:

$$\mathrm{SE}(D_i) = \frac{\mathrm{SD}(\phi_y)}{\sqrt{n}}$$

CV (detection probability) was obtained from the cross-channel line transect correction applied by estimating the standard error (SE) of density values, D_i:

$$\mathrm{CV}_{\mathrm{detection\_probability}} = \frac{\mathrm{SE}(D_i)}{D_i}$$

Features of the Environment

We investigated whether group size and density estimates are related to the region (Amazon and Orinoco river basins), genus (*Inia* and *Sotalia*), seasons (high, low and transitional water periods), habitat type (main river, channel, island, tributary, confluence, lake) and country (Bolivia–Iténez, Bolivia–Mamoré, Colombia–Amazon, Colombia–Meta River, Venezuela, Ecuador, Peru). The variables group size and density were tested for normality and homogeneity of variances. When residuals did not meet assumptions of parametric tests (Lilliefors test, $P < 0.05$; Levene's test, $P < 0.05$), non-parametric tests were used. Analysis was conducted using SYSTAT Version 12.0.

Population Size

Population size (N_i) of river dolphins for each habitat i, was calculated as:

$$N_i = A_i D_i$$

The overall coefficient of variation of the total estimate for each location (country) surveyed l was calculated as:

$$\mathrm{CV}(N_l) = \frac{\sqrt{\sum \mathrm{SE}(N_i)^2}}{\sum N_i}$$

Satellite images of each study site were used to calculate the area A_i (km^2) of each habitat type, using ArcView version 3.2 (ESRI, Redlands, CA). Polygons of 200 m width were created to calculate the area of the river that follows land borders, which are potentially surveyed by using 200 m strip-width transects. Areas which are potentially surveyed by using cross-channel line transects (center of main rivers) were calculated by estimating the total size of the study site (satellite images) minus the area covered by the 200 m width polygons (strip transects). Habitat-specific density estimates were extrapolated to all areas of dolphin habitat to estimate total population size within the location surveyed.

Results

A total of 2,704 linear km were surveyed in selected large rivers of the Amazon and Orinoco river basins. The total size of the study area was 5,708 km^2. Effort varied between research areas for logistical reasons. Overall, 96% of transects were surveyed during good and moderate sighting conditions. Forty-three percent of transects were conducted with no or low sun glare, 17% with medium glare, and 1% with strong glare. Ninety-two percent were conducted with small ripples and 8% with medium and large ripples. Group size ranged from 1 to 15 for *I. geoffrensis*, 1 to 10 for *I. boliviensis*, and 1 to 26 for *Sotalia fluviatilis.* Group sizes of *Sotalia* were significantly larger than *Inia* (Mann-Whitney U-test, $P < 0.05$, 1 df), and group sizes varied with habitat type (Kruskal-Wallis $P < 0.05$, 5 df) being largest in the confluences (Table 3).

Data for cross-channel line transects from all study areas were combined and imported into software DISTANCE. These data include 38 sightings for *Inia* and 27

Table 3. Mean group sizes (GS) (mean number of dolphins sighted during an encounter) within region, country and habitat type for *Inia* and *Sotalia* using 200 m strip-width transects. Data were not obtained in the field (blank spaces) for some habitat types in some countries. No SE was obtained (—) for some habitat types (only one sighting).

	Habitat type													
	Channel		Confluence		Island		Lake		Main river		Tributary		Total	
Species/region	GS	SE	GS	SE	GS	SE	GS	SE	GS	SE	GS	SE	GS	SE
Inia (total)	1.7	0.13	2.4	0.37	1.9	0.22	1.9	0.23	1.7	0.10	1.7	0.04	1.8	0.04
Amazon														
Bolivia	1.6	0.21					1.9	0.19			1.7	0.04	1.7	0.04
Colombia	1.6	0.18	3.3	1.67	1.7	0.18	1.9	0.49	1.4	0.10	1.3	0.25	1.7	0.14
Peru	1.8	0.37	1.6	0.31					1.4	0.06	1.9	0.19	1.6	0.10
Ecuador			1.8	0.25			2.5	0.50			1.5	0.27	1.7	0.20
Orinoco	2.4	0.51	2.8	0.28	2.7	0.68			2.6	0.31			2.6	0.23
Colombia	2.8	0.48	2.7	0.33	4.0	2.00			2.0	0.50			2.4	0.35
Venezuela	1.0	—	2.9	0.46	2.2	0.58			2.9	0.39			2.8	0.30
Sotalia (total)	3.1	0.36	5.1	1.57	2.6	0.37	4.0	0.97	2.9	0.15	2.3	0.21	2.9	0.14
Amazon														
Colombia	3.1	0.37	11.3	7.36	2.4	0.34	4.0	0.97	2.8	0.28	2.0	—	3.1	0.29
Peru	2.0	—	4.0	0.76	7.0	—			2.7	0.21	2.4	0.22	2.7	0.16
Ecuador			2.0	—							1.0	—	1.3	0.25
Orinoco			2.5	0.50	2.0	—			3.5	0.32			3.4	0.30
Venezuela			2.5	0.50	2.0	—			3.5	0.32			3.4	0.30

Table 4. Densities, coefficient of variation and 95% confidence interval for *Inia* and *Sotalia* obtained from cross-channel line transect surveys combining all study areas. D is density (dolphins/km^2), ESW is effective half-strip width (m) ($1/f(0)$).

Species	Number sightings	Group size	ESW	CV (ESW)	D	CV (D)	D	95% CI
Inia	38	1.5	97.2	0.24	0.96	0.31	0.53	1.75
Sotalia	27	3.37	113.8	0.23	1.51	0.37	0.75	3.05

for *Sotalia.* Densities were estimated for the cross-channel areas using the hazard-rate model for both species (Tables 4, 5; Fig. 2).

The proportion of groups of dolphins sighted by the rear platform within 50 m of the transect line that were missed by the front platform was not very large, being 23% (141/611) of *Inia* sightings and 5% (7/133) of *Sotalia* sightings. Assuming the probabilities of missing dolphins from the forward and aft platforms are equal, then using the formula derived in the Methods section, we estimated $g(0) = 0.947$ (CV = 0.025) for *Inia*, and $g(0) = 0.997$ (CV = 0.003) for *Sotalia*. Thus for both species $g(0)$ is very close to 1, and the CVs are sufficiently small that they have no bearing on the overall precision of the density and population estimates.

The majority of *Inia* (96%) and *Sotalia* (85%) sightings were obtained while conducting 200 m strip-width transects. Sightings observed outside the 200 m strip-width on these transects were excluded from the analysis. Highest densities overall were found in the lake and confluence habitat types. Few transects were conducted in these habitat types and often transects were less than 1 km in length. When considering tributaries, highest densities were in the Samiria River in Peru (5.94 *Inia*/km^2, 6.08 *Sotalia*/km^2) and the lowest densities in the tributaries of Ecuador (2.78 *Inia*/km^2, 0.28 *Sotalia*/km^2). When considering the main river habitat type, the highest density was in the Marañón River in Peru (2.72 *Inia*/km^2, 4.87 *Sotalia*/km^2) followed by the Amazon River in Colombia (1.82 *Inia*/km^2, 3.35 *Sotalia*/km^2), and the lowest values were in the Orinoco River in Venezuela (1.14 *Inia*/km^2, 1.06 *Sotalia*/km^2) and the Meta River in Colombia (0.57 *Inia*/km^2). Channel and island habitat types had slightly higher density estimates within each main river (Tables 6, 7).

Based on a hypothetical plan of a river basin, we plotted overall density estimates for all surveys combined. Density in the center of the main river was obtained through mid-center line transects. Densities in the other habitat types were obtained through 200 m strip-wide transect surveys, with values presented for each 50 m strip-width. Overall, highest densities of *Inia* and *Sotalia* dolphins are within 100 m from the shore. For *Inia*, highest densities are in lakes, and for *Sotalia* highest densities are in confluences (Fig. 4).

Highest estimated population sizes were obtained for *Inia* dolphins, the largest being in Bolivia (Iténez River) with 3,201 dolphins (CV = 0.40) and the lowest for the area surveyed in Ecuador with only 147 dolphins (CV = 1.38) (Table 8). The largest population of *Sotalia* was found in Colombia (Amazon River) with 1,545 dolphins (CV = 0.61), and the lowest in the areas surveyed in Ecuador with only 19 dolphins (CV = 1.37).

There were no significant differences in dolphin density across the different species (Mann-Whitney U-test, $P = 0.596$, 1 df) or seasons (K-W test, $P = 0.07$, 2 df).

Table 5. Results of detection function model selection by species.

	Inia				*Sotalia*			
Model	AIC	Number of parameters	ΔAIC	ESW (CV)	AIC	no. parameters	ΔAIC	ESW (CV)
Hazard-rate	398.57	2	0	97.2 (0.24)	292.31	2	0	113.8 (0.23)
Uniform	399.64	2	1.06	107.8 (0.13)	293.43	2	1.12	139.5 (0.17)
Half-normal	399.66	2	1.09	93.7 (0.16)	293.96	2	1.64	109.4 (0.16)

Table 6. Mean sighting rate (n/l), estimated densities (D), standard error, coefficient of variation for the detection probability (dp), for the encounter rate (er) and estimated population sizes (N) for *Inia* within region, country and habitat type using 200 m strip-width transects. Data were not obtained in the field (blank spaces) for some categories.

	Amazon river basin					Orinoco river basin	
Inia	Bolivia (Iténez)	Bolivia (Mamoré)	Colombia	Ecuador	Peru	Colombia	Venezuela
Main River							
n/l			0.35	0.00	0.52	0.11	0.22
D			**1.82**		**2.72**	**0.57**	**1.14**
SE			2.11		3.88	3.07	4.06
CV (dp)			0.09		0.09	0.05	0.09
CV (er)			1.15		1.42	5.41	3.55
CV			1.16		1.42	5.41	3.55
N			**123**		**213**	**228**	**315**
Tributary							
n/l	0.62	0.68	0.73	0.17	0.61	0.73	0.00
D	**3.21**	**3.52**	**3.77**	**2.78**	**5.94**		
SE	1.23	1.04		7.75	4.65		
CV (dp)	0.10	0.10	0.08	0.06	0.04		
CV (er)	0.37	1.14	n/a	2.79	0.78		
CV	0.38	1.14		2.79	0.78		
N	**2986**	**1369**	**199**	**135**	**288**		
Channel							
n/l	0.47		0.50	0.00	0.95	0.35	0.05
D	**2.94**		**2.58**		**4.92**	**1.96**	**0.28**
SE	2.54		1.99		0.56	3.74	0.68
CV (dp)	0.07		0.09		0.11	0.06	0.15
CV (er)	0.86		0.77			1.91	2.45
CV	0.86		0.77			1.91	2.45
N	**150**		**157**		**7**	**32**	**6**
Island							
n/l			0.37	0.00	0.00	0.12	0.26
D			**1.91**			**0.60**	**1.33**
SE			2.07			2.87	2.97
CV (dp)			0.10			0.06	0.11
CV (er)			1.08			4.80	2.22
CV			1.08			4.80	2.23
N			**103**			**80**	**168**
Lake							
n/l	1.56		3.56	0.11			
D	**8.10**		**18.48**	**0.56**			
SE	4.91		29.03	2.15			
CV (dp)	0.06		0.14	0.11			
CV (er)	0.60		1.57	3.87			
CV	0.61		1.57	3.87			
N	**65**		**177**	**4**			
Confluence							
n/l	0.00		2.48	0.55	0.81	1.79	1.92
D			**12.86**	**2.87**	**4.22**	**9.29**	**9.96**
SE			15.51	2.87	1.93	9.89	10.70
CV (dp)			0.06	0.06	0.04	0.04	0.06
CV (er)			1.20	1.00	0.45	1.06	1.07
CV			1.21	1.00	0.46	1.06	1.07
N			**22**	**9**	**11**	**8**	**84**

Table 7. Mean sighting rate (n/l), estimated densities (D), standard error, coefficient of variation for the detection probability (dp), for the encounter rate (er) and estimated population sizes (N) for *Sotalia* within region, country and habitat type using 200 m strip-width transects. Data were not obtained in the field (blank spaces) for some categories.

Amazon river basin				Orinoco river basin
Sotalia	Colombia	Ecuador	Peru	Venezuela
Main River				
n/l	0.67	0.00	0.97	0.21
D	**3.35**		**4.87**	**1.06**
SE	5.14		8.52	2.86
CV (dp)	0.32		0.26	0.18
CV (er)	1.50		1.73	2.69
CV	1.53		1.75	2.70
N	**226**		**382**	**292**
Tributary				
n/l	0.84	0.02	0.64	
D	**4.21**	**0.28**	**6.08**	
SE		1.29	4.91	
CV (dp)	0.09	0.09	0.10	
CV (er)	n/a	4.66	0.80	
CV		4.66	0.81	
	222	**13**	**237**	
Channel				
n/l	1.02	0.00	0.62	0.00
D	**5.10**		**3.09**	
SE	4.35		0.31	
CV (dp)	0.34		0.10	
CV (er)	0.78			
CV	0.85		0.10	
	311		**4**	
Island				
n/l	0.35	0.00	0.42	0.00
D	**1.74**		**2.10**	
SE	2.53		5.14	
CV (dp)	0.43		0.10	
CV (er)	1.39		2.45	
CV	1.46		2.45	
	94		**47**	
Lake				
n/l	2.45	0.00		
D	**12.32**			
SE	7.63			
CV (dp)	0.26			
CV (er)	0.56			
CV	0.62			
	118			
Confluence				
n/l	5.61	0.39	1.73	0.28
D	**28.14**	**1.97**	**8.69**	**1.41**
SE	32.75	2.80	1.43	2.01
CV (dp)	0.09	0.10	0.10	0.10
CV (er)	1.16	1.41	0.13	1.41
CV	1.16	1.42	0.16	1.42
N	**49**	**6**	**24**	**12**

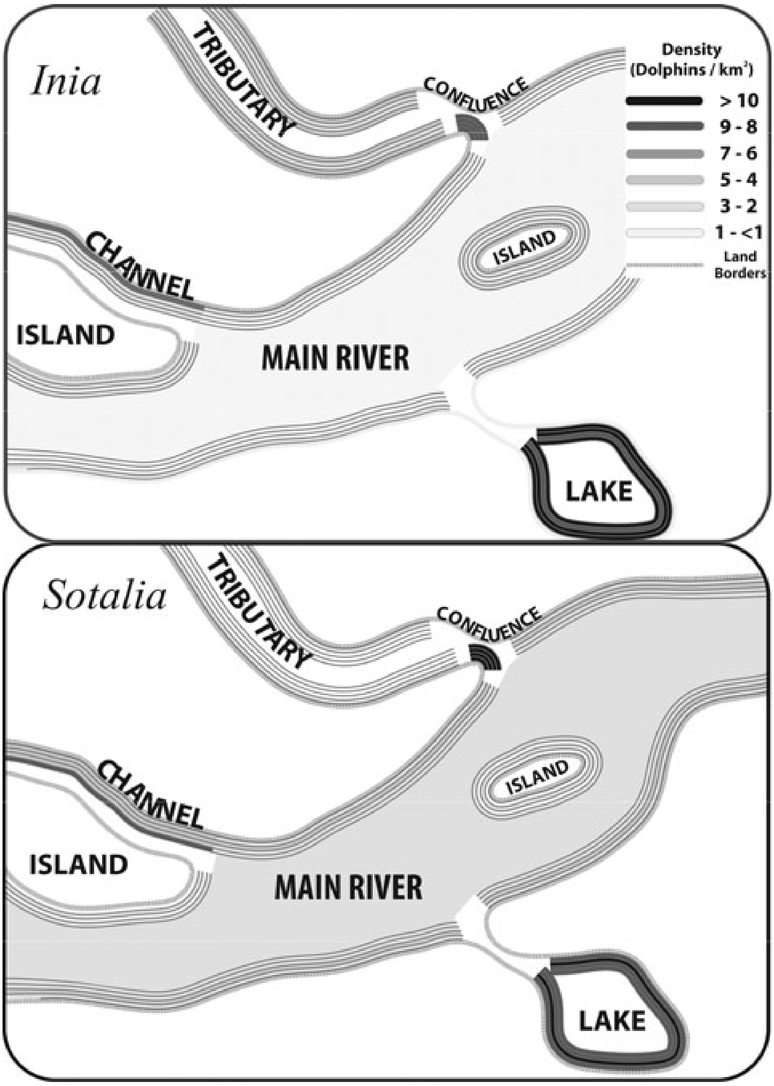

Figure 4. Scheme of a hypothetical section of a river basin. Results show overall density estimates for *Inia* and *Sotalia* for each habitat surveyed. Density in the center of main river was obtained through cross-channel line transects and densities in the other habitat types were obtained through 200 m strip-width transect surveys, with values presented for each 50 m width strip.

There were significant differences in densities between regions (Mann-Whitney U-test, $P < 0.05$, 1 df: highest densities in the Amazon river basin), between habitat type (K-W test, $P < 0.05$, 5 df: highest in confluences and lakes), and between country (K-W test, $P < 0.05$, 6 df) with densities being the highest in Peru and Bolivia, and the lowest in Ecuador and Venezuela.

Table 8. Total areas, surveyed areas, overall population size and (CV) for *Inia* and *Sotalia* for the areas and species surveyed in the Amazon and Orinoco river basins. Some species are not distributed in some of the areas surveyed (blank spaces).

		Area (km^2)[a]		Population size	
River basin	Country	Total	This study	Inia	Sotalia
Amazon		6,547,000	2,794		
	Bolivia (Iténez)			3,201 (0.40)	
	Bolivia (Mamoré)			1,369 (1.14)	
	Colombia			1,115 (0.78)	1,545 (0.61)
	Ecuador			147 (1.38)	19 (1.37)
	Peru			917 (0.34)	1,319 (0.43)
Orinoco		953,598	2,915		
	Colombia			1,016 (0.85)	
	Venezuela			1,779 (0.87)	2,205 (0.89)

[a]Source for total areas of the Amazon and Orinoco river basins: Meade *et al*. 1991, Junk *et al.* 1997, Revenga *et al.* 1998.

Discussion

This study has estimated group size, density, and population numbers for river dolphins across selected rivers of the Amazon and Orinoco river basins. The highest density of river dolphins was found in areas close to the river banks and in lakes and confluences. These results are useful in identifying critical habitat and hotspots for river dolphins, as well as locations where threats may be of special concern.

Methodology

The design of boat-based surveys in riverine systems is complex. We used a combination of 200 m strip-width transects and cross-channel line transects. This combination allows an adequate coverage of the different habitats within rivers with significant effort in the areas where the majority of river dolphins are found (Vidal *et al*. 1997, Dawson *et al*. 2008).

We used several techniques to perform a reliable survey with adequate detection process all along the strip width: (1) visual effort was equal on both sides of the track line; (2) short-dive intervals of river dolphins (dives generally do not last more than 2 min) and a constant low velocity of the vessels increased the probability of seeing most of the animals (Best and da Silva 1993, Herman *et al*. 1996, Aliaga-Rossel 2002, Martin and da Silva 2004, Aliaga-Rossel *et al*. 2006); (3) at least three observers with previous experience using the current method were present in all surveys; (4) members of the survey team had previous experience in river dolphin research; and (5) observers at the front and aft platforms were in communication to record sightings that were not recorded by one of the platforms. Although the proportion of animals missed by the front platform was not very large, by using two platforms $g(0)$ was able to be estimated and was increased to very nearly 1, and therefore we recommend that further surveys continue using both platforms.

The methods used to conduct line transect surveys for cetaceans vary with species and conditions of the survey. For instance, some studies conduct "closing mode" surveys, leaving the transect line when a group of individuals is seen in order to estimate the group size and identify species accurately (*e.g.,* Zerbini *et al.* 2007). Alternatively, "passing mode" surveys estimate the group size and species without leaving the transect line in order to avoid double-counting of individuals, as in this study. In order to reduce the bias, "passing mode" is recommended for species that have small group sizes and that are hard to track at the surface (Dawson *et al.* 2008). The inconspicuous behavior of river dolphins at the surface and the dark-colored waters make it hard to track multiple groups surfacing at different positions. Therefore, by maintaining the same speed without leaving the track line (passing mode), we can minimize the probability of double-counting individuals. River dolphins' small group sizes and the different surfacing behaviors of *Inia* and *Sotalia* facilitate accurate group size estimation and species identification. Using experienced observers and both aft and front platforms also aid sighting, accurate species identification, and group size estimation. Overall, for river dolphins in the Amazon and Orinoco basins, we recommend using the "passing mode" methodology when conducting line and strip transects.

Buckland *et al.* (2001) recommended a minimum of 60 sightings for accurate estimation of detection functions. As the number of sightings obtained during the cross-channel transects was less than this, our results should be treated cautiously. However, detection probabilities for models selected had similar density and detection function estimates. Thus, model selection may not be critical (Buckland *et al.* 2001).

Most of the effort was during the 200 m strip-width transects, but because not all dolphins are detected within the strip, a correction factor was applied using the cross-channel line transects. This correction factor did not seem to have a large effect on the precision of the overall density estimate, as reflected by the low coefficient of variation of the detection probability.

The effective half-strip width varies according to the size and behavior of the species, weather conditions, and height of the observation platform, among other factors (Buckland *et al.* 2001). Given the sighting conditions, *Sotalia* dolphins are easier to see than *Inia*. Therefore, as expected, the effective half-strip width for *Inia* in mid-center line transects (ESW = 97.16 m, 38 sightings) was smaller than for *Sotalia* (ESW = 113.78 m, 27 sightings). A previous study conducted in the Colombian Amazon reported a larger effective half-strip width of 245 m, for both *Inia* and *Sotalia* species combined (13 sightings) (Vidal *et al.* 1997). For further studies it would be important to conduct additional line transects in order to obtain a larger number of sightings to improve the estimation of the effective strip-width, and to examine how it varies between platforms and sighting conditions (Dawson *et al.* 2008). Given the differences in the surfacing behavior and group sizes of *Inia* and *Sotalia*, effective half-strip width should be calculated independently for each genus, as in this study. As a comparison, effective strip-widths of cetaceans at sea are smaller for species with shy behavior, small dorsal fins, and small group sizes and are larger for species that are easier to see because of conspicuous behavior, large group sizes, or prominent blows for large whales (Wade and Gerrodette 1993). Given the large CVs, caution should be applied when comparing results from areas and habitat types of this study. In addition, because we used different vessel types, densities in various habitat types might be biased. Our samples were not large enough to fit separate detection functions for different vessel types, but further research should take these issues into consideration.

Although lakes and confluences are the smallest areas surveyed (~1%) they contain the highest density and group sizes of dolphins. We need to monitor these areas accurately, but the current method used in these habitats must be improved. For instance, group size estimation in lakes and confluences might be biased since the large number of dolphins makes it hard to distinguish independent sightings and to estimate group sizes. Dolphins in lakes seem to aggregate with the presence of a boat, increasing the probability of double-counting individuals. Moreover, it was problematic to calculate the total area in the confluences due to their small size and proximity to the main river and tributary. Therefore, when surveying lakes and confluences, other approaches to estimating density and population are worth investigating. Mark-recapture by photo-identification of natural marks might be a suitable method for these high-density areas (Trujillo 1994, McGuire and Henningsen 2007). We therefore recommend line/strip transect surveys for most of the habitat types (*e.g.*, main rivers, tributaries, islands, and channels) when population and density estimates across large areas are needed, and we recommend photo-identification effort in high-density areas (*e.g.,* confluences and lakes). The efficiency of photo-identification using natural marks has improved due to the availability of more sophisticated equipment including high-resolution digital cameras, and computer-aided software to assist in the matching of photographs.

Because surveys in each area were conducted during different seasons and because river dolphin density varies seasonally, caution should be applied when comparing results with other areas and studies. For instance, local reductions in the availability of water and resources during the dry season cause an increase in the density of river dolphins (Martin *et al.* 2004). In this study, results from Peru (surveyed during the dry season) may reflect the highest density values in the area. In contrast, results from Ecuador (surveyed during the rainy season) may represent the lowest values of density. Results from surveys conducted in Colombia, Brazil, Venezuela, and Bolivia (surveyed during the transitional water season) reflect the most frequent density values in these areas. Thus, repetitive surveys should be conducted in riverine areas to investigate how seasonality, habitat type, and other potential environmental variables drive variation in density. If repetitive surveys cannot be implemented, we suggest surveying areas during the transitional water periods where most of the habitat types are available (*e.g.,* channels are not completely dry and lakes are still connected to the main rivers) to make studies more comparable.

Densities and Population Estimates

Densities of river dolphins were higher in the Amazon than in the Orinoco river basin. Whether this difference is due to differential anthropogenic impacts, productivity, or both in each watershed is worth investigating further.

The majority of previous river dolphin population estimates have come from sporadic studies each with a different methodology and during different hydrologic conditions. Compared with our surveys, these previous studies typically used fewer observers and only one platform in front of the boat. Field effort and data analysis were not focused on obtaining density and population estimates. Therefore, caution needs to be applied when comparing results with this study. Here we consider results for several different survey locations, within or close to the areas surveyed in this study.

Mamoré and Iténez Rivers (Bolivia)

This study (June 2007 and August 2007, transitional water period) surveyed an area of 1,113.5 km^2 of the Iténez River with a large population size of 3,201 *Inia* (CV = 0.40) and an area of 389 km^2 of the Mamoré River with 1,369 *Inia* (CV = 1.14). Our encounter rates in the Mamoré River (0.68 dolphins/km) were lower than the ones previously reported in the Mamoré River (222 km, 1.6 dolphins/km, 361 dolphins ± 32.23 SD) and some of its tributaries (65 km, 3.41 dolphins/km, 229 dolphins ± 42.1 SD) (Aliaga-Rossel *et al.* 2006). However, no conclusive trends can be established because surveys were conducted using different methods and during the low water season (August–September 1998). This river basin has a low level of anthropogenic threats when compared with the other areas surveyed. The threats include entanglements of river dolphins in nets, occasional killing of river dolphins, gold mining (which leads to traces of mercury in the water), and boat traffic. The potential construction of a hydroelectric power station in the upper Madera River means that human threats could be expected to increase drastically in the near future (Tavera *et al.* 2010). The Amazon River basin in Bolivia contains the only population of *I. boliviensis* in the world, and although densities are higher than for *Inia* in other areas studied so far, the fact that this population is geographically isolated and has a significantly smaller range than *I. geoffrensis* needs to be taken into consideration.

Marañón and Samiria Rivers (Peru)

This study (September 2006, low water period) surveyed the Samiria River (tributary) and a stretch of the Marañón River between the city of Iquitos and the confluence with the Samiria River. Densities in the Marañón River (2.72 *Inia*/km^2, 4.87 *Sotalia*/km^2) were lower than in the Samiria River (5.94 *Inia*/km^2, 6.08 *Sotalia*/km^2), but both values were the highest density values of this study for the main river and tributary habitats, respectively. In an area of 554.4 km^2, we estimated relatively large population sizes of 917 *Inia* (CV = 0.34) and 1,319 *Sotalia* (CV = 0.43). The area surveyed is located partially within the Pacaya-Samiria Natural Reserve, which is a well-managed FWPA with a low level of anthropogenic threats compared to the other areas surveyed. This might explain the high population estimates recorded. The high density estimates are also a result of the surveys being conducted during the low water period, when animals and resources are concentrated. Because the anthropogenic threats in the Samiria River are minimal and are not expected to increase in the near future, this area is a good candidate for conducting year-round repetitive surveys to investigate the variation of density estimates with seasonality and other environmental factors.

Previous density estimates available for the Samiria River were obtained during the falling water period, 15 yr previous to this study (0.5 *Inia*/km^2 and 0.4 *Sotalia*/km^2) (Leatherwood 1996). Monitoring efforts in this area have been conducted from 1991 to 2000, and most estimates are given in dolphins/km. Encounter rates have ranged between 3.5 *Inia*/km during the low water period to 0.2 *Inia*/km during the rising water period; and 0.8 *Sotalia*/km during the rising water period to 0.1 *Sotalia*/km during the falling water period (Leatherwood 1996, McGuire and Aliaga-Rossel 2010). We are not aware of previous population estimates in the area surveyed. In this river, dolphins become entangled in fishing gear, are occasionally killed as a result of negative interactions with fishermen and there is substantial boat traffic (McGuire and Aliaga-Rossel 2010).

Napo, Cuyabeno, Yasuni, Lagartococha, and Aguarico Rivers (Ecuador)

This location was the smallest area surveyed in this study (144 km^2, July 2006, high water season) with the lowest density and population sizes estimates: 147 *Inia* (CV = 1.38) and 19 *Sotalia* (CV = 1.37). Previous research on *I. geoffrensis* in tributaries of the Ecuadorian Amazon (similar to our study location) gave encounter rates ranging from 0.03 to 0.4 *Inia*/km (Utreras 1996, Utreras *et al.* 2010). No previous estimates were found for *Sotalia* for this area. These estimates (although not comparable with those from this study), the low population estimates of this study and the general lack of dolphin sightings in the Napo River, are of very serious concern. The Napo River has been the site of major commercial efforts to take over land for oil and timber, oil spills have occurred periodically, and conflicts between oil companies, the military, and local communities are growing. This was the most threatened area surveyed in this study and it might be the most threatened population of river dolphins in South America studied so far.

Amazon, Loretoyacu, and Javari Rivers (Colombia)

For this location (February 2007, transitional water period), an area of 592.6 km^2 was surveyed, giving a total population estimate of 1,115 *Inia* (CV = 0.78) and 1,545 *Sotalia* (CV = 0.61). Density estimates in the Amazon River (main river) were the second highest of all areas for *Inia* and *Sotalia*. Lakes and confluences had the highest density estimates of the entire study. Previous research in the Colombian Amazon was conducted 13 yr ago during the low water season in a smaller area enclosed within the boundaries of this study, and it is the only study comparable in terms of methodology (Vidal *et al.* 1997). Overall density estimates in the Amazon River from this study (1.82 *Inia*/km^2 and 3.35 *Sotalia*/km^2) are similar to the study in 1993 (2.02 *Inia*/km^2 and 2.78 *Sotalia*/km^2) with the exception of lakes and confluences that have very high density estimates in our study. However, the 1993 study was conducted during the low water period (June 1993) when densities of dolphins are expected to be the highest, did not account for dolphins missed by the observers in the strip transects, did not use two platforms to account for dolphins missed and did not correct for undetected clusters during the 200 m strip-width transects given the density gradient detected with distance from the shore, making comparisons problematic. The major threats in the area surveyed are the entanglement of dolphins in nets (which have been reduced during the last 10 yr), competition with fisheries, and an increase in the number of people and motor boats in the area. Recently, there have been reports of *Inia* dolphins being killed in one of the tributaries located on the frontier of Peru and Brazil, the Javari River, to be used as bait in the "mota" fishery (see below). If this continues, the population size of dolphins in this area will likely decrease in the near future.

Meta River (Colombia)

The Meta River is one of the most important tributaries of the Orinoco River. Only *Inia* dolphins are found in this area. There are no previous estimates of *Inia* densities and population sizes in this location. Our study (August 2006, transitional period) was conducted throughout the entire Meta River, from its confluence with the Orinoco to near its headwaters in the Andean mountains. Densities in the Meta River, which is one of the largest areas surveyed in this study (1,231.1 km^2), were the lowest for the main river (0.57 *Inia*/km^2) with a small population size of 1,016 *Inia* (CV = 0.85). The anthropogenic threats in this area are substantial and are expected to increase. The Meta River is an important navigation link between the Orinoco region of Colombia and Venezuela, and therefore there are plans to transform it into a waterway. The economy of this region in Colombia is based on agriculture, cattle ranching, and oil extraction. New oil reservoirs have been discovered during the last years and oil extraction is expected to increase in the years to come.

Orinoco River (Venezuela)

Density estimates of *Inia* in the Orinoco River (May 2006, transitional water period) were higher than in the Meta River, but lower than surveys in the rivers of the Bolivian, Ecuadorian, Peruvian, and Colombian Amazon (1.10 *Inia*/km^2, 1.06 *Sotalia*/km^2). We estimated a population size of 1,779 *Inia* (CV = 0.87) and 2,205 *Sotalia* (CV = 0.89) in a total area surveyed of 1,684 km^2. The Orinoco River is considered to be one of the most threatened rivers in South America. Some of the anthropogenic threats in this area include gold mining (resulting in mercury contamination), the oil industry, water development projects, such as waterways and hydroelectric, intense fisheries, and boat traffic. In addition, there are reports of dolphins being killed for the "mota" fishery in this area. Although densities are not as low as in Ecuador, this is one of the most threatened areas in this study, and we know of no plans to mitigate these threats.

Hot Spots and Critical Habitat

We define hot spots of river dolphins as the locations with highest density estimates of *Inia* and *Sotalia*. In this study, all hot spots occurred in well-protected and well-managed areas that could act as examples for conservation actions in other locations. The highest density estimates in this study were observed in the Samiria River (Peru) and in the Iténez and Mamoré Rivers in Bolivia. The Samiria River is located in the Pacaya-Samiria National Reserve, which was created specifically to protect freshwater ecosystems (Saunders *et al.* 2002). Similarly, the highest densities that have been recorded for any cetacean worldwide were obtained for *Inia* (up to 18 dolphins/km^2 in floodplain channels) in the Mamiraua Sustainable Development Reserve in Brazil (Martin and da Silva 2004) which is the largest protected area of flooded forest (Pires 2006). Thus, high densities of river dolphins seem to be found in well-managed FWPAs. The rivers in the Bolivian Amazon (Mamoré and Iténez) are characterized by a low level of anthropogenic effects compared with the other areas surveyed, which may be related to the high densities of *Inia* dolphins observed. Thus, the Pacaya Samiria Natural Reserve in Peru, the Mamiraua Sustainable Development Reserve in Brazil and the Mamoré and Iténez river basins should be considered as hotspots for river dolphins in South America.

Critical habitat is defined as areas that are fundamental for daily and long-term survival for a whole species or a specific population (Hoyt 2005). At a regional scale, we suggest that the critical habitat for river dolphins is within 200 m of the river banks, and the confluence and lake habitat types, where fish species concentrate (Fig. 4; Trujillo 2000, Vidal *et al.* 1997, Martin and da Silva 2004). Areas close to river banks are also favored by fishermen as in the Ganges River, where river dolphins

(*Platanista gangetica*) preferentially occupy areas where gillnetting occurs (Smith *et al.* 2006).

Conservation Status

Inia and *Sotalia* inhabit larger areas than their counterparts in China (*Lipotes vexillifer*) and the vaquita in Mexico (*Phocoena sinus*) considered functionally extinct and in serious danger of extinction, respectively (Jaramillo-Legorreta *et al.* 1999, Rojas-Bracho *et al.* 2006, Turvey *et al.* 2007). Even though the numbers of river dolphins in South America are overall higher than for these species, it is of concern that the scenario in terms of anthropogenic threats is very similar. We know of no management plans to mitigate these threats. In contrast, there are plans to increase the number of water development projects and expand the oil industry. *Inia* and *Sotalia* are currently listed by IUCN as data deficient partially because of a lack of population estimates (Reeves *et al.* 2008), and although the listing of species under Red List categories is not an ultimate goal, it is an important step in raising awareness within governments and institutions about the possible decline in dolphin numbers if human threats are not mitigated. For instance, rigorously obtained abundance estimates of the vaquita have demonstrated their small and likely decreasing population size, leading to the listing of this species as "critically endangered" by the IUCN (Jaramillo-Legorreta *et al.* 1999, Gerrodette *et al.* 2011). This, as a consequence, has raised awareness about the conservation status of the vaquita and the need to mitigate direct threats to their survival. We hope that the population and density estimates presented in this paper will contribute to such a process for the South American river dolphins.

Density estimates of river dolphins vary widely across South America (*e.g.,* 0.28 *Sotalia*/km^2 in the tributaries in Ecuador and 6.08 *Sotalia*/km^2 in the Samiria River in Peru). Thus, in order to properly capture their conservation status, we may need independent listings for geographically distinct populations. For instance, each river basin could be considered a potentially distinct subpopulation. A river basin is defined as the area drained by a major river system or by one of its main tributaries (Revenga *et al.* 1998). Although this categorization only takes into account ecological characteristics of the watersheds, we believe that this approach could be the most optimal categorization given the lack of information on river dolphin populations. No genetic studies of these populations have been conducted. However, we do not expect large movements of river dolphins within these river basins given the results of studies conducted in other areas showing short-distance movements and high fidelity of individuals to areas where they are born (Trujillo 1994, Martin and da Silva 2004, Martin *et al.* 2004, McGuire and Henningsen 2007, Ruiz-Garcia *et al.* 2007).

We obtained the areas of each river basin (the area of water drained by a major river system or by one of its main tributaries) based on other studies and compared them with the areas sampled in this study (Meade *et al.* 1991, Junk *et al.* 1997, Revenga *et al.* 1998, Rosales-Godoy *et al.* 1999). We sampled about 0.04% of the Amazon river basin (surveys in the Bolivian, Peruvian, Ecuadorian, and Colombian Amazon) and 0.3% of the Orinoco river basin (surveys in the Venezuelan and Colombian Orinoco) (Table 8). Although these estimates correspond to a very small fraction of the entire potential range of river dolphin populations, it is the largest study done so far to estimate density and population sizes using standardized methods.

Surveying all areas in all river basins seems unlikely, and therefore, we recommend that further studies should examine methods of extrapolating densities of dolphins from surveyed to un-surveyed areas within river basins in order to obtain overall abundance estimates. These studies would extend the results in this paper by examining how well ecological conditions and measures of human threat predict dolphin abundance within basins. Any extrapolation should also take into account the actual distributions of the species, as the presence of river dolphins in all river basins is not certain, as well as the effective areas of their distribution, especially for *Sotalia* that has more distributional constraints than *Inia* (shallow waters, narrow channels and tributaries) (Borobia *et al*. 1991, da Silva and Best 1996, Aliaga-Rossel *et al*. 2006).

In terms of anthropogenic threats, entanglements of river dolphins in gillnets occur sporadically, but the main concerns should be the overexploitation of resources due to large-scale fisheries, like the mota (*Callophysys macropterus*) fishery in the Brazilian Amazon. Approximately 600 *Inia* dolphins are being killed per year to be used as bait for this fishery, which is widespread in Brazil (Loch *et al.* 2009). The number of dolphins killed per year in Brazil is at least half of the entire population sizes of river dolphins estimated in this study for some of the locations surveyed (Table 8). If the killing of river dolphins spreads from Brazil to other countries, population sizes will likely decline within a few years. Finally, caution should be applied when considering different species. For instance, the population size of *Sotalia* dolphins in the Amazon and Orinoco river basins is smaller than that of *Inia*. *Sotalia* dolphins are restricted to open areas with significant water depth and they cannot access very shallow and narrow riverine areas. Thus, their distribution is significantly smaller. This should be taken into account when evaluating the impact of different anthropogenic threats for both species given as smaller and more localized populations are likely to be more vulnerable.

Conclusions

This study provides a baseline of population and density estimates of river dolphins in South America. Major variations in densities of dolphins by location suggest that caution should be applied when extrapolating results to areas that have not been surveyed. This study used density estimates to propose hotspots (*e.g.,* Pacaya Samiria Reserve in Peru, Mamiraua Reserve in Brazil, Iténez, and Mamoré rivers) and critical habitat (area within 200 m from the shore, lakes, and confluences) for river dolphins in order to prioritize and encourage management actions at a regional scale. These surveys are part of an on-going study that represents an extensive effort to estimate the population size of river dolphins in South America. Results from surveys in other river basins will be available soon, and it is expected that efforts to evaluate the population levels will be the first step in raising awareness about the current conservation status of river dolphin populations and about the current and increasing anthropogenic threats in the Amazon and Orinoco river basins.

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