

# Population estimate and identification of major conservation threats for the river dolphin (*Inia geoffrensis humboldtiana*) at the Colombian Orinoquia

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South American sub-continent, housed the largest diversity of river dolphins on the planet, here there are two species in the genus *Sotalia* and three species in the genus *Inia*. Tonina, present on the Orinoco basin, are exposed to many different anthropogenic threats, such as: the fragmentation and loss of aquatic ecosystems; acoustic contamination; risk of collision with boats; entanglement; deaths by retaliation, resulting from biological and operational interactions with artisanal and industrial fisheries; biomagnification of heavy metals such as mercury in the aquatic trophic web; capture of individuals for their usage as bait for the fishery of *Calophysus macropterus*, primarily on borderline localities between Colombia and Venezuela; and finally, the negative effects of climate change. We conducted a study to determine population sizes and anthropogenic threats affecting river dolphins populations during the beginning of high-water season, between November 2018 and February of 2019, along 1,402 km. We calculated the degradation index for streams of continental waters and density of the river dolphins. Water quality, habitat transformation, species exploitation, and the increment in number of human settlements were identified as the main conservation stressor in the analyzed area. We obtained density values by habitat type for different aquatic environments and population sizes for river dolphins and the value in the index of degradation, with a potential increment in value through time. River confluences were identified as priority areas for the conservation of the species. Water quality, habitat modification, and species exploitation were particularly intense. Our results highlight a potential transformation of the ideal conditions that allow for the establishment of the species, explaining its distribution with predicted values between 46.6 % and 70.1 % for the evaluated timeframe due to the effects of climate change on aquatic ecosystems. The Meta River, has the highest value for the index of freshwater ecosystems degradation followed by the Orinoco basin, water quality and species exploitation appear to be the major stressors for dolphins in these areas. Finally, river confluences were identified as conservation hot spots for dolphin populations. We point out on the importance of river dolphins as bioindicator, sentinel species, and one of the most susceptible to the negative effects of climate change.

El subcontinente Suramericano, contiene la mayor diversidad de delfines de río del planeta, registrándose dos especies para el género *Sotalia* y tres especies para el género *Inia*. La Tonina, presente en la cuenca del Orinoco, está expuesta a diferentes amenazas de origen antrópico, como: la fragmentación y pérdida de los ecosistemas acuáticos; contaminación acústica; riesgo de colisión con embarcaciones; enmallamientos; muerte por retaliación, producto de interacciones biológicas y operacionales con pesquerías artesanales e industriales; biomagnificación de metales pesados como el mercurio en la red trófica acuática; captura de individuos para su uso como atrayente en la pesquería de *Calophysus macropterus*; y finalmente, los efectos negativos del cambio climático. Esta investigación determinó los tamaños poblacionales y las amenazas de origen antrópico que están afectando las poblaciones de delfines de río durante el período de aguas en ascenso, entre los meses de noviembre 2018 y febrero de 2019, a largo de 1,402 km. Se calculó el índice de degradación de ecosistemas acuáticos continentales y la densidad de los delfines de río. La calidad del agua, la transformación del hábitat, la explotación de especies y el incremento en el número de asentamientos humanos se identificaron como los principales estresores para la conservación de la especie en el área analizada. Se obtuvieron los valores de densidad por ambientes acuáticos y los tamaños de poblacionales para los delfines de río y el valor en el índice de degradación, con un potencial incremento en el valor a través del tiempo. Las confluencias entre ríos fueron identificadas como áreas prioritarias para la conservación de la especie. La calidad del agua, la modificación del hábitat y la explotación de especies fueron particularmente intensas. Los resultados evidencian una transformación potencial de las condiciones ideales que permiten el establecimiento de la especie, explicando su distribución con valores predictivos entre 46.6 % y 70.1 % para el período de tiempo evaluado, influenciado por los efectos del cambio climático en los ecosistemas acuáticos. El Río Meta tiene el valor más alto para el índice de degradación de los ecosistemas acuáticos continentales seguido por la cuenca del Orinoco, la calidad del agua y la explotación de las especies parecen ser los principales estresores para los delfines en estas áreas. Finalmente, las confluencias de los ríos fueron identificados como puntos clave para la conservación para las poblaciones de delfines. Destacamos la importancia de los delfines de río como bioindicadores, especies centinela, y una de las más susceptibles a los efectos negativos del cambio climático.

**Keywords:** Aquatics mammals; climate change; Orinoco basin; pink dolphins; population density.

## Introduction

The global decline in species richness and species diversity has been estimated to affect one to ten percent of world-wide biodiversity over a ten-year period (Sittig *et al.* 2018), but it has also been shown that human interaction accelerates extinction events (Wilcove *et al.* 1998; Chapin *et al.* 2000; Dawson 2011; IUCN 2013). To manage the effective conservation of a given animal species, an understanding of its habitat and life history is critical. Although many animal species have been described in detail, standardized population data are still lacking. These studies are necessary to monitor population development and for subsequently determining the level of threat to the species in question, in order to develop and prioritize conservation strategies (Sittig *et al.* 2018).

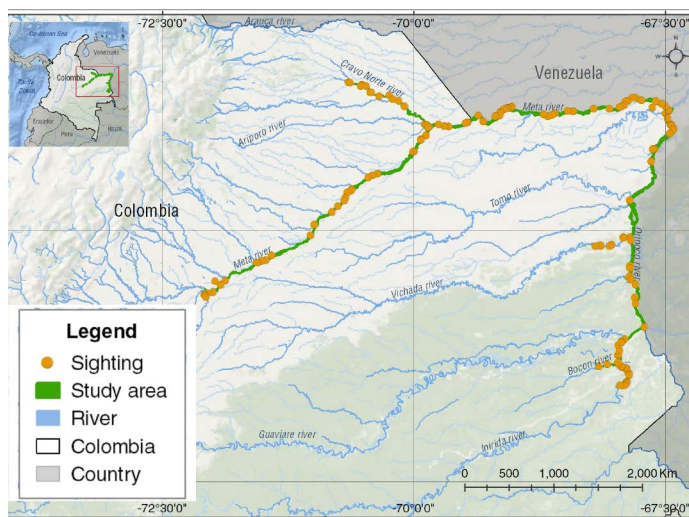
River dolphins are among the most threatened cetaceans on the planet (Reeves and Leatherwood 1994; Reeves *et al.* 2003; Davidson *et al.* 2009; Ávila *et al.* 2018); they have been only documented in South America and Asia, in geographic areas that in the last century have experienced some of the most intense transformations due to the impact of human activities (Reeves and Leatherwood 1994; IWC 2000; Reeves *et al.* 2000, 2003; Smith and Braulik 2008; Trujillo *et al.* 2010; Mosquera-Guerra *et al.* 2015). In 2005, it was reported the extinction of the Chinese river dolphin, or baiji, *Lipotes vexillifer* at the Yangtze River (Turvey *et al.* 2007; Ross *et al.* 2010), constituting one of the most recent extinctions of a large mammal (Trujillo *et al.* 2019). In addition, there are two other species of Asian dolphins under risk of extinction: *Platanista gangetica* (EN), distributed across the Ganges River complex (India and Nepal), and *P. minor* (EN), from the Indo (Pakistan) and Megna (Bangladesh) River systems (Smith *et al.* 2006; Smith and Braulik 2008). The South American sub-continent, housed the largest diversity of river dolphins on the planet with two species in the genus *Sotalia* and three species in the genus *Inia* (Mosquera-Guerra *et al.* 2015, 2018). The genus *Sotalia*, is represented by *S. fluviatilis* exclusive of continental environments of the Amazon basin (Da Silva 2002), and *S. guianensis*, documented from the mid-basin and the delta of the Orinoco river, the Maracaibo lake, and the Atlantic Coast in Central and South America from the south of Nicaragua to southern Brazil (Caballero *et al.* 2007). Molecular data point to a recent divergence of continental populations of *S. guianensis* (600,000 years), from their coastal counterparts (Cavajal-Castro *et al.* 2015; Caballero *et al.* 2017). Furthermore, vicariate events among basins, associated with the presence of rapids and waterfalls, and the influence of climatic fluctuations, gave origin to three species within the genus *Inia*: *I. geoffrensis* (Da Silva 2009), with the subspecies: *I. g. geoffrensis*, distributed on the Amazon basin (Da Silva 2002), and *I. g. humboldtiana*, occurring on the Orinoco basin (Herrera *et al.* 2017). *I. boliviensis*, from the Mamoré, Itenez, Grande, and upstreams from the Madeira River in Bolivia (Aliaga-Rossel 2002; Banguera-Hinestroza *et al.* 2002; Aliaga-Rossel *et al.* 2006; Ruiz-García *et al.* 2008; Ruiz-García 2010; Gravena *et al.* 2014). *I. araguaiaensis*, from the hydrologic complex of the Tocantins-Araguaia rivers in Brazil (Hrbek *et al.* 2014).

Recently the international threatened category of *I. geoffrensis* was elevated from Data Deficient (DD), to Endangered (EN; da Silva *et al.* 2018), and in Colombia, this taxon is considered as vulnerable (VU; Trujillo *et al.* 2006; Minambiente 2017). In addition, the species is within in Appendix II of The Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES 2019). Populations of *I. g. humboldtiana*, present on the Orinoco basin (Trujillo 2000; Diazgranados and Trujillo 2004; Mosquera-Guerra *et al.* 2018a), are exposed to many different anthropogenic threats (Mosquera-Guerra *et al.* 2016), such as: the fragmentation and loss of aquatic ecosystems; acoustic contamination (Davidson *et al.* 2012); risk of collision with boats (Ávila *et al.* 2018). Entanglement; deaths by retaliation, resulting from biological and operational interactions with artisanal and industrial fisheries (Trujillo *et al.* 2006, 2010; Da Silva 2011; Mintzer *et al.* 2013). Biomagnification of heavy metals such as mercury in the aquatic trophic web (Mosquera-Guerra *et al.* 2015a, 2018c). Capture of individuals for their usage as bait for the fishery of the mota, simí, piracathinga or come muerto (*Calophysus macropterus*), primarily on borderline localities between Colombia and Venezuela on the Arauca, Meta, and Orinoco rivers (Mosquera-Guerra *et al.* 2015c). Finally, river dolphins are affected by the negative effects of climate change on their habitats and populations (Mosquera-Guerra *et al.* 2015b).

Because of the current scenario, urgent conservation actions are needed to guarantee the persistence of *I. g. humboldtiana* on the Colombian Orinoco basin; but their construction and implementation require appropriate data collection on the species habitat use (Gomez-Salazar *et al.* 2011), as well as, standardized and statistically supported population density estimations (Gomez-Salazar *et al.* 2012a). This information also provides elements for monitoring *I. g. humboldtiana* population trends in these rapidly changing landscapes of the Orinoco region (Reeves and Leatherwood 1994; IWC 2000; Reeves *et al.* 2000; Gomez-Salazar *et al.* 2012a). We determined the populations size and conservation threats of toninas in three regions of the Colombian Orinoquia (Meta, Casanare and Vichada), across the Meta, Ele, Cravo Norte, Casanare, Orinoco, Vichada and Inirida rivers, at the beginning of high-water season, between November 2018 and February of 2019, along a total of 1,402 km. Our information on *I. g. humboldtiana* occurrence, was used to feed predictive species distribution models for the next 20 years at the Colombian Orinoquia.

## Material and Methods

**Study area.** Between November 2018 and February of 2019, three scientific expeditions were conducted: A) Meta (6.11027°, -67.28218° / 4.21653°, -72.04838°). B) Ele, Cravo Norte and Casanare Rivers (6.58977°, -70.7209° / 6.04325°, -69.83514°). C) Orinoco, Vichada and Inirida Rivers (6.18417°, -67.47140° / 3.86514°, -67.93397°); in order to evaluate the population status and Orinoquian pink dolphins (*I. g. humboldtiana*); as well as to identify the major threats for the subspecies in the region (Figure 1).



**Figure 1.** Study area: Meta river transect, from the municipality of Puerto Carreño (Vichada) up to Puerto Gaitán (Meta; 720 km). Ele, Cravo Norte and Casanare transect, from Arauca (Arauca) up to Paz de Ariporo (Casanare; 410 km), and Orinoco. Vichada and Inirida rivers transect, from Puerto Carreño (Vichada) up to Puerto Inirida (Guania; 210 km), and records of *I. g. humboldtiana* employed in the construction of different models of distribution for the species in the Colombian Orinoquia.

**Transect design.** Sampling was conducted with a combination of line and strip-transect methods (Gomez-Salazar et al. 2012a), performing four strip transects of 2.5 km altogether in length and every a width of 200 meters; then, switching into a line transect between 1.0 and 2.5 km, depending on river width. Boat speed ranged between eight and 12 km/hour and data gathering happened between 5:30 and 17:30 hours. The whole sampling occurred within the high-water season, allowing for the evaluation of different types of habitats including main rivers, channels, confluences, tributaries, and river islands (Table 1). Boats ranged from 11 to 43 meters of length and were equipped with observation platforms on both bow and stern, varying from two to six meter in height and supporting six previously trained observers on each one. Observers were clockwise rotated in position each two hours. Each platform was considered independent and only one effort recorder knew about the differences in observations between the two platforms, registering them with assigning codes following Gomez-Salazar et al. (2012a).

*Inia g. humboldtiana* sighting locations were recorded in geographic coordinates with a GPS Garmin 64sc; sight angle was documented with a compass and distance from the dolphin was estimated with a laser range finder distance meter Bushnell Trophy 4X de 20 mm. For each observation the distance to the shore was estimated in ranges as follow: 0 to 50 m, 50 to 100 m, 100 to 150 m and 150 to 200 m; in the same way riversides were classified into: mainland; forest; bushes; beaches; cliffs; rocks; human settlement; floating grasses. In addition, information on the environmental conditions, including: glare strength; water type (backwaters, white waters, and mix waters, by limnological criteria); river state, was recorded *in situ*.

Habitat were stratified to generate a differential report on population density with ecological support follow-

ing Gomez-Salazar et al. (2012a) and Trujillo et al. (2011): i) main river, ii) tributaries, iii) lake, iv) island, v) channels y vi) confluences. The sampling experimental design followed Gomez-Salazar et al. (2012a; 2012b), Williams et al. (2016), and involved a combination of two types of strip transects (parallel to the shore) and lineal (crossing diagonally the river width).

**Human stressors and index of freshwater ecosystems degradation.** We determined the degradation index of freshwater ecosystems by transect following Gomez-Salazar et al. (2012b), authors that consider 10 human stressors (Table 2 and 3), grouped into four categories i) water quality; ii) habitat modification; iii) species exploitation; and iv) human settlements and cities (Table 4). Each stressor was valued with a code, according to four categories of impact: 0) absence of disturbance; 1) low disturbance; 2) mid disturbance; and 3) high disturbance. Overall score index of freshwater habitat degradation was obtained by summing over these three major categories with overall value ranges from 0 to 8.5 (8.5 being the highest degradation). In addition, the information on human population size (Table 2) for each river area surveyed was obtained using the databases of the population census for each country surveyed (DANE 2018). The future trend in freshwater habitat degradation was estimated for each human stressor based on current knowledge of, for example, water development projects planned (Table 3). Information used to provide current and future degradation index scores consisted of observations in the field, published and unpublished reports, and personal communications with researchers from each location surveyed (see also Gomez-Salazar et al. 2012b).

**Population estimation.** Population estimate was calculated in DISTANCE version 5.0 y 6.0 (Buckland et al. 2001; Gomez-Salazar et al. 2011a) based on this formula:  $D = n$

**Table 1.** Studied habitats by river: Main rivers, Channels, Confluences, Tributaries, and Islands for the transects: Meta; Ele, Cravo Norte and Casanare; and Orinoco, Vichada and Inirida rivers; Area; Transect length; N trans (number of transects by habitat type); S (stripe transects; and line transects).

Basin	Rivers	Habitat type	Area Km <sup>2</sup>		Transect Length Km		No. trans		
			S	L	S	L	S	L	
Orinoco	Meta	Channel	65.7	-	131.4	-	53.0	-	
		Tributary	3.7	-	7.3	-	3.0	-	
		Main river	257.6	4.5	515.2	9.0	209.0	6.0	
	Ele, Cravo Norte and Casanare	Channel	4.9	-	9.8	-	4.0	-	
		Confluence	2.5	-	5.0	-	2.0	-	
	Orinoco, Vichada and Inirida	Main river	Channel	100.3	-	200.6	-	82.0	-
			Confluence	11.7	-	23.4	-	10.0	-
		Island	Channel	1.8	-	3.7	-	2.0	-
			Main river	189.1	25.5	378.2	50.9	127.0	25.0
Total	by type of transect	Tributary	6.8	-	13.6	-	6.0	-	
		Subtotal	27.0	-	54.0	-	7.0	-	
			671.1	30.0	1.342	60.0	537.0	31.0	
			701.2	1.402	568.0				



**Table 2.** Principal human stressors responsible for freshwater degradation and their impact on the ecosystems proposed by [Gomez-Salazar et al. \(2012b\)](#).

Human stressors	Impact of stressors on freshwater ecosystems
Water quantity	Water withdrawals by domestic, industrial and agricultural needs, reservoir storage capacity ( <a href="#">Alcamo et al. 2003, 2005</a> ).
Water quality	Source point and non-source point pollutants (e. g., organic pollutants, increased nutrients, heavy metals, microbial contamination, toxic organic compounds), suspended particles, temperature ( <a href="#">Hoekstra et al. 2011</a> ).
Habitat modification	Roads, dams, reservoirs, land transformation, land use intensity, agriculture, vegetation cover, fragmentation ( <a href="#">Moyle and Randall 1998; Revenga et al. 2000; Vörösmarty et al. 2010; Alkemade et al. 2009</a> ).
Exploitation of species	Fishing pressure, destructive fishing practices (e. g., blast fishing or fishing using poison or explosives), excessive by-catch and discards, aquaculture ( <a href="#">GIWA 2002</a> ).
Climate change	Increasing water temperature, decreasing precipitation, increasing acidification, changes in primary production ( <a href="#">Vörösmarty et al. 2000; Milà-Canals et al. 2009</a> ).
Introduced species	Increasing the rates of species introduced in freshwater systems and the success rate of those introduced ( <a href="#">Falkenmark 1997; Karr and Chu 1999; Bennett et al. 2004</a> ).

$E(i) f(0) / 2L g(0)$ . In which  $n$  is the number of observed groups of dolphins;  $E(i)$  is the group mean observed in habitat ( $i$ );  $f(0)$  is the probability of detection of a density from a perpendicular distance 0;  $L$ , refers to the length of the transect; and  $g(0)$  is the probability of detection of a group on the line of the transect.

For  $g(0)$  we follow the assumptions, as well as the indications in the calculation of the variance in [Gomez-Salazar et al. \(2011a\)](#). For the detection function, we analyze three different models in DISTANCE: uniform, half-normal and hazard rate, that were selected following the Akaike Information Criteria (AIC). Taking into account that we detected a gradient of dolphin density from the shore to the center of the river, the probability of detection  $g(0)$  was calculated in a scaled manner using a range of distances (0 to 50 m, 50 to 100 m, 100 to 150 m and 150 to 200 m). The population size for river dolphins ( $N_i$ ) was calculated for each habitat  $N_i = A_i * D_i$  ([Gomez-Salazar et al. 2011a](#)).

**Data collection and distribution models for climate change scenarios.** In order to construct models of potential distribution for *I. g. humboldtiana* in future climate change scenarios for 2018, 2023, 2028, and 2038. Occurrence data represented by 177 georeferenced records obtained from direct observations of dolphins across the Orinoco basin in 2018, were combined with climate datasets from ASCII files for 2020, 2030, 2040 and 2050 with the algorithm Maxent ([Graham and Hijmans 2006, Phillips et al. 2006, Peterson et al. 2007](#)). Occurrence data was filtered to avoid redundancy following protocols proposed in [Phillips et al. \(2009\)](#), and was visualized in ArcGIS 10.2.2 ([ESRI 2014](#); Figure 1). Nineteen climatic variables, derived from Worldclim ([Hijmans et al. 2005](#); Table 5), were used in combination with climate shapefiles obtained from the web portal Climate Change, Agriculture and Food Security (CCAFS), selecting the method Delta IPCC AR4 for

the region B12. For the intermediate temporalities 2018, 2023, 2028 and 2038 a regression was performed in geo-statistical software “R” ([R Core Team 2013](#)). We applied the cubic convolution interpolation method in order to down-scale bioclimatic variables with a pixel resolution of 100 meters for the analyzed years ([ESRI 2019](#)). In addition, we also considered two hydrological variables: i) flux accumulation and ii) flux direction along with a digital elevation model.

In order to select the most informative climate variables for our *I. humboldtiana* presence data set, we implement the function *vifstep* from the *usdm* library in the software R ([R Development Core Team 2011](#)).

## Results

**Human stressors and estimation of freshwater ecosystems degradation.** The index of freshwater ecosystems degradation, reported low to intermediate values ranging between 2.05 and 4.5, as follows by transect: a) Meta (4.5). b) Ele, Cravo Norte and Casanare (2.05). c) Orinoco, Vichada and Inirida Rivers (4.25; Table 6).

**Table 3.** Human stressors and definitions for each impact category proposed by [Gomez-Salazar et al. \(2012b\)](#). Codes for impact categories are (0) no disturbance reported, (1) low disturbance, (2) medium disturbance, (3) high disturbance. Some human stressors do not include high impact categories (-).

Human stressors		Impact categories [range distance from the study area]		
		Low (1)	Medium (2)	High (3)
I. Water quality				
1. Oil exploitation	Any size	100–200 km	50–100 km	Within 50 km
2. Tourism	Tourist resorts	50–100 km	Within 50 km	–
3. Ship traffic	Commercial, fishing, naval or transportation.	Sporadic routes.	Known shipping routes.	–
4. Mining	Any	100–200 km	50–100 km	Rango 50 km
II. Habitat modification				
5. Dams	Any size	500–1,000 km downstream or 100–200 km upstream.	200–500 km downstream or 50–100 km upstream.	Within 200 km downstream and/or within 50 km upstream.
6. Waterways	Any size	500–1,000 km downstream or 100–200 km upstream.	500–1,000 km downstream or 100–200 km upstream.	Within 200 km downstream and/or within 50 km upstream.
III. Exploitation of species				
7. Entanglements/ killing of dolphins to avoid competition for resources (fish).	Number of dead dolphins due to entanglements/ or direct killing.	Rare (recorded once or twice in the area).	Occasional (recorded once per year).	Frequent (recorded at least once per month).
8. Killing of river dolphins for bait	Number of dead dolphins killed for bait.	Rare (recorded once or twice in the area)	Occasional (recorded once per year).	Frequent (e.g., mota fishery established in the area).
9. Fisheries		Subsistence.	Commercial, main destination is cities within the river basin.	Commercial, main destination is cities within and outside the river basin.
IV. Human settlements and cities				
10. Human population size		Less than 100,000.	Between 100,000 and 200,000.	More than 200,000.

**Table 4.** Overall score index for each impact category (high, medium and low, see Table 3) and risk trend levels of freshwater ecosystem degradation. The overall score index is the sum of the means over the four main categories of human stressors (water quality, habitat modification, exploitation of species, cities and human settlements, Table 3).

	Overall score index	Summing over the different types of human stressors
High	Majority of human stressors are classified as high or medium, no stressors are classified as low.	$\geq 4$
Medium	Majority of human stressors are classified as medium.	$\geq 3$ and $< 4$
Low	Majority of human stressors are classified as low or no known, no stressors are classified as high.	$< 3$
<b>Risk trend (within the next 10 years)</b>		
↑	Risk is expected to increase (e.g., construction of water development projects planned, increase number of oil stations, etc.).	
→	Risk is expected to remain similar, although some increase in human population size is expected.	
↓	Risk is expected to reduce given some conservation or management actions in the area.	
-	Risk not recorded in the area, and not expected to appear in the next year.	

**Population status.** For 1.402.2 km surveyed, at the beginning of the rainy season, a total of 654 individuals were recorded, discriminated by river as follows: Meta = 206; Ele, Cravo Norte and Casanare = 89; and Orinoco, Vichada and Inirida = 359 (Table 7).

The greatest values of density were registered for the type of habitat “confluences”, with the confluence

**Table 5.** Bioclimatic variables used in the potential distribution models of *I. g. humboldtiana* in the Orinoco basins.

Variables	Description
Elevation	Height in meters above sea level
Bio 1	Annual average temperature
Bio 2	Average daytime range (Mean of the month (Max Temp - Min Temp))
Bio 3	Isothermality ((Bio 2/Bio 7) * 100)
Bio 4	Seasonality of temperature (Standard deviation * 100)
Bio 5	Maximum temperature of the hottest month
Bio 6	Minimum temperature of the coldest month
Bio 7	Annual temperature range (Bio 5 - Bio 6)
Bio 8	Average temperature of the wettest quarter
Bio 9	Average temperature of the driest quarter
Bio 10	Average temperature of the warmest quarter
Bio 11	Average temperature of the coldest quarter
Bio 12	Annual rainfall
Bio 13	Precipitation of the wettest month
Bio 14	Precipitation of the driest month
Bio 15	Seasonality of precipitation (Coefficient of variation)
Bio 16	Precipitation of the wettest quarter
Bio 17	Precipitation of the driest quarter
Bio 18	Precipitation of the warmest quarter
Bio 19	Precipitation of the coldest quarter
Rad	Solar radiation

**Table 6.** Score index and risk trends of freshwater ecosystem degradation, and human population size across the three areas surveyed. The direction of the arrows indicates whether the risk of degradation is expected to increase, decrease or remain the same. Overall score index is the sum of the means over the four main categories of human stressors (water quality, habitat modification, exploitation of species, cities and human settlements; Gomez-Salazar et al. 2012b).

Human stressors	Rivers		
	Meta river	Ele, Cravo Norte and Casanare rivers	Vichada Orinoco and Inirida rivers
Overall score risk	4.5	2.05	4.25
I. Water quality	2.5	0.75	2.25
1. Oil	3↑	1↑	-
2. Tourism	2↑	-	3↑
3. Ship traffic	2↑	1↑	3↑
4. Mining	3↑	1↑	3↑
II. Habitat modification	-	-	-
5. Dams	-	-	-
6. Waterways	-	-	-
III. Species exploitation	2→	1.3→	2→
7. Accidental entanglements / dolphin deaths due to competition for resources (Fishes)	2↑	2↑	2↑
8. Killing of river dolphins for bait	1↑	-	1↑
9. Fisheries	3↑	2↑	3↑
IV. Cities and human settlements	-	-	-
10. Human Population Size	181,276	3,331	34,274

between the Meta-Orinoco yielding a density value  $D = 17.6$  *Inia*/km<sup>2</sup>, following by the confluence of the river system of Ele, Cravo Norte and Casanare,  $D = 1.2$  *Inia*/km<sup>2</sup> (Table 8). Average group size was 2.9 ( $SD = 1.5$ ) for the Ele, Cravo Norte and Casanare rivers; 2.6 ( $SD = 1.9$ ) Orinoco, Vichada and Inirida; and 2.0 ( $SD = 1.4$ ) Meta.

The habitat type “main river” showed values ranging between  $D = 1.6 - 0.8$  *Inia*/km<sup>2</sup> for Meta, Ele, Cravo Norte and Casanare; while, Vichada River had a value of  $D = 0.6$  *Inia*/km<sup>2</sup>. Channels had density values ranging from  $D = 0.3$  to  $0.5$  *Inia*/km<sup>2</sup> only recorded for the Meta and Orinoco-Vichada. Finally, Island density was  $D = 0.6$  *Inia*/km<sup>2</sup> for the Orinoco and Vichada (Figures 2a-b).

**Niche modeling and climate change.** We modeled the potential distribution of *I. g. humboldtiana* for predicted scenarios of climate change for the following temporal windows: 2018 yield an area of 1,467 km<sup>2</sup> (AUC: 0.97); 2023, 784.3 km<sup>2</sup> (AUC: 0.96), 2028, 575.6 km<sup>2</sup> (AUC: 0.96), and finally 2,038 440 km<sup>2</sup> (AUC: 0.94; Figures 3a-d).

## Discussion

River dolphins are considered ideal biological models to understand the dynamics of the aquatic ecosystems at the basin scale; characteristics such as: i) low population size; ii) high habitat requirements; iii) differential use of their habitats; iv) location as top predators within the trophic web; v) long pregnancy (Martin and Da Silva 2018; Boede et al.

**Table 7.** Values of the density of *I. g. humboldtiana* in the different types of habitat sampled for each of the systems evaluated. *Di* is the densities for the habitat type, *Ai* is the survey area and *Ni* is the population size calculated for the river dolphins.

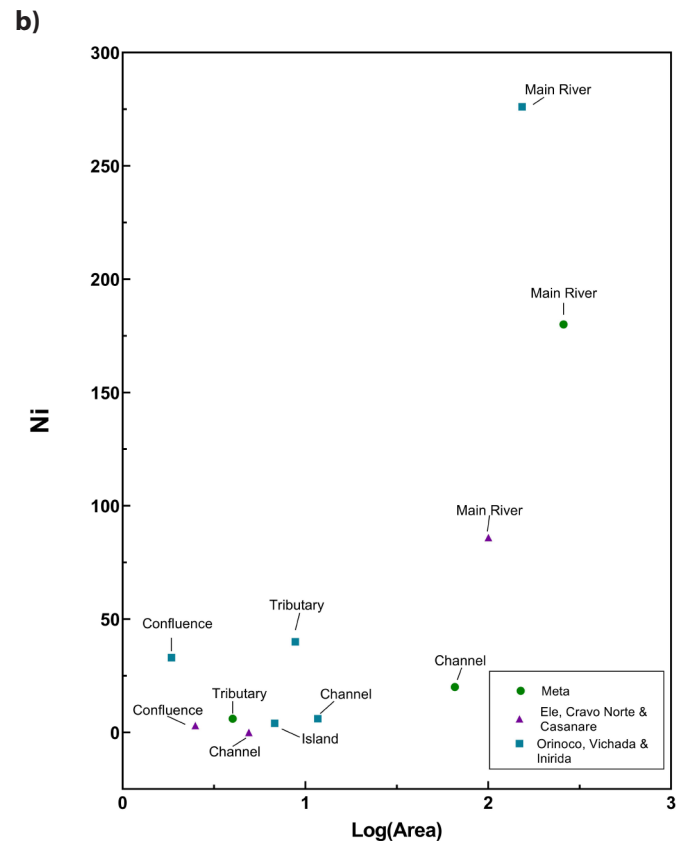
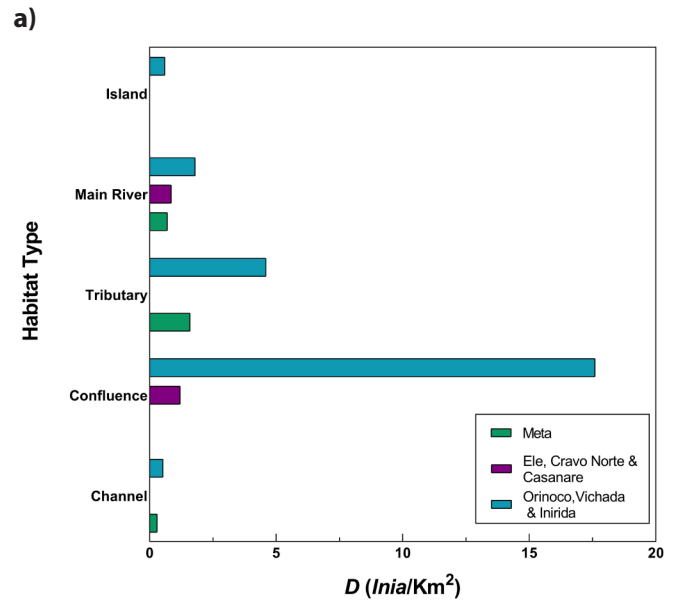
River	Habitat type	Area (km <sup>2</sup> )	<i>Di</i>	<i>Ni = Ai*Di</i>
Meta	Channel	65.7	0.3	20
	Tributary	4.0	1.6	6
	Main River	258	0.7	180
Ele, Cravo Norte and Casanare	Channel	4.9		0
	Confluence	2.5	1.2	3
	Main River	100.3	0.8	86
Orinoco, Vichada and Inirida	Channel	11.7	0.5	6
	Confluence	1.8	17.6	33
	Main River	153	1.8	276
	Island	6.8	0.6	4
	Tributary	8.8	4,6	40

2018); and vi) long term parental care (Boede et al. 2018). Make these cetaceans sensitive to the environmental changes, and by means sentinel and bioindicator species of the aquatic environments (Trujillo et al. 2010; Gomez-Salazar et al. 2012; Herrera et al. 2017; Mosquera-Guerra et al. 2018; Trujillo et al. 2019). The constant direct and indirect threats faced by river dolphins and their habitats across the Colombian Orinoquia, had made a priority the construction of conservation actions to guarantee their existence, as into account for the appropriate design of conservation strategies is the generation of well as the multiple structural functions these cetaceans offer to their environments. One of the most important aspects to take information on population size and its relationship with the health of the environment across species distribution (Trujillo et al. 2011; Mosquera-Guerra et al. 2018). After almost a decade of continues research, we have population estimates for *I. g. humboldtiana* across the Orinoco basin in the Arauca, Meta, Bitu, Orinoco, Guaviare, Guayabero and Losada Rivers (Mosquera-Guerra et al. 2015, 2018; Trujillo et al. 2019).

*Human stressors and estimation of freshwater ecosystems degradation.* These values are in agreement with data reported in Gomez-Salazar et al. (2011) and Mosquera-Guerra et al. (2015, 2016) the mid Orinoco River. It is important to mention that human stressors have a differential intensity along the hydrologic systems evaluated, varying in parameters such as: water quality; the type of habitat

**Table 8.** Average of the sighting rate (*n / l*), density estimate (*D*) and coefficient of variation to measure the rate of encounter CV (er) for the aquatic systems evaluated during the hydrological period of low water.

Habitat	Meta River			Ele, Cravo Norte and Casanare Rivers			Orinoco, Vichada and Inirida Rivers		
	N/L	D <i>Inia</i> / km <sup>2</sup>	Cv(er)	N/L	D <i>Inia</i> / km <sup>2</sup>	Cv(er)	N/L	D <i>Inia</i> / km <sup>2</sup>	Cv(er)
Channel	0.06	0.30	0.16				0.10	0.50	0.10
Confluence				0.20	1.20	0.10	3.10	17.60	0.08
Tributary	0.30	1.60	0.30	0	0	0	0.10	4.60	0.04
Main River	0.10	0.70	0.30	0.20	0.80	0.10	0.10	1.80	0.01
Island							0.10	0.60	0.03



**Figures 2.** Values of density and population size of *I. g. humboldtiana*, in the different types of habitat sampled for each of the systems evaluated. a) values of density in km<sup>2</sup> and b) population size calculated for the river dolphins in Log (area).

modifications; fisheries exploitation; and boat traffic volume, among others.

Other aspect that contributes to the affectations complexity, is derived from the natural heterogeneity of the savannas of the Colombian *Llanos Orientales*, enclosing at least 156 different types of ecosystems, 49 correspond to areas with some degree of human transformation (Romero et al. 2004). The agroindustrial plantations establishment of African palms (*E. guineensis*), maize (*Z. mays*), and rice (*O. sativa*), and during the last twenty years, the increment in

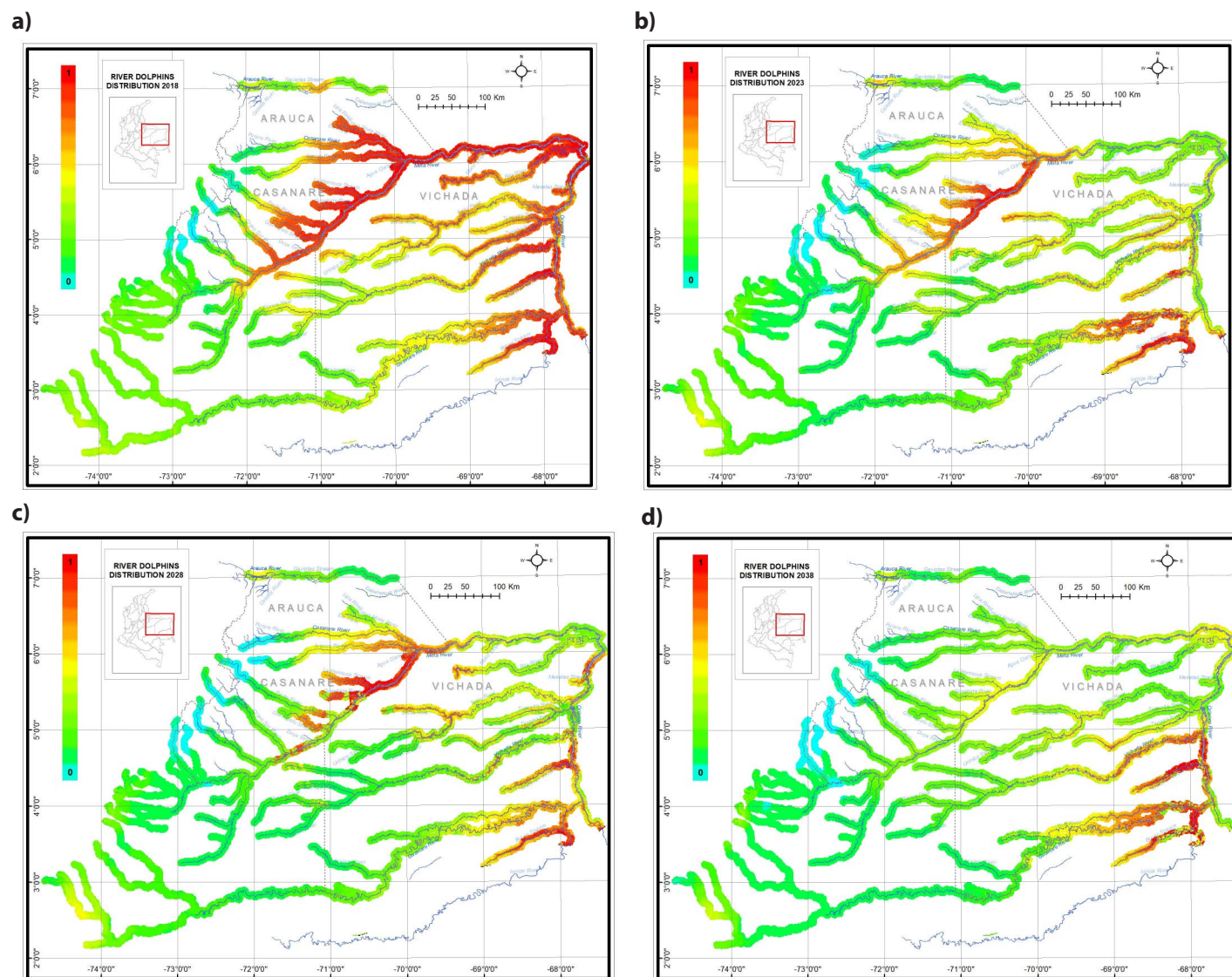


acacias (*Acacia sensu*) and eucaliptus (*Eucalyptus* sp.) plantations. In conjunction, monocultures are some of the transformation gears at the landscape scale in the Orinoquia (Andrade et al. 2009). Agro-industrial activities demand large volumes of water, situation that in combination with the natural hydrological stress, derived from the region seasonality, affecting, in particular, the tributaries contribution, compromising the ecological dynamics as a consequence of his dependence of structural changes in area and volume, importance variables for large aquatic vertebrates such dolphins. The situation aforementioned is particularly true for the Casanare, Cravo Sur, and Meta Rivers, tributaries of the Meta basin (Mosquera-Guerra et al. 2015). The increment in human settlements and cities, consequence of massive migration is an outgrowth of agroindustrial megaprojects in the Colombian Orinoquia (Mosquera-Guerra et al. 2016). Major human centers in the region are characterized by a poor infrastructure and coverage for water treatment. Sewage dumping in municipalities such as Puerto Carreño (Vichada), Cravo (Arauca) and Orocué (Casanare), as well

as the disposal of solid residuals along the Meta, Ele, Cravo Norte, Casanare, Vichada, Orinoco, and Inirida rivers.

Deforestation and fires intentionally promote by human activities, along the river shores, compromised their structural stability, increasing the amount of sediments discharged into the river systems, and the total dissolved soils, affecting biogeochemical cycles, the turbidity, conductivity, acidity and amount of heavy metals. All these effects result in changes in the ecological dynamics of water systems (Mosquera-Guerra et al. 2015a, 2018c). Previous estimation showed that the region suffers an annual transformation of 1.3 % of its forest coverage.

In contradiction with these statistics, and despite the warnings they have raised among scientists, at the Consejo Nacional de Política Económica y Social (2014) implemented a new economic policy for the Altillanura (non-flooded savannah), in which the “Departamento de Planeación Nacional” (DNP) suggest that around 2.8 millions of hectares in the region are free to be transformed into productive systems (Mosquera-Guerra et al. 2015).



Figures 3. Models of potential distribution for *I. g. humboldtiana* in the Orinoco basin for a) 2018, b) 2023, c) 2028, and d) 2038.

We also evidence an expansion of oiling activities across the study area, in particular for the high and middle basin of the Meta River (Gomez-Salazar *et al.* 2011; Mosquera-Guerra *et al.* 2016). Since the 1980's oil spills, due to subversive activities of the guerrillas, resulted in 1.5 million of barrels, contaminating primarily the aquatic systems of the Arauca and Casanare basins (Trujillo *et al.* 2010). Product of these perturbations, large amounts of heavy metals are released into the hydrological system, starting a process of biomagnification, with large vertebrate carnivores (river dolphins, giant otters, and cat fishes, among other animals) as final repositories of these metals in their tissues. Mosquera-Guerra *et al.* (2015a, 2018c), report the maximum amount of mercury (Hg) among South American river dolphins, in muscle tissue samples of *I. g. humboldtiana* from the Arauca River (3.5 mg/kg<sup>-1</sup>).

We also identify that the inadequate closure of oil drills, are a potential threat of oil spills. The new economic policies that authorize the implementation of extractive techniques like the fracking emerge as new potential threat for the aquatic environments (Mosquera-Guerra *et al.* 2016). On the other hand, touristic activities, are generating an increment in the traffic of boats, raising the number of evidence of collisions (scars in the fins and even dead animals have been documented) in particular for the Orinoco and Vichada Rivers, also the considerable increment of acoustic contamination, associated with commercial activities, and human transportation, taking into consideration that these two rivers in a region that lacks of other ways to access affect the dolphin reproductive sites, such as the confluences of Meta-Orinoco and Vichada-Orinoco Rivers. The structural modification of the river courses to in order favor a greater volume of boat traffic (hydro-highways), will also carry many of the serious problems mentioned above. One of the major causes for the extinction of the Chinese baiji (*Lipotes vexillifer*) was the fragmentation of their population (Trujillo *et al.* 2010).

*Population status.* These results agree with information reported in Gomez-Salazar *et al.* (2011, 2012a, 2012b), Mosquera-Guerra *et al.* (2015, 2018) and Pavanato *et al.* (2016). The reported values of group size in the present work are within the averages documented by Gomez-Salazar *et al.* (2011) and Mosquera-Guerra *et al.* (2015), for Orinoco basin. Variation in density is strongly influenced by habitat type. The ecological heterogeneity of aquatic habitats across the Orinoco basin, determines a differential spatial-temporal use of the river by these cetaceans. Species in *Inia* can differentially use, main rivers, their tributaries, and flooded forest environments at different spatial and temporal scales. Confluences, tributaries, lakes and flooded forest are commonly used for feeding; shallow waters are the environments where individuals of the species mate and socially interact; and lakes and channels are used for the birth and care of offspring (Trujillo 2000; Martin and da Silva 2004, 2006; Gomez *et al.* 2012, Mosquera-Guerra *et al.* 2018b). *Inia* is intrinsically dependent on the dynamics of flood pulses of

the basins and their effect on the temporal and spatial distribution of their fish prey (Mosquera-Guerra *et al.* 2018b). Other studies have reported variations in density values for river dolphin density and group size associated with ecological factors such as flood pulses, highlighting that at low waters, river dolphins are concentrated on the channels, river confluences and tributaries. But, at high waters, individuals spread into other aquatic systems, associated with the flooded forest, in the foraging for fish preys (Trujillo *et al.* 2011, Gomez-Salazar *et al.* 2012a and Mosquera-Guerra *et al.* 2015a).

The present study corroborates, the ecological importance of river confluences for pink dolphins, in particular, Meta-Orinoco and Orinoco-Vichada; evidencing, its relevance as prioritized conservation areas for the subspecies (Figure 4a). River confluences are ecotones in which contrasting ecological conditions determine the selection of a differential fish communities. In the Orinoco basin, white water rivers such as the Meta, Arauca, and Casanare, encounter clear water rivers such as the Bitá, Tomo, Tuparro and Vichada and are obligated passes for fish populations moving up and down-streams. The last generates: i) ideal conditions for dolphin fishing success and ii) it conditions the generation of social groups among dolphins.

The highest values among analyzed habitats, reported by confluences, agrees with Trujillo (2000), Trujillo and Diazgranados (2004), Gomez-Salazar *et al.* (2011), Trujillo *et al.* (2016) and Mosquera-Guerra *et al.* (2018b). These authors, also associated the greatest number of individuals with the confluence of the Meta-Orinoco Rivers. In part, the greatest density of dolphins reported for the confluences, is closely related with the presence of fish in these areas that offer connection among different aquatic environments. In summary the stressors of human origin that influence the population dynamic of river dolphins are: habitat degradation, loss of connectivity, contamination, conflict with fisheries, increment of the traffic, climate change, and construction of hydroelectric infrastructure (Sandin *et al.* 2008; Baum and Worm 2009; Gomez-Salazar *et al.* 2012b; Mosquera-Guerra *et al.* 2015a; Trujillo *et al.* 2010a). Population estimates for river dolphins in Colombia and South America, have produced concrete results during the last 12 years, resulting in the change in the category of threat for *I. geoffrensis* by the IUCN, from Data Deficient (DD) to Endangered species (EN) in 2018 along with the formulation and implementation of regional and national management plans.

We infer a strong annual population reduction of *I. g. humboldtiana* at the Orinoco basin (7.14 %). This inference is derived from the comparison of our population data (2017 to 2018; 654 individuals) with that in Gomez-Salazar *et al.* (2012), representing a decrease of 35.7 % in the number of individuals in six years. Our data is in agreement with Williams *et al.* (2016) for the Colombian Amazon; who reported a reduction of 10 % per year for the populations of *I. g. geoffrensis* between 1993 and 2007. This condition in both basins (Amazon and Orinoco) can be explained by the increasing in



direct captures of dolphins to be used as bait for the fishery of the mota, simí, piracathinga or come muerto (*Calophrys macropterus*); augment in entanglements; and recently, strandings due to rapid changes in river flow.

**Niche modeling and climate change.** The Orinoquia is one of the most vulnerable ecoregions to climate change in Colombia. As suggested by the tools of climate action of the Ministry of Environment and Sustainable Development (MADS) of Colombia, and the Integral Regional Plan of Climate Change for the Orinoquia, it is thought that by 2100, temperature in the region will experience an increment between 2.61 °C and 2.7 °C above the average reference value (1976 to 2005), and precipitations will decrease in average a 10 % for the whole Orinoquian savannahs (CIAT et al. 2018). The region encloses strategic aquatic ecosystems highly vulnerable and with low resilience such as the humedales de sabana ecosystems that contribute with the hydrologic balance of many basins of Andean origin including the: Arauca, Casanare, y and Meta basins, as well as Orinoquian origin such as the: Bitá, Tomo, Tuparro and Vichada basins, part of the Orinoco macrobasin. Within this context, it is necessary to identify those negative effects of climate change on the aquatic ecosystems associated with the ecoregion. River dolphins are natural bio-indicators, widely distributed across the basin, allowing for an exploration of the changes in the climate niche of a large aquatic mammals, responsible of the structure of the vertebrate community in this type of systems. Our results highlight a potential transformation of the ideal conditions that allow for the establishment of the species, explaining its distribution with predicted values between 46.6 % and 70.1 % for the evaluated timeframe. The areas that within our models are going to experience the most drastic changes are associated with the Inirida and Guaviare basins, area of transition between the bioregions of the Amazon and the Guayana.

This results are in agreement with Trujillo et al. (2010, 2011, 2016) and Mosquera-Guerra et al. (2015, 2018), these authors document the increment in habitat transformation important for river dolphin populations, due to the variability of the hydrologic courses across the Orinoco basin, phenomenon mostly associated with climate change. This situation is evidenced by the increment in the number of stranded of river dolphins between 2015 to 2019 in localities such as Caño Agua Limón, tributary the Arauca River, main channel of the Arauca River (Arauca) and Orinoco (Vichada), in the surroundings of Santa Helena island, in where more than 10 stranding events have been reported in recent years (Figure 4b).

Due to their high seasonality, the Colombian Orinoquia is one of the most vulnerable regions to the negative effects of climate change in the country. The whole region intrinsically depends on water pulses that determine the phenological cycles of plants and animals in particular fish production. Hydrometeorological data in the Orinoquia, have documented strong variations in temperature and hydrologic dynamics, with episodes of both drastic



**Figures 4.** a) Hunting behavior of two individuals of *I.g. humboldtiana* obtained at the confluences between the Meta-Orinoco and Bitá-Orinoco rivers. b) Adult female's stranding events of *I.g. humboldtiana* in the Agua Limón spout (Arauca) in the Colombian Orinoquia.

droughts and intense floods. As already mentioned, river dolphins are highly dependent on the stability of the river pulses, and their effect in the maintenance of the different aquatic habitats they use to complete their biological cycle.

### Acknowledgements

This study is part of the project: "Formulación del Plan de Conservación para el delfín de río o delfín rosado (*Inia geoffrensis*)". We thank the support of Corporinquia, as well as all the people that help us within the field work; we thank Colciencias (National Doctorate Scholarship 785); this research is part of the Strategic Plan of the South American River Dolphins Initiative (SARDI), supported by WWF in Brazil, Colombia, Perú, Ecuador and Bolivia. Special gratitude to M. Oliveira, S. Usma, D. Amorochó, D. Willems, K. Berg, L. Sainz, J. Rivas, J. L. Mena, J. Surkin, and M. Wulms from the WWF network.

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Associated editor: Juan Pablo Gallo

Submitted: June 12, 2019; Reviewed: August 12, 2019;

Accepted: September 18, 2019; Published online: December 2, 2019

