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Population estimates of Amazonian river dolphins in the Mamirauá Sustainable Development Reserve before and after the "piracatinga" fishery moratorium

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Introduction

Abundance is one of the paramount parameters to assess, measure and predict impacts on animal population dynamics. National and regional action plans (ICMBio 2019, Trujillo et al. 2010, 2014; Utreras et al. 2013), the International Union for Conservation of Nature's Red Lists, and the International Whaling Commission (IWC 2018) stimulate the improvement of density, abundance and trend estimates for Amazon endemic *Inia* (boto) and *Sotalia* (tucuxi) dolphins, to subsidize conservation or recovery planning processes. However, population size of either species for the whole area is presently unknown.

Efforts to estimate numbers of South American river dolphins based on visual surveys date back to the middle 1950s, based on encounter rates, and remained so for almost 40 years (Layne 1958, Pilleri & Gihr 1977, Magnusson et al. 1980, da Silva et al. 1984, Best and da Silva 1989, Herman et al. 1996). Following Vidal et al.'s (1997) use of a protocol combining line and strip transects to account for river particularities in the region, other studies followed suit, expanding our knowledge on the matter (Aliaga-Rossel 2002, McGuire 2002, Martin and da Silva 2004, Martin et al. 2004). The protocol was further developed by Gómez-Salazar et al. (2012a) and in the last few years efforts have been further increased and generated a new suite of analyses (Pavanato et al. 2016, Williams et al. 2016, Mosquera-Guerra et al. 2020, Paschoalini 2019, Pavanato et al. 2019, Paschoalini et al. 2020).

Amazonian river dolphins' distribution overlaps with that of humans in the most productive areas, and a number of threats have been listed as a consequence of such proximity (i.e., incidental and directed mortality, increased boat traffic, noise, plastic, oil, heavy metal and chemical pollution, habitat degradation, dams, food resources reduction, and climate change) (Estupiñan et al. 2003, Loch et al. 2009, Trujillo et al. 2010, Gómez-Salazar et al. 2012, Smith and Reeves 2012). This is only partially the case with dolphins at Mamirauá Sustainable Development Reserve (MSDR). Being distributed in one of the most protected floodplain areas, which has been recognized as providing protection and shelter to river dolphin populations (Mintzer et al. 2013, 2015), current threats are likely more restricted to human-related mortality than any of the other factors.

Until 2011 *Inia geoffrensis* was considered data deficient (DD) due to lack of enough information to enable risk assessment. Da Silva et al. (2011) suggested a 10% annual population reduction in a portion of the Mamirauá Reserve and by 2018 *I. geoffrensis* was upgraded to IUCN's Endangered

category (da Silva et al. 2018), with a suspected reduction of at least 50% in its total population within 75 years (as of the year 2000). The decline was mostly attributed to the use of dolphins as bait in the piracatinga fishery, identified in the area in the early 2000s (Estupiñan 2003, Silveira and Viana 2003). Starting in January 2015, the Brazilian government established a 5-year ban on fishing and commercialization of piracatinga in order to halt the illegal hunt while generating information about the dolphin population (Franco et al. 2016).

Since 1993 the Mamirauá Institute has been collecting data on dolphin mortality (including associated with piracatinga), and more recently conducting boat, canoe and drone surveys, both in and around MSDR and other river systems as well, under a regional effort named SARDI (South American River Dolphin Initiative). This study was originally designed to monitor areas of graded effect of piracatinga fishery in order to evaluate its possible effects on dolphin populations along the Mamirauá and Amanã reserve borders.

Here, we reevaluated the paper submitted in 2020 to the IWC (Marmontel et al., 2020) seeking to investigate the specificities of each sub-area sampled within the Mamirauá Reserve, and adding an expedition made in 2014 to the same locations for population analysis before the "piracatinga" fishery moratorium.

Material and methods

Study area

The study was conducted in the 120,000-ha southeastern most portion of the MSDR. The MSDR has a total area of 1,124,000 ha and is located in the Central Amazon surrounded by Solimões and Japurá rivers (southern and eastern limit: 03°09'35" S 64°47'37" W; northern limit: 01°50'05" S 65°42'19" W; western limit: 02°32'50" S 67°22'08" W). It is inserted in an alluvial dense rain forest ecosystem (floodplain) with humid equatorial climate with monthly thermal amplitude of 8 - 10° C. Seasons are defined according to the water cycle, based on dry, flood, raising and receding regimes. Water level variation can reach vertically 10.6 m and hundreds of meters in the horizontal plan (Plano de Gestão MSDI, 2010). The flood and dry peaks occur in June and between October and November, respectively, and transitional periods of rising from December to May and falling waters from July to September (Ramalho et al. 2009).

The monitoring of river dolphins occurred in three key sites of the Mamirauá Reserve: sub-areas I, II, and III (Figure 1). These areas were selected because they concentrated a high effort of piracatinga fishery along the Solimões and Japurá rivers.

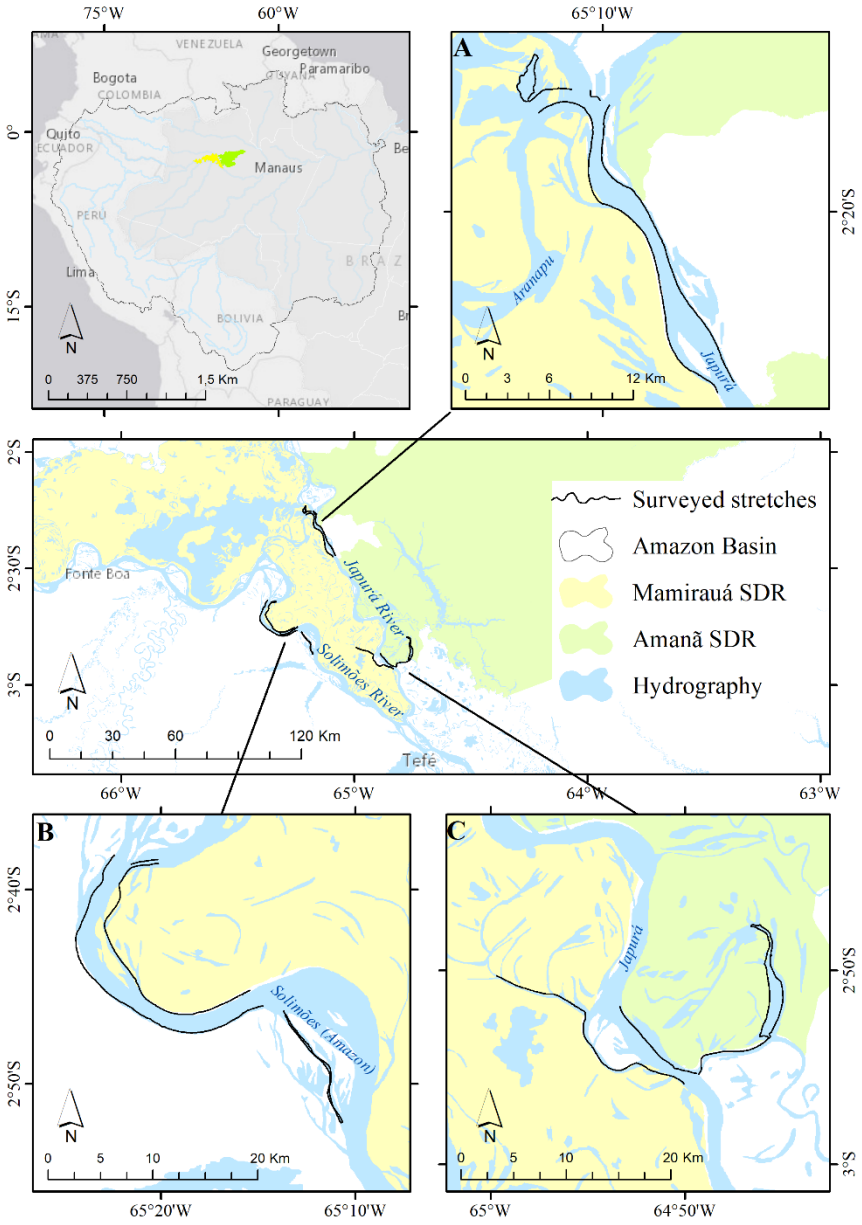

Figure 1. Study area Mamirauá Sustainable Development Reserve. The sub-areas sampled are Sub-area II (A), Sub-area I (B), and Sub-area III (C).

The sub-area I is located on the Solimões River (02°45'11" S 65°15'24" W) and its water bodies are typically white water. The sampled habitats in sub-area I comprised the main river, small channels and islands. The sub-area II is located on the Japurá River (02°26'37" S 65°04'54" W) at the entrance of the Auati Paranã Channel, and is bounded on the right margin by the MSDR and on the left side by the Amanã Sustainable Development Reserve (ASDR). This area is composed by a mixture of white and black waters, the latter coming from the marginal lakes and inland creeks. Sub-area II habitats comprise the main Japurá River, Jutaí Lake, confluence, channel, and island channel. Finally, sub-area III (02°50'19" S 64°59'37" W) is predominantly composed by flooded forests throughout

the year. In this area, the main Japurá River, channel, island channel, and Pantaleão Lake habitats were sampled.

Data collection

Surveys took place during the rising water period of 2014 (before the "piracatinga" fishery moratorium) and rising (January and February) and receding (July and August) water seasons from 2017 to 2020 (after the moratorium), totalizing eight sampling efforts. The seasons were chosen to standardize the water transition periods, in which most part of the habitat types is available and dolphins are theoretically randomly distributed (Gómez-Salazar et al. 2012).

The sampling protocol followed methodology proposed by Gómez-Salazar et al. (2012), surveying strip transects parallel to the river margin at a pre-established distance of 100 m (i.e., a 200 m strip width) using a small 6- to 8-m long boat traveling at an average speed of 10 km/h. The total effort comprised 233 km along the three areas surveyed (sub-area I: 97.8 km; sub-area II: 67 km; sub-area III: 68.2 km). Data collection was conducted using double platform configuration with three observers (two at the bow and one at the stern). The observations of both platforms were assumed to be independent, i.e. the observers at the stern platform were unaware of detections made by those at the bow ('one-way' independence), to enable the correction of missed sightings.

Sighting effort was conducted under good environmental conditions, and at each sighting the observers reported species, group size, presence of calves, radial distance between the sighting and the vessel, the radial angle, distances from the dolphin groups to the margin, habitat type (river, confluence, lake, channel or island channel), position of the group through GPS, and presence and type of fishing gear.

Data analysis

In this paper, we refined the analysis made in 2020 per sub-area in order to investigate each region. Our goals were to: i) compare the encounter rate of dolphin groups from 2014 to 2020; ii) estimate density by season and year across the three sub-areas. Data analyses were performed using the statistical software R (version 3.4.3, R Core Team 2015).

As dolphins are not 100% detected during visual boat surveys, a general detection function was used to estimate the proportion of individuals that were not detected, and, from there, an estimate of the population density was obtained (Buckland et al. 2001; Thomas et al. 2002). The detection function for Amazonian river dolphins was investigated by Gómez-Salazar et al. (2012) through line-transect sampling efforts, and recently improved by Paschoalini (2019). Considering a strip width of 200 m from the shore, the probability detection for groups sighted between 0 and 50 m from the trackline (P_1) at perpendicular distances is the same of 50–100 m and 100–150 m from the shore; and the probability detection for groups sighted between 50 and 100 m from the trackline (P_2) is the same

of 0–50 m and 150–200 m from the shore. We used the estimated P_k parameters for *I. geoffrensis* as $P_1 = 0.960$ and $P_2 = 0.630$ (*shape* = 0.37 (SE = 0.12), *scale* = -2.61 (SE = 0.42)) and for *S. fluviatilis* as $P_1 = 0.998$ and $P_2 = 0.893$ (*shape* = 0.99 (SE = 0.15), *scale* = -2.24 (SE = 0.41)) according to Paschoalini (2019).

We used a general probability of detection on the trackline (g(0)) for each species as 0.81 (CV = 0.05) for *I. geoffrensis* and 0.99 (CV = 0.006) for *S. fluviatilis* (updated in Paschoalini (2019) following methods proposed by Gómez-Salazar et al (2012)).

Density was estimated by means of stratification for each habitat type (river margin, island channel, channel, confluence, lake) as follows:

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

where E_i is the estimated group size at habitat type i, L_i is the total transect length at habitat i, and W is the strip width (200 m).

The overall density (D) of both species in the whole study area was calculated as the weighted average obtained by dividing the estimated abundance (sum of the abundance for each habitat type) by the area in squared km. Variances were obtained following Gómez-Salazar et al. (2012) methods, and the overall CV was calculated as follows:

$$\text{CV} = \frac{\sqrt{\sum(SEDi^2)}}{\sum Di}$$

where SE_i is the standard error of the density at habitat i.

For the 2014 expedition, we could only assess the encounter rate of dolphin groups per kilometer, because some distance measurements needed to estimate density were not collected in the field. Therefore, we decided to make a comparison between the animal encounter rate over the years, in order to investigate the populations before and after the “piracatinga” fishery moratorium.

The overall density and encounter rate along the years and across seasons were plotted using the *stat_smooth* function of *ggplot2* package (Wickham 2016), assuming the "loess" method chosen based on the size of the dataset (less than 1,000 observations).

Results

The effort, group size and encounter rate from 2014 to 2020 are in tables 1 (rising water) and 2 (receding water). The population density was only possible to estimate from 2017 to 2020. Figure 2 shows the encounter rate of groups per km from 2014 to 2020 for each species. It is possible to see a stability across the years for *Inia* and *Sotalia*.

Figures 3 and 4 show the density of populations of *Inia* and *Sotalia*, respectively. We analyzed the density per sub-area, and, according to the graphics, both species in sub-areas II and III are stable. However, in sub-area I, *Inia* shows a downward trend from 2019.

Table 1. Population estimates of *Inia geoffrensis* and *Sotalia fluviatilis* during the raising water from 2014 to 2020 in three key areas of Mamirauá Sustainable Development Reserve. L = effort; GS = group size; Er = encounter rate (number of groups sighted per km); D = density (number of individuals per km²). All values are followed by their coefficient of variation (CV).

Year	L (km)	Sub-area I			Sub-area II			Sub-area III		
		GS (CV)	Er (CV)	D (CV)	GS (CV)	Er (CV)	D (CV)	GS (CV)	Er (CV)	D (CV)
					Inia geoffrensis					
2014	246.2	1 (0.55)	0.92 (2.33)	-	1 (0.31)	0.39 (0.98)	-	1 (0.51)	0.88 (2.5)	-
2017	203.5	1 (0)	0.08 (1.6)	0.93 (0.96)	1 (0.27)	0.64 (1.18)	2.97 (0.28)	1 (0.5)	0.71 (1.49)	2.23 (0.83)
2018	224.8	1 (0.44)	0.73 (1.33)	4.71 (0.38)	1 (0.34)	0.79 (1.1)	6.53 (0.44)	1 (0.39)	1.59 (1.22)	8.03 (0.55)
2019	219.7	2 (0.87)	1.06 (1.97)	5.38 (0.12)	1 (0.6)	1.19 (1.83)	8.72 (0.7)	1 (0.42)	0.86 (0.91)	6.32 (0.23)
2020	211.1	2 (1.08)	0.79 (1.83)	2.94 (0.22)	2 (1.31)*	1.11 (1.57)*	7.87 (0.55)*	2 (0.59)	1.11 (1.24)	11.86 (0.3)
					Sotalia fluviatilis					
2014	246.2	2 (0.42)	0.11 (1.77)	-	2 (0.6)	1.18 (1.14)	-	2 (0.51)	0.91 (1.4)	-
2017	203.5	2 (0.5)	0.06 (1.4)	0.42 (0.59)	2 (0.6)	1.17 (1.22)	7.4 (0.54)	2 (0.65)	1.35 (1.47)	4.94 (0.56)
2018	224.8	2 (0.43)	0.47 (1.99)	1.8 (0.21)	3 (0.8)	0.98 (1.13)	15.52 (0.33)	2 (0.95)	1.23 (0.86)	11.03 (0.75)
2019	219.7	3 (0.56)	0.17 (0.96)	2.59 (0.48)	3 (0.73)	0.41 (1.25)	10.78 (0.63)	3 (0.7)	0.53 (1.21)	9.96 (0.72)
2020	211.1	2 (0.42)	0.26 (1.33)	2.89 (0.81)	3 (0.52)*	0.77 (1.06)*	10.03 (0.81)*	3 (0.68)	1.28 (0.88)	14.78 (0.65)

* values refer to a December 2019 expedition, as it was not possible to sample sub-area II in January 2020.

Table 2. Population estimates of *Inia geoffrensis* and *Sotalia fluviatilis* during the receding water from 2017 to 2029 in three key areas of Mamirauá Sustainable Development Reserve. L = effort; GS = group size; Er = encounter rate (number of groups sighted per km); D = density (number of individuals per km²). All values are followed by their coefficient of variation (CV).

Year	L (km)	Sub-area I			Sub-area II			Sub-area III		
		GS (CV)	Er (CV)	D (CV)	GS (CV)	Er (CV)	D (CV)	GS (CV)	Er (CV)	D (CV)
					Inia geoffrensis					
2017	218.7	1 (0.33)	0.49 (1.61)	2.3 (0.23)	1 (0.5)	0.76 (1.27)	5.15 (0.78)	1 (0.45)	1.05 (1.02)	13.05 (0.38)
2018	206.2	1 (0.61)	0.85 (1.54)	4.96 (0.1)	1 (0.41)	0.47 (1.37)	6.47 (0.56)	1 (0.67)	1.9 (1.04)	15.55 (0.38)
2019	207.7	1 (0.94)	0.32 (1.55)	4.15 (1.32)	1 (0.89)	0.5 (0.93)	5.78 (0.81)	2 (0.56)	1.72 (1.11)	12.71 (0.63)
					Sotalia fluviatilis					
2017	218.7	1 (0.39)	0.05 (1.26)	1.18 (0.19)	3 (0.58)	1.2 (2.16)	9.01 (1.05)	2 (0.93)	0.54 (1.23)	8.83 (0.88)
2018	206.2	2 (0.76)	0.12 (1.23)	2.18 (0.82)	3 (0.84)	1.21 (1.19)	13.21 (0.61)	4 (0.78)	0.8 (1.11)	15.92 (0.25)
2019	207.7	2 (0.92)	0.22 (1.43)	4.15 (1.3)	2 (1.09)	1.36 (1.63)	5.78 (0.81)	2 (0.72)	1.34 (0.74)	12.71 (0.64)

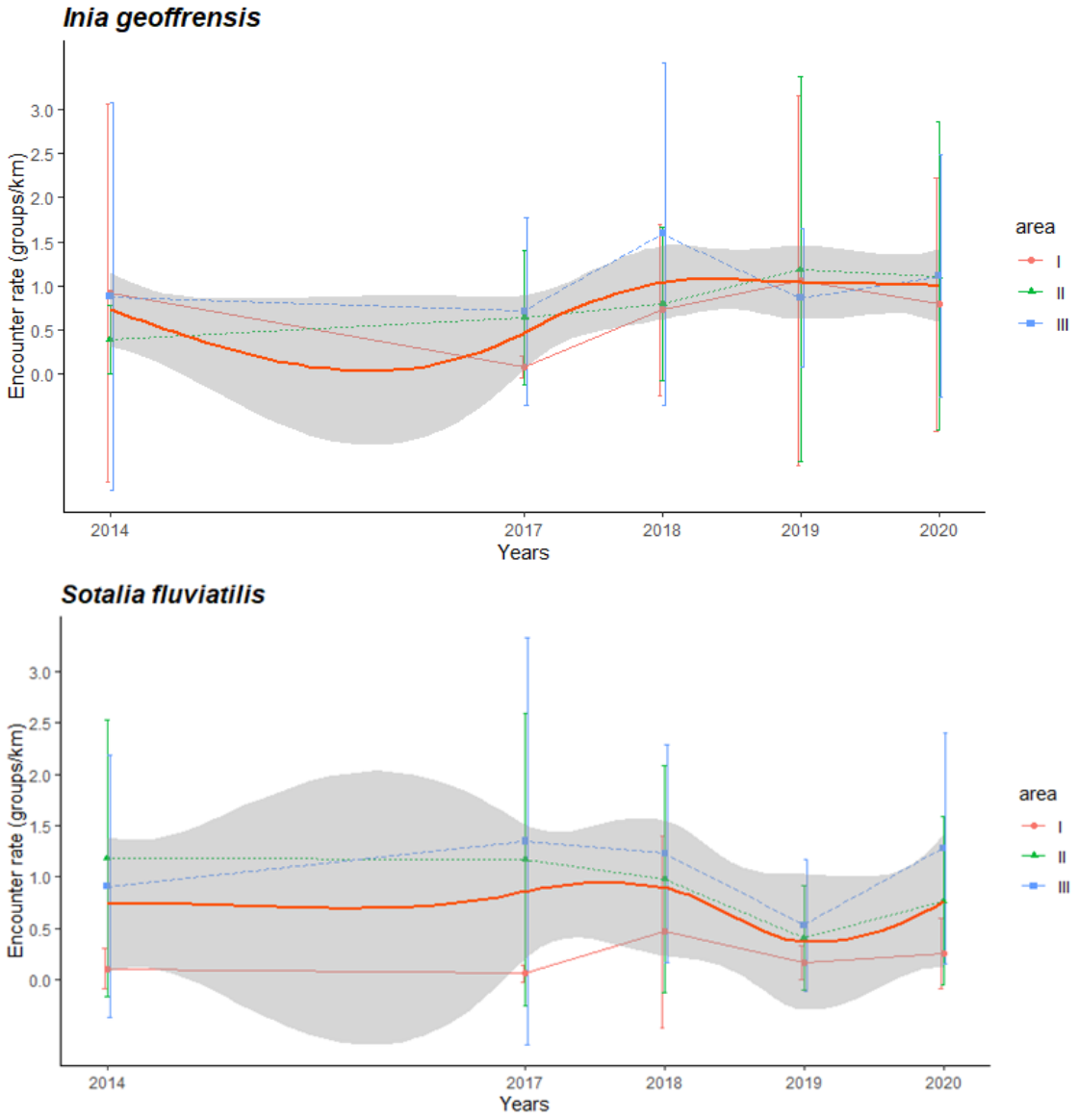

Figure 2: Time series of the encounter rate of *Inia geoffrensis* and *Sotalia fluviatilis* groups or individuals per km in three sub-areas of the Mamirauá Sustainable Development Reserve from 2014 to 2020.

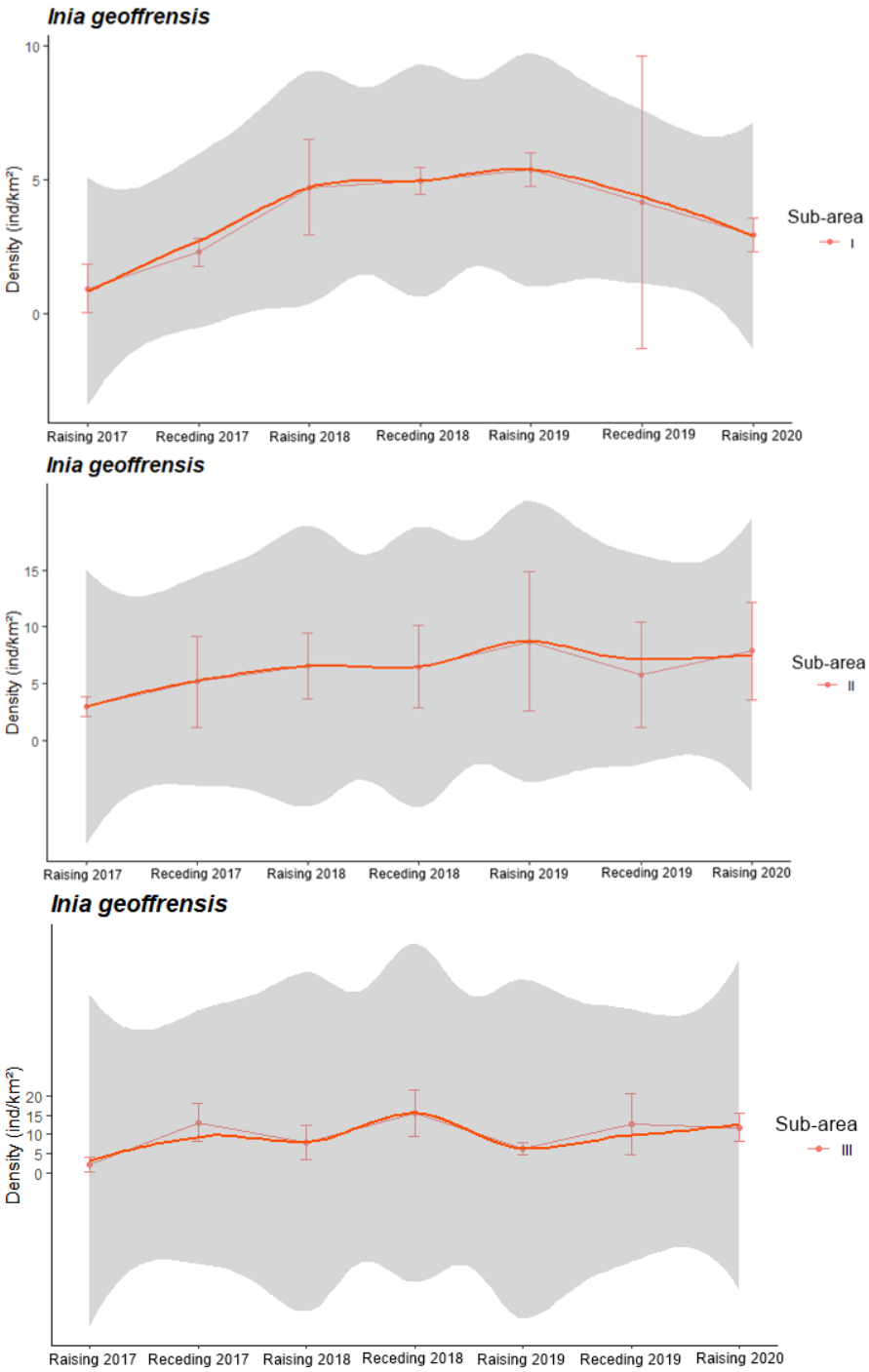

Figure 3: Time series of the density of *Inia geoffrensis* per sub-area of the Mamirauá Sustainable Development Reserve from 2017 to 2020.

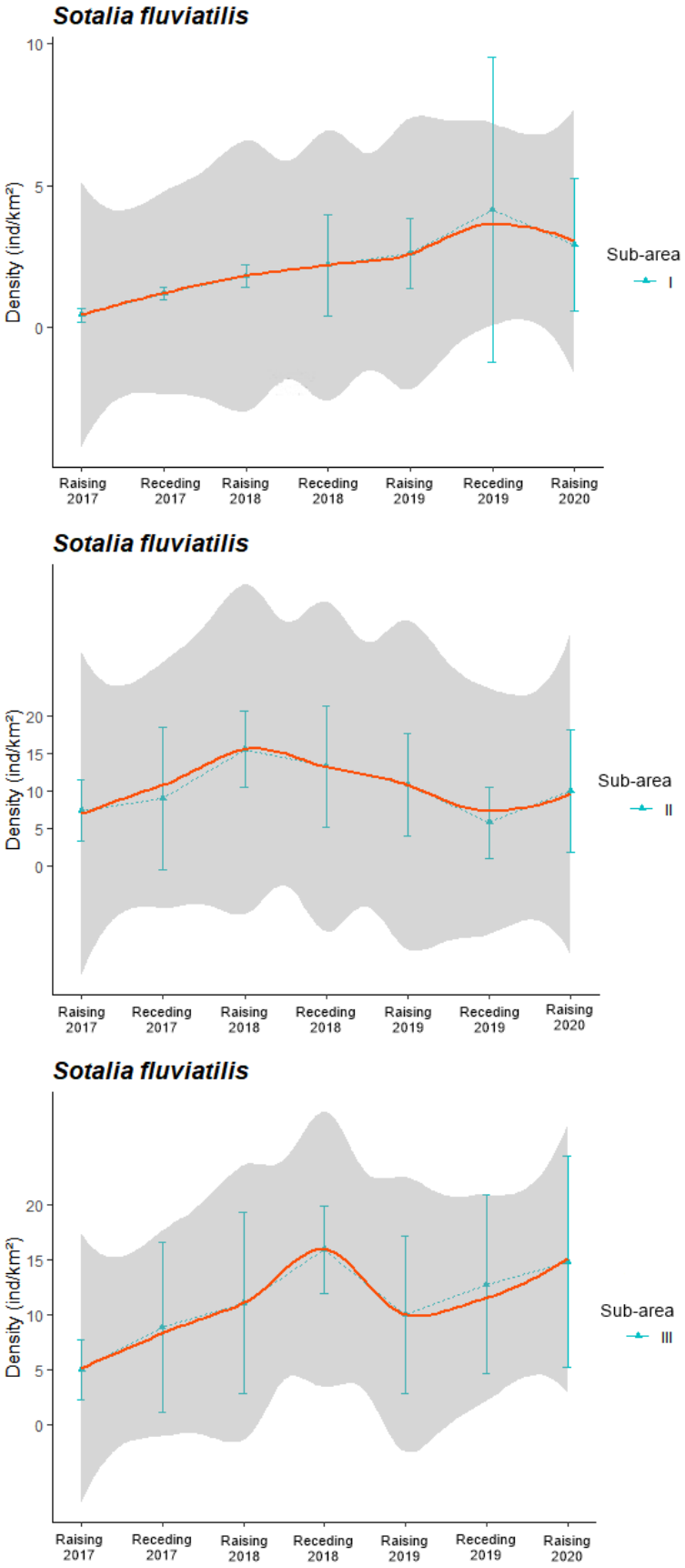

Figure 4: Time series of the density of *Sotalia fluviatilis* per sub-area of the Mamirauá Sustainable Development Reserve from 2017 to 2020.

Discussion

The systematized research since 2014 on the populations of river dolphins of the Mamirauá Reserve showed that, at first, there is stability in the populations of boto and tucuxi. According to figure 2, it is possible to see that there was a small drop in the dolphin encounter rate from 2014 to 2017. More specifically, this drop was greater in sub-area I, but soon there was an increase followed by stabilization. Since piracatinga fishing was allowed until 2015, and botos were used as bait in the studied areas, this result reflects a stabilization of the boto population after the fishing ban. As for the tucuxi, we did not observe this drop from 2014 to 2017, since it is not a species used as bait for piracatinga fishery. We can see a drop in the year 2019 for *Sotalia*, which could be a natural fluctuation, since it will grow again in 2020.

As it was not possible to obtain density data for 2014, we compared the density of species in each sub-area as of 2017, during periods of rising and receding waters. Sub-area I is located on the Solimões River and has a great fishing pressure. According to the Mamiraua Institute's Demographic and Economic Monitoring System of 2019, this region has seven communities and 482 local inhabitants. Fishing is one of the main economic activities of the communities, together with agriculture. There were records of fishing artifacts used for fishing piracatinga (box traps) until 2019, indicating that there may still be threats to dolphins in this region, in addition to the widespread use of fishing nets, which are the main cause for bycatch of aquatic mammals. According to figure 3, the boto density increased from 2017 to 2018, but started to decrease during the 2019 receding water and remained falling in the 2020 rising water period, something that should be further investigated in subsequent years.

Sub-area II, located on the Japurá River, was the region with most fishing artifacts registered, mainly fishing nets. It has eleven communities throughout the sampled region, but it was not possible to access the total population size. We obtained access to the census of five communities, totaling 243 local people. The remaining communities are even larger and are part of the Cuiú-Cuiú indigenous land. There were records of boxes used in piracatinga fishing in 2017, 2018 and 2019. Sub-area II is the most distant among the three areas from the research institution. In comparison with sub-areas I and III, sub-area II, being more remote, is less frequented by researchers from the Mamirauá Institute, and perhaps less supervised. Therefore, it is a region that deserves greater attention and field effort to investigate dolphin populations. Even with these circumstances, we found that both *Inia* and *Sotalia* have had their populations stable since 2017.

Dolphin populations in sub-area III also proved to be stable. This area was where we found the least fishing pressure, probably because it has only three communities with 204 local people in total. We also did not find a piracatinga box in the region on any expedition.

In relation to the paper submitted in 2020 (Marmontel et al., 2020), in the present work we analyzed the populations in each sampled sub-area in order to have greater reliability in the data and understand the specificities of each region. This was important to see a possible drop in the population of *Inia* in sub-area I and the stability of the populations of *Inia* and *Sotalia* in the other sub-areas of the Mamirauá Reserve. Knowing the great fishing pressure in sub-areas I and II, we can direct our efforts to such regions, mainly in the investigation of piracatinga fishing and bycatch in fishing nets. As it was possible to see in the analyzes since 2014, the boto populations had a slight increase after the moratorium in 2015 and remain stable, showing the importance of such a conservationist measure. Therefore, it is important that monitoring in these areas continues, as impacts may occur due to other human activities, such as bycatch. Moreover, further research on the fluctuation of the population of these species over time is crucial, as our current view is limited due to the relatively short time of monitoring.

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