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Surviving the Tide: Assessing Guiana dolphin persistence amidst growing threats in a protected estuary in South-eastern Brazil

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ABSTRACT

This study investigated the population viability of *Sotalia guianensis* in the Cananéia Estuarine-Lagoon Complex, considering current and potential future scenarios. Simulations, using VORTEX software v. 10.5.5.0, spanned 100 years and were iterated 1000 times. Scenarios encompassed adjustments to demographic and environmental factors, evaluating population trajectories (baseline; increase fisheries; increase tourism; and increase harbour activity scenarios). Findings revealed a potential stochastic growth rate and population stabilization in baseline and increase tourism scenarios when major threats were absent. Conversely, increase fishing and harbour activity scenarios exhibited population decline, leading to eventual extinction within 100 years. Projected growth rates for all Scenarios were 0.0298 (SD=0.0424), −0.2650 (SD=0.2825), 0.0294 (SD=0.0654), and −0.0334 (SD=0.1145) respectively, with extinction probabilities of 0.0 for baseline and increase tourism scenarios, 1.0 for increase fishing scenario with mean estimated extinction time at 14 years, and 0.4430 for increase harbour activity scenario with mean estimated extinction time at 80.1 years. Sensitivity testing identified the percentage of adult females breeding and female mortality as the parameters most significantly impacting population trends. The simulations provided important insights into the primary factors impacting the viability of *Sotalia guianensis* and lay the groundwork for future population assessments and conservation plans.

1. Introduction

Wild populations are subject to both stochastic and deterministic events that can alter demographic trends (Brook et al., 2002). The fluctuation of population sizes can cause ecological disturbances that reverberate throughout food webs, ultimately reshaping ecosystem functioning (McCauley et al., 2015). Global assessments of anthropogenic impingement on marine ecosystems suggest that coastal zones, where many marine animals spend part of their life cycles, are particularly imperilled (McCauley et al., 2015). While extinction rates in the marine realm remain relatively low, ongoing anthropogenic impacts, such as changes in oceanic water quality, coastal habitat degradation, and overexploitation of marine resources, could herald waves of local extinction (Costello & Ballantine, 2015; McCauley et al., 2015; Woodcock et al., 2017).

The Guiana dolphin, *Sotalia guianensis* (van Beneden, 1864), is typically found in coastal waters, estuaries, and protected bays across the South-Western Atlantic Ocean, ranging from Honduras to Santa Catarina, Brazil, including the Abrolhos Archipelago in Bahia and Trinidad and Tobago Islands (Simões-Lopes, 1988). Exhibiting varying degrees of site fidelity, typically remain within the same area year-round and not undertake extensive migrations (Araújo et al., 2007; Hardt et al., 2010; Monteiro-Filho et al., 2018; Santos et al., 2019).

Distinct levels of threat can be observed among *S. guianensis* populations inhabiting different geographical areas. Notably, main threats within estuarine environments encompass accidental entanglement in fishing gear, resource exploitation, vessel traffic, and tourism (Crespo et al., 2010; Flores et al., 2018; Secchi et al., 2018).

Classified as Near Threatened by The IUCN Red List of Threatened Species (IUCN, 2019) and as Vulnerable in the Red Book of Endangered Brazilian Fauna (ICMBIO, 2018; Ministério do Meio Ambiente, 2022), the Guiana dolphin faces ongoing conservation challenges. Despite efforts and extensive literature providing information on abundance, habitat use, group structure, reproduction, and growth throughout species distribution (e.g., Azevedo et al., 2017; De Almeida et al., 2023; de Moura et al., 2023; Di Beneditto & Ramos 2004; Espinoza-Rodríguez

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et al., 2019; Filla & Monteiro-Filho, 2009; Godoy et al., 2015; Havukainen et al., 2011; Oliveira & Monteiro-Filho, 2008; Oshima & Santos, 2016; Rollo, 2002; Santos et al., 2010), data on abundance, density, dispersion, survival rates, and population trends remain significant gaps in our knowledge of the species (Secchi et al., 2018).

Understanding temporal changes in populations is crucial for species conservation, both locally and globally (Cantor et al., 2012). Estimating and monitoring demographic parameters and trends are essential for assessing conservation status, ensuring long-term viability, and mitigating threats (Azevedo et al., 2017; Cantor et al., 2012; de Moura et al., 2023; Luck et al., 2022; Swift et al., 2023).

Population viability analysis (PVA) offers quantitative predictions on species abundance over time and the likelihood of persistence or extinction, integrating demographic, ecological, genetic, and environmental data into computer simulations of stochastic and deterministic models (Akçakaya, 2000; Boyce, 1992; Brook et al., 2000; Lacy, 2000). Such models enable the identification of fundamental viability requirements, assessment of relative risks, and evaluation of the most impactful management strategies (Akçakaya & Sjögren-Gulve, 2000; Lindenmayer et al., 1993; Thompson et al., 2000; White, 2000). It facilitates critical analysis of available information, identifies gaps in life-history data, and elucidates demographic patterns under various environmental changes (Akçakaya & Sjögren-Gulve, 2000; Boyce, 1992; Brook et al., 2002; Drechsler & Burgman, 2004; Fieberg & Ellner, 2001).

Endangered species across various taxa benefit from PVA, including mammals, birds, reptiles, amphibians, fishes, invertebrates, and plants (Akçakaya & Raphael, 1998; Armbruster et al., 1999; Crain et al., 2019; Desbiez et al., 2020; Famelli et al., 2012; Ferreras et al., 2001; Flockhart et al., 2015; Gerber et al., 2007; Haines et al., 2006; Heinsohn et al., 2004; Luck et al., 2022; Marmontel et al., 1997; Paula et al., 2007; Pickett et al., 2016; Swift et al., 2023; Taylor et al., 2009; Wildhaber et al., 2017).

With the goal of understanding potential population trajectories of *S. guianensis* and identifying key life history attributes that significantly influence species population dynamics, we assessed the viability of the population within the Cananéia Estuarine-Lagoon Complex, South Atlantic, under current and potential future scenarios. The area is a representative mosaic of protected and preserved wetland landscapes within the Atlantic Forest, featuring remarkable natural diversity and a myriad of endemic species (UNESCO, 2004).

2. Material and methods

2.1. Study area

The Cananéia Estuarine-Lagoon Complex, situated at 25°1′28′′S and 47°55′56′′W in São Paulo State, Brazil, encompasses the Environmental Protection Area of Cananéia-Iguape-Peruíbe and contributes to the Lagamar Mosaic of Conservation Units. It holds global designation as a World Heritage Site and UNESCO Biosphere Reserve (UNESCO, 2004). Rich in productivity, the entire expanse is fringed by mangroves, characteristic of the Atlantic Forest biome (Schaeffer-Novelli et al., 1990).

Comprising Baía de Trapandé, Mar de Cananéia, and Mar de Cubatão, the complex encircles Ilha de Cananéia, demarcating it from the mainland, Ilha Comprida and Ilha do Cardoso (Fig. 1). Mar de Cananéia and Cubatão are slender channels, ranging between 1 and 3 km wide and reaching depths of up to 20 m at certain points, with an average depth of around 6 m (Tessler & Souza, 1998). Baía de Trapandé

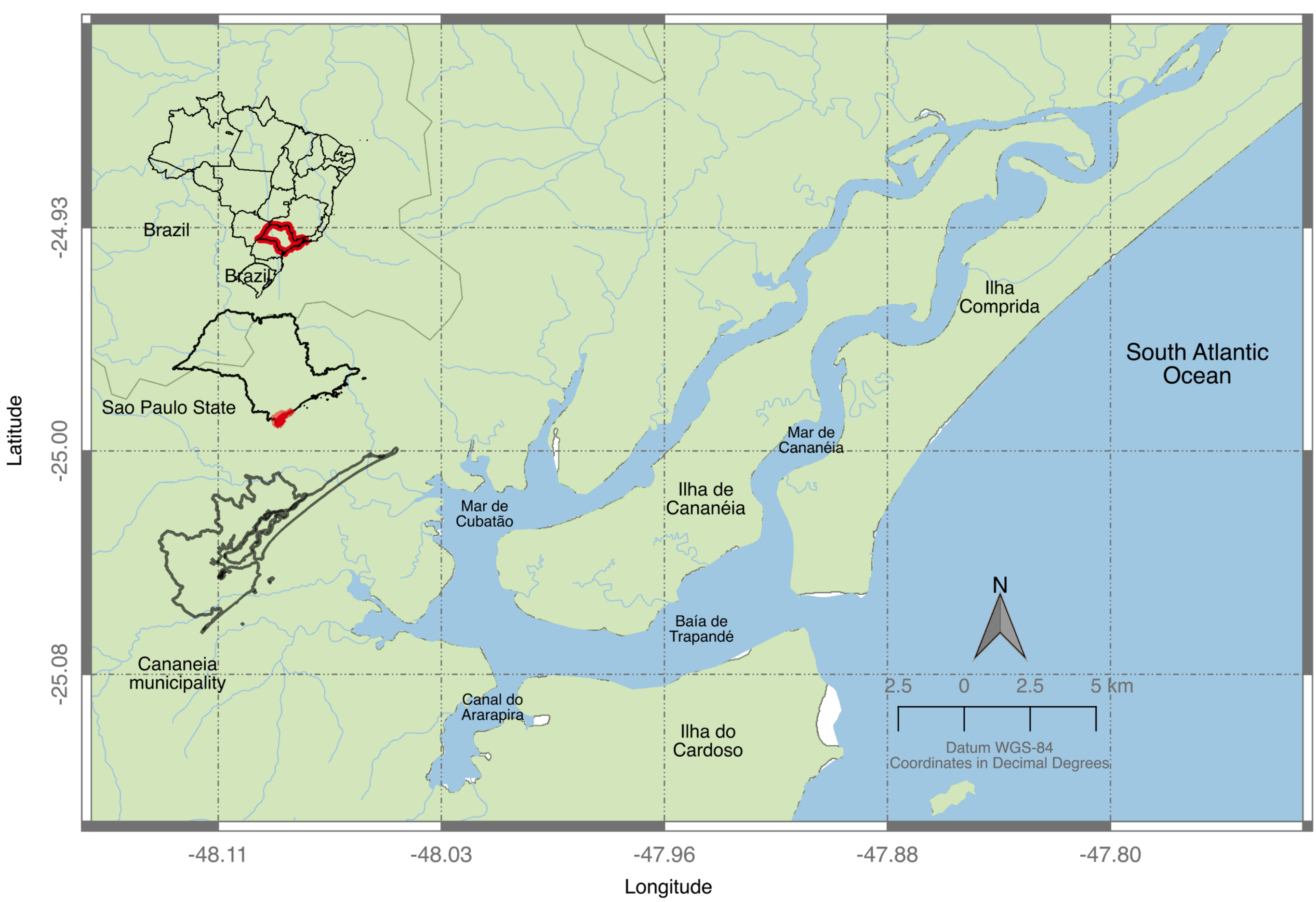

Fig. 1. Cananéia Estuarine-Lagoon Complex, São Paulo, Brazil.

exhibits greater width and depth compared to the channels, connecting the northern to the southern portion of the complex. It is subject to currents generated by tidal waves entering the complex through larger channels and by temporal variations in freshwater discharge, affecting both the channels and the bay (Kumpera, 2007; Tessler & Souza, 1998).

Salinity fluctuates with tidal cycles and freshwater influx, peaking in winter and reaching its lowest levels during summer (Kumpera, 2007). Rainfall is typically higher between December and April, while the dry season extends from May to November. The mean annual temperature stands at 21.48 °C, with sea temperatures averaging 23.88 °C (Kumpera, 2007).

2.2. Population viability analysis

The population viability analysis utilized VORTEX v. 10.5.5.0 (Lacy & Pollak, 2021), a software employing the Monte Carlo method for random sampling to estimate probabilities of future events by simulating various scenarios, thereby demonstrating risk variability (Lacy, 2000; Lacy et al., 2021). These simulations, based on demographic, ecological parameters, and environmental data, consider both deterministic and stochastic effects impacting the life cycles of sexually reproductive organisms, influencing wild population health and integrity (Boyce, 1992; Brook et al., 2000; Lacy, 2000; Lacy et al., 2021). The Vortex PVA software (Lacy & Pollak, 2021) is available under a Creative Commons Attribution-No Derivatives International License, courtesy of the Species Conservation Toolkit Initiative (https://scti.tools).

2.3. Baseline model

The baseline model depicts the current resident population of *S. guianensis* within the Cananéia Estuarine-Lagoon Complex with no significant threats. All life history parameters incorporated in the PVA were estimated based on the available literature about the species.

Initial population size was estimated at 193 individuals (95 % CI=158–237) (De Almeida et al., 2023), using the Distance Sampling method along linear transects and analysis with the Distance program (Buckland et al., 2001; Buckland et al., 2016).

Age, growth, and reproductive parameters were estimated based on studies conducted with populations from southeastern Brazil (Di Beneditto & Ramos, 2004; Rosas et al., 2010; Rosas & Monteiro-Filho, 2002). Reproduction occurs year-round with no specific birthing seasons, utilizing a mating system involving multiple partners and sperm competition. Sexual maturity is attained between 5 and 7 years of age, with gestation lasting between 11.5 and 12 months. Calves are born singly and nursed for approximately 8 months, receiving intensive parental care during the first 2 years. Signs of aging become apparent after 25 years, and based on dental studies, their lifespan is estimated to be around 30 years (Di Beneditto & Ramos, 2004; Rosas et al., 2010; Rosas & Monteiro-Filho, 2002).

Mortality rates were estimated based on a long-term population dynamics study by Cantor et al. (2012), which estimated a survival rate probability of 0.88 (±0.07 SE) for the species in the Caravelas river estuary, eastern Brazil. The state variables were designed to indicate minimal environmental degradation to date and reflect high survival rates for young individuals due to extensive parental care.

Abundance estimates for the Cananéia population in recent decades suggest small fluctuations in the number of individuals (Rollo, 2002; Havukainen et al., 2011; De Almeida et al., 2023). Considering a stable population in a protected environment, carrying capacity is unlikely to be much greater than the current population (Begon et al., 1996). To account for some population fluctuation and growth, while reflecting possible trends, the carrying capacity (K) was assumed to be around 25 % greater than current abundance estimates (Fantle-Lepczyk et al., 2018).

Given limited knowledge regarding individual dispersion, population dynamics, and gene flow, this study assumed the Cananéia estuary population was unsupplemented, with no dispersal or inbreeding depression. Extinction was defined as the persistence of only one sex (Lacy, 2000; Lacy et al., 2021). Simulations spanned 100 years and were repeated 1,000 times. Baseline scenario parameters are outlined in Table 1.

2.4. Scenarios modelling

According to the literature, the primary threats to *S. guianensis* include incidental catch in fishing nets, tourism, and vessel traffic (Crespo et al., 2010; Filla & Monteiro-Filho, 2009; Secchi et al., 2018). In this context, three scenarios were modeled, each incorporating variations in specific parameters (environmental carrying capacity, harvest, reproduction, mortality, and catastrophes) to assess population trends and the potential effects of human activities on the Cananéia estuary population. All scenarios and parameter variations were estimated according to the Vortex PVA software guidelines (Lacy et al., 2021; Lacy & Pollak, 2021).

First scenario reflects increased fishing pressure, adjusting carrying capacity and harvest parameters to replicate prey depletion and incidental capture through net entanglement or bycatch.

Second scenario represents increased tourism activities with adjustments for environmental variation in adult females breeding per year to model disturbances caused by vessel approach and noise pollution disrupting natural behaviours such as foraging and mating.

Third scenario portrays heightened harbour activities, involving adjustments in mortality, reproduction, and catastrophes to reflect higher mortality from vessel collisions, changes in reproductive patterns due to disruption, and the increased likelihood of chemical pollution and oil spills affecting survival and reproduction.

Models input parameters are presented in Table 2.

2.5. Sensitivity analysis

Sensitivity tests were performed to identify the most influential parameters on model outcomes, particularly those impacting the risk of population decline (Lacy et al., 2021; McCarthy et al., 1995). Carrying

Table 1
Vortex parameter inputs for baseline model of *Sotalia guianensis* population viability analysis in the Cananéia Estuarine-Lagoon Complex, São Paulo, Brazil.

Parameter	Values	Reference
Reproductive system	Polygynous	Rosas & Monteiro-Filho, 2002
Age of first offspring females	6 years	Di Beneditto & Ramos,
Age of first offspring males	7 years	2004Rosas et al., 2010
Max # of broods/year	1	
Max # of progeny/brood	1	
Sex ratio at birth in % males	50	
Males in breeding pool %	50	
Max age of reproduction	25 years	
Max lifespan	30 years	
Adult females breeding %SD due to EV	5010	
Offspring dependent on their	Yes	
damFor how long	2 years	
Age-specific mortality	10	Cantor et al., 2012
Age 0–2	10	
Age 2–6	10	
Age 6 + females	0	
Age 7 + males	2	
SD due to EV	33	
Age 0–2		
Age 2–6		
Age 6 + females		
Age 7 + males		
Initial population size (N)	193	De Almeida et al., 2023
Carrying capacity (K)SD in K due to EV	2500	Rollo, 2002
		Havukainen et al., 2012
		De Almeida et al., 2023

Table 2
Model assumptions and Vortex input values for *Sotalia guianensis* population viability analysis in the Cananéia Estuarine-Lagoon Complex, São Paulo, Brazil, depicting scenarios of increased fishing pressure, increased tourism, and increased harbour activity. [For reference on how to deal with input parameters, report to the Species Conservation Toolkit Initiative website (https://scti.tools/manuals/Vortex10Manual.pdf)].

Parameter	Values		
	Increase Fisheries	Increase Tourism	Increase Harbour Activity
Reproductive system	Polygynous	Polygynous	Polygynous
Age of first offspring females	6 years	6 years	6 years
Age of first offspring males	7 years	7 years	7 years
Max # of broods/year	1	1	1
Max # of progeny/brood	1	1	1
Sex ratio at birth in % males	50	50	50
Males in breeding pool %	50	50	50
Max age of reproduction	25 years	25 years	25 years
Max lifespan	30 years	30 years	30 years
Adult females breeding per year %SD due to EV	5010	5020	5020
Offspring dependent on their damFor how long	Yes 2 years	Yes 2 years	Yes 2 years
Age-specific mortality	10	0	20
Age 0–2	10	10	20
Age 2–6	10	10	20
Age 6 + females	0	10	0
Age 7 + males	2	0	2
SD due to EV	33	2	33
Age 0–2		3	
Age 2–6		3	
Age 6 + females			
Age 7 + males			
Initial population size (N)	193	193	193
Carrying capacity (K)	250	250	250
SD in K due to EV	25	0No	0No
Future change in K	Yes		
Over how many years% annual decrease in K	5 years10		
Catastrophe	No	No	Oil spill and Chemical pollution
Frequence and extent of occurrence			Local 10 %
Severity on reproduction			0.6
Severity on survival			0.75
Population harvested	Yes	No	No
First year of harvest	1		
Last year of harvest	100		
Interval between harvests	1		
Age-specific harvest	1		
Age 1–2	0		
Age 2–3	1		
Age 3–4	1		
Age 4–5	1		
Age 5–6 females	55		
Age 5–7 males			
Age 6 + females			
Age 7 + males			

capacity, proportion of breeding adult females, female mortality rate, and male mortality rate were adjusted individually, while keeping all other parameters at their baseline values. Minimum and maximum estimates were incorporated across a range of realistic values in a single-factor analysis (Table 3). Variations in parameter values alter population trajectories, and sensitivity is expressed as changes in the risk of decline or extinction (McCarthy et al., 1995).

3. Results

The population viability analysis of *S. guianensis* indicates a growth trend in both the baseline and tourism increase models. No risk of extinction was observed over a 100-year period, with mean population

Table 3
Input values for sensitivity tests of the effects of carrying capacity (K), proportion of breeding adult females, female mortality rate, and male mortality rate changes on *Sotalia guianensis* population trend in the Cananéia Estuarine-Lagoon Complex, São Paulo, Brazil.

Parameter	Sensitivity test		
	Lowest value	Highest value	Increment
Adult females breeding per year %	10	50	10
Age-specific mortality	00	2020	55
Age 2–6			
Age 6 + females			
Age 7 + males			
Carrying capacity (K)	20	300	20

sizes at year 100 of 247.04 and 241.62 individuals, respectively. However, scenarios involving an increase in fisheries and harbour activity displayed population decline and eventual extinction in less than 100 years, with mean population sizes at year 100 of 0 and 11.94 individuals, respectively. The extinction probability was 1.0 and 0.4430, with mean extinction times estimated at 14 years and 80.1 years, respectively (Fig. 2). Projected stochastic growth rates for all scenarios were 0.0298 (SD=0.0424), −0.2650 (SD=0.2825), 0.0294 (SD=0.0654), and −0.0334 (SD=0.1145) (Table 4).

Sensitivity tests revealed that the proportion of adult females breeding per year and the female mortality are the most influential parameters on population trends. Decline and extinction risks were detected in less than 100 years when the proportion of reproductive females falls below 40 % and when female mortality exceeds 15 %. Similarly, variations in carrying capacity led to decline and extinction risks when k is below 40 individuals. Male mortality showed no significant influence on population trends. See Table 5 for detailed information on sensitivity testing.

4. Discussion

The models reflect current and potential future scenarios in Cananéia Estuarine-Lagoon Complex involving increasing fishing, growing tourism, and harbour expansion, especially amid recent changes in environmental protection policies toward coastal ecosystems like sandbanks and mangroves.

The baseline model projections indicate population growth and stabilization without any risk of decline, portraying a healthy population in a well-preserved environment. Previous studies by Rollo (2002) and Havukainen et al. (2011) demonstrate a stable population trend in Cananéia. Less impacted areas, like the Cananéia estuarine complex, suggest a high long-term survival rate for the species (Cantor et al., 2012).

The model incorporating potential effects associated with increased fishing activity has projected a sharp population decline and potential extinction within less than 15 years, a timeframe shorter than the species' life cycle. In the Cananéia region, the fishing industry is the main commercial activity, comprising both an industrial fleet that operates in deeper marine waters beyond Ilha Comprida, and an artisanal fleet that predominantly operates within the estuary (Chiba et al., 2012; Desvaux, 2013).

In recent years, fishermen from both fleets have reported a decline in fish production, particularly for species targeted by industrial fishing, such as the acoupa weakfish (*Cynoscion acoupa*) and the Atlantic seabob (*Xiphopenaeus kroyeri*) (Chiba et al., 2012; Desvaux, 2013). Additionally, fishermen with over 30 years of experience have observed a gradual reduction in fish size (Chiba et al., 2012). Continuous fishing interferes with the environment's ability to restore its population stocks, potentially preventing target species from reaching adulthood and reproductive phases (Chiba et al., 2012; Desvaux, 2013).

Depletion of food resources, a key component of carrying capacity (K), disrupts population dynamics and viability by reducing individual

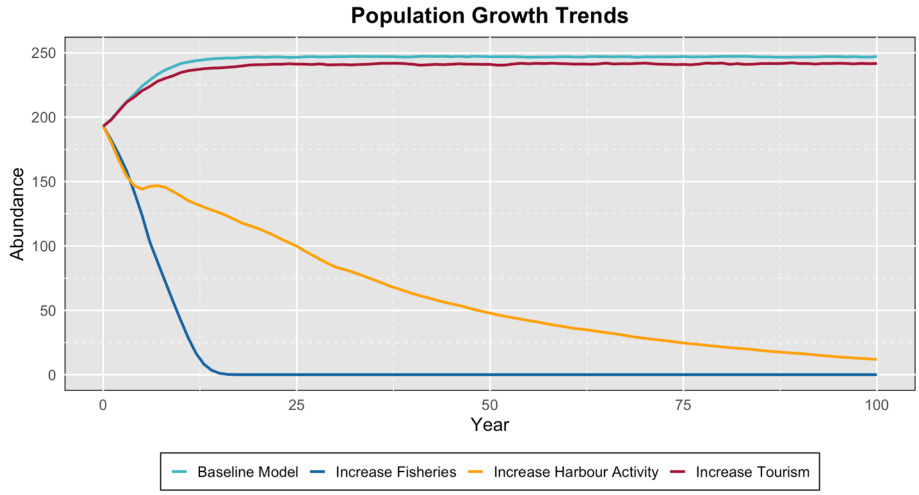

Fig. 2. Projections of population abundance for *Sotalia guianensis* in the Cananéia Estuarine-Lagoon Complex, São Paulo, Brazil, under models of stochastic and deterministic factors depicting different scenarios using Vortex 10.5.5.0.

Table 4
Population viability analysis of *Sotalia guianensis* in Cananéia Estuarine-Lagoon Complex, São Paulo, Brazil, showing a 100-year trajectory under different scenarios in Vortex 10.5.5.0.

	det-r	stoch-r	SD(r)	PE	N-all	SD(Nall)	MeanTE
Baseline Model	0.0309	0.0298	0.0424	0.0	247.04	6.64	–
Increase Fisheries	0.0309	−0.2650	0.2825	1.0	0.0	0.0	14.0
Increase Tourism	0.0309	0.0294	0.0654	0.0	241.62	13.61	–
Increase Harbour Activity	2.2827	−0.0334	0.1145	0.4430	11.94	17.00	80.1

*det-r = deterministic growth rate; stoch-r = stochastic growth rate; SD(r) = r standard deviation; PE=extinction probability; N-all = mean population size; SD(Nall) = standard deviation for mean population size; MeanTE=mean extinction time in years.

Table 5
Population viability analysis of *Sotalia guianensis* in Cananéia Estuarine-Lagoon Complex, São Paulo, Brazil, showing a 100-year trajectory under different scenarios in Vortex 10.5.5.0.

	det-r	stoch-r	SD(r)	PE	N-all	SD(N-all)	MeanTE
ST(1) k = 20	0.0309	0.0203	0.1106	0.2220	12.72	7.76	59.8
ST(2) k = 40	0.0309	0.0268	0.0730	0.0080	36.26	6.23	64.5
ST(3) k = 60	0.0309	0.0280	0.0607	0.0	57.11	4.73	–
ST(4) k = 80	0.0309	0.0288	0.0540	0.0	77.64	4.22	–
ST(5) k = 100	0.0309	0.0293	0.0505	0.0	97.63	4.65	–
ST(6) k = 120	0.0309	0.0296	0.0484	0.0	117.53	4.86	–
ST(7) k = 140	0.0309	0.0296	0.0462	0.0	137.18	5.59	–
ST(8) k = 160	0.0309	0.0299	0.0452	0.0	157.20	6.03	–
ST(9) k = 180	0.0309	0.0297	0.0443	0.0	177.22	5.74	–
ST(10) k = 200	0.0309	0.0302	0.0435	0.0	197.17	5.90	–
ST(11) k = 220	0.0309	0.0299	0.0428	0.0	217.00	6.44	–
ST(12) k = 240	0.0309	0.0300	0.0427	0.0	237.36	6.07	–
ST(13) k = 260	0.0309	0.0299	0.0423	0.0	256.64	7.32	–
ST(14) k = 280	0.0309	0.0298	0.0419	0.0	276.80	6.41	–
ST(15) k = 300	0.0309	0.0301	0.0418	0.0	296.20	7.94	–
ST(16) 10 % of adult females breeding	−0.0916	−0.0929	0.1207	1.0	0.0	0.03	45.3
ST(17) 20 % of adult females breeding	−0.0429	−0.0479	0.1076	0.7610	1.84	3.37	76.7
ST(18) 30 % of adult females breeding	−0.0117	−0.0138	0.0607	0.0100	61.17	38.65	93.5
ST(19) 40 % of adult females breeding	0.0118	0.0106	0.0457	0.0	232.41	21.72	–
ST(20) 50 % of adult females breeding	0.0309	0.0300	0.0424	0.0	247.06	6.54	–
ST(21) 0 % of female mortality	0.1182	0.1177	0.0349	0.0	250.11	2.70	–
ST(22) 5 % of female mortality	0.0756	0.0746	0.0429	0.0	249.69	2.90	–
ST(23) 10 % of female mortality	0.0309	0.0300	0.0424	0.0	246.81	6.74	–
ST(24) 15 % of female mortality	−0.0162	−0.0186	0.0607	0.0580	39.43	26.29	87.3
ST(25) 20 % of female mortality	−0.0648	−0.0648	0.1035	0.9850	0.20	1.26	55.1
ST(26) 0 % of male mortality	0.0309	0.1124	0.0276	0.0	250.29	2.95	–
ST(27) 5 % of male mortality	0.0309	0.0307	0.0395	0.0	247.36	6.25	–
ST(28) 10 % of male mortality	0.0309	0.0300	0.0424	0.0	246.78	6.53	–
ST(29) 15 % of male mortality	0.0309	0.0301	0.0445	0.0	247.04	6.28	–
ST(30) 20 % of male mortality	0.0309	0.0301	0.0461	0.0	246.31	6.91	–

fitness. As prey diminishes, dolphins spend more time foraging, leading to greater energy expenditure. Consequently, reduced food availability decreases energy acquisition, impacting growth and reproduction. This can ultimately lead to population loss, with coastal species and small populations being particularly vulnerable (DeMaster et al., 2001).

Although artisanal fishing represents a small fraction of global production, it poses a significant threat to cetacean and coastal species owing to underreporting, lack of monitoring, and management (Chiba et al., 2012; Desvaux, 2013). Incidental captures of Guiana dolphins in gill nets are a frequent cause of mortality for the species across their range (Brownell et al., 2019; Crespo et al., 2010; Hallwass et al., 2024; Moore et al., 2021). In the Cananéia region, bycatch is reported by both artisanal and industrial fishermen, predominantly in marine-estuarine transition zones like the Mar de Cananéia and Baía de Trapandé (Desvaux, 2013). Theses areas are primary habitats for the species due to their diverse resources and hydrological complexity (De Almeida et al., 2023; Havukainen et al., 2011). Although bycatch occurs with the industrial fleet, most are attributed to artisanal fishing with gill nets the species' coastal and estuarine distribution overlapping with the artisanal operations (Desvaux, 2013).

The mortality of marine mammals in small-scale fisheries, especially coastal gillnet fisheries, is a significant threat leading to population decline (Lewison et al., 2004; Luck et al., 2022). This issue is exemplified by species like the vaquita, *Phocoena sinus*, the world's most endangered cetacean, and the Baiji, *Lipotes vexillifer,* declared extinct in previous decades (D'Agrosa et al., 2000, Turvey et al., 2007). This underscores the importance of maintaining environmental quality and highlights the impact of removing reproductive individuals from small populations.

The model assessing increased tourism impacts on cetacean populations indicated growth and stabilization without a risk of decline. Studies in Cananéia revealed that Guiana dolphins exhibit varying reactions based on vessel approach, speed, and duration of interaction, emphasizing the importance of dolphin-watching guidelines to elicit neutral or positive responses (Filla & Monteiro-Filho, 2009; Rollo et al., 2008).

Motorized vessel traffic is a primary disturbance for cetaceans, disrupting natural behaviours, altering their acoustic environment, and increasing oceanic noise levels, thereby influencing reproductive rate (Filla & Monteiro-Filho, 2009; Kassamali-Fox et al., 2020; Marega-Imamura et al., 2018; Rollo et al. 2008). Resident coastal species are particularly vulnerable due to cumulative effects from repeated vessel interactions (Kassamali-Fox et al., 2020; Marega-Imamura et al., 2018).

For *S. guianensis*, responses to noise pollution include altered behaviour, decreased frequency of breaths, increased breathing synchrony, changes in vocalization patterns (including duration, range, and frequency), displacement, area abandonment, and population decline (Azevedo et al., 2017; Edwards & Schnell, 2001; Filla & Monteiro-Filho, 2009; Gamboa-Poveda & May-Collado, 2006; Martins et al., 2016; Rollo et al., 2008; Rollo et al., 2016). In Guanabara Bay, Rio de Janeiro, a 37 % decline over 16 years was recorded likely on account of anthropogenic actions leading to habitat degradation, intense vessel traffic, bycatch, and pollutant-related immunosuppression, resulting in low survival and recruitment rates (Azevedo et al., 2017). The species abandonment of areas within their distribution range has been observed in response to increased human activities, particularly boat traffic (Edwards & Schnell, 2001; Filla et al., 2008). In Costa Rica, changes in whistle production have been documented (Gamboa-Poveda & May-Collado, 2006), with similar alterations observed in calls, whistles, clicks, and breathing patterns in other cetacean species (Chalcobsky et al., 2020; Erbe et al., 2019; Kassamali-Fox et al., 2020; Marega-Imamura et al., 2018).

While this scenario suggests that such activities pose a low risk to the population, it is important not to overlook the influence of reproductive rates and environmental variability on population dynamics. In Vortex population viability analyses, environmental variation (EV) accounts for annual fluctuations in reproduction and survival due to changes in environmental conditions (Desbiez et al., 2020). While environmental variation plays a crucial role in driving temporal fluctuations in large populations—encompassing changes in temperature, climate, prey abundance, predator dynamics, and disease prevalence—demographic stochasticity becomes paramount for smaller populations. Random fluctuations in demographic patterns such as survival, sex ratio, and reproduction have a disproportionately significant impact on smaller populations (Akçakaya, 2000; Araújo et al., 2014; Lindenmayer et al., 1993b; Miller, 2016).

The model for increased harbour activities, including higher mortality rates as a result of vessel collisions with dolphins, changes in reproductive patterns stemming from alterations in natural behaviours, and increased probability of occurrence of disasters such as chemical pollution and oil spills, revealed significant impacts leading to population decline and extinction within less than 100 years.

Vessel collisions have emerged as a concern by the International Whaling Commission Conservation Committee (IWC-CC) in recent years. They can result in injuries ranging from sublethal to lethal, leading to reduced welfare for affected animals due to stress, pain, and impaired locomotion. Such injuries, including the loss of flukes and flippers, disrupt foraging, displacement, and social interactions, ultimately diminishing fitness and increasing the risk of death over time (Schoeman et al., 2020). Previous studies have documented similar injuries on cetacean carcasses in the study area (Desvaux, 2013).

Catastrophic events, defined as unpredictable occurrences beyond normal environmental variations, pose additional threats to species' survival and reproduction. A single catastrophic incident can cause a significant decline in survival and reproduction rates (Desbiez et al., 2020). Species with nearshore habitats or restricted ranges, such as Guiana dolphins, bottlenose dolphins, and river dolphins like the Amazon River dolphin (*Inia sp.*), Ganges River dolphin (*Platanista gangetica*), and Irrawaddy River dolphin (*Orcaella brevirostris*), are particularly vulnerable to oil spills and chemical pollution in view of their site fidelity and specific habitat requirements (Helm et al., 2015). Cetaceans along the São Paulo state coast rank as some of the most contaminated marine mammals in South America (Yogui et al., 2010), with *S. guianensis* showing record-high lead concentrations in the estuary (Salgado et al., 2018). These findings are concerning, especially considering the potential development of nautical and marine facilities along the southern coast of São Paulo state, which could significantly alter the ecological and biological dynamics of the Cananéia estuary region (Filla et al., 2008).

Anthropogenic and environmental changes can directly impact demography and population trends. Threats such as habitat loss, deteriorating conditions, and individual removal synergistically influence population dynamics, exacerbating mortality rates, particularly in smaller populations (Araújo et al., 2014; Cheney et al., 2019). Models combining synergistic effects, such as increasing fisheries and harbour activities scenarios, predict rapid population declines and the potential for extinction within a short timeframe.

Sensitivity analyses revealed that the proportion of adult females breeding annually and female mortality had the most significant influence on population trends, driving populations toward extinction. Increased male mortality had less impact, aligning with expectations for species with polygenic mating systems, where females dictate reproductive success and population growth (Desbiez et al., 2020). Changes in carrying capacity, representing declines in environmental quality, also played a pivotal role.

These findings highlight the necessity of prioritizing research and conservation efforts targeting these parameters. The removal of individuals, especially females, from small populations can severely disrupt dynamics and reproductive capacity (Araújo et al., 2014; Blázquez et al., 2020; Smith et al., 2016; Vermeulen & Bräger, 2015). For long-lived species, fluctuations in female survival and reproductive rates profoundly influence population dynamics, potentially elevating mortality rates, imperilling offspring survival, diminishing growth rates, and compromising population fitness and resilience against threats

(Cheney et al., 2019; Desbiez et al., 2020).

Noteworthy, small and isolated populations are particularly vulnerable to extinction vortexes, characterized by a combination of demographic, environmental, and genetic stochasticity leading to a loss of evolutionary potential (Brook et al., 2002; Dulvy et al., 2003; Frankham et al., 2008). Thus, information on dispersal of individuals among populations and gene flow are crucial for gaining insights into population fitness and resilience. As population-specific life history, demographic, and genetic data become available, parameter estimation can be refined, leading to more accurate models (de Moura et al., 2023; Fantle-Lepczyk et al., 2018).

Concerning conservation actions for *S. guianensis* in the Cananéia estuary, an amalgamation of strategies including protected areas, habitat management, demographic parameter monitoring, and reinforcement of regulations governing fishing and tourism activities appears to be both suitable and effective.

Protected areas, designed to safeguard biodiversity and ensure environmental integrity, typically concentrate on locations pivotal for behaviours vital to the fitness and survival of wild species, encompassing breeding, offspring care, resting, and feeding (McCauley et al., 2015; Smith et al., 2016). Longitudinal studies have underscored that the establishment of protected areas and habitat enhancement fosters cetacean population growth (Bossley et al., 2017; Costello, 2024; Cheney et al., 2019).

Enforcing regulations such as speed limits for vessels, protocols for approaching tourist boats, maintaining adequate distances, limiting durations of stay, and overseeing harbour activities can reduce collision incidents, minimize disruptions to natural behaviours, and ensure a healthy population and sustainable boat-based enterprises (Costello, 2024; Kassamali-Fox et al., 2020; Manlik et al., 2016).

This study adopts a conservative stance, guided by the precautionary principle, outlining potential effects of various threats to the Guiana dolphin in Cananéia estuary and projecting plausible near future scenarios. Even minor alterations in environmental conditions, carrying capacity, mortality rates, and catastrophic events can significantly influence their long-term persistence. Nevertheless, these findings should not be construed as pessimistic; rather, they serve as indicators of the primary factors impacting the viability of the *Sotalia guianensis* population, aiding local managers and stakeholders in comprehending the ramifications of anthropogenic factors and formulating effective conservation measures. Furthermore, the models developed in this study lay the groundwork for future population assessments of the species across its range, accommodating the integration of new data and information to construct more intricate models and explore diverse approaches.

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CRediT authorship contribution statement

Inaê Guion de Almeida: Writing – review & editing, Writing – original draft, Visualization, Validation, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Alexandre Reis Percequillo:** Writing – review & editing, Supervision, Resources. **Mario Manoel Rollo:** Writing – review & editing, Visualization, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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