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How much is too much? A carrying capacity study of white shark cage diving in Guadalupe Island, Mexico

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A B S T R A C T

The Guadalupe Island Biosphere Reserve is one of the main aggregation sites for the white shark *Carcharodon carcharias* and is considered to be the best place in the world for white shark cage diving. From 2014 to 2019, the number of cage diving vessels in Guadalupe Island grew from 6 to 10, with an estimated 2800 tourists participating in white shark cage diving during the 2019 season. In 2016, the National Commission of Protected Natural Areas of Mexico requested a carrying capacity in which current regulations, white shark behavior, and the management capacity of the reserve were considered. To characterize the movement patterns of the white shark, 12 individuals were acoustically tracked. Based on the critical habitat of the white shark determined by an analysis of kernel densities, three carrying capacity scenarios (i.e., critical, optimal , and expanded) were calculated in which 1, 6, or 11 vessels, respectively, could operate simultaneously. It is important to consider that as the number of simultaneously operating cage diving vessels increases, the probability of sighting a white shark decreases [$>$ 0.9 (critical scenario), $>$ 0.5 (optimal scenario), and $>$ 0.1 expanded scenario]. The results of this study may act as a baseline for the management of other white shark tourism and aggregation sites in the world. However, future studies should also include other variables, such as the energy budget, due to the use of attractants in cage diving that may potentially affect individual behavior.

1. Introduction

Ecotourism and wildlife tourism are ecosystem services that allow human beings to come into close contact with the natural world [1]. In addition, these forms of nature-based tourism constitute important policy instruments that are used to help conserve biodiversity [2]. Wildlife tourism activities can often take place in remote, pristine, and ecologically important regions that have been established as protected areas to conserve biodiversity [3,4]. As such, the appropriate management of these activities will help to ensure the long-term conservation of the species that attract tourists as well as their ecosystems [4,5]. However, wildlife tourism activities are often lucrative and can modify the

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behaviors of target species to such an extent that their ecological and biological characteristics are negatively affected (e.g., diminished reproductive success) [6]. Moreover, wildlife tourism activities have been blamed for habitat degradation and ecosystem disturbances that have reduced the fitness of the species present [4,7]. For these reasons, it is necessary to implement precautionary and protective guidelines for wildlife tourism activities [8–10].

Worldwide, many wildlife tourism activities revolve around specific shark species (hereinafter referred to as shark tourism) [6,11]. The majority of shark tourism occurs in Oceania (22%) and North America and the Caribbean (16%), with a particular focus on reef sharks (33%), whale sharks (30%), hammerhead and requiem sharks (22%), and white sharks (13%) [12]. The use of attractants or bait is not necessary for all shark tourism activities, particularly those that are conducted in pristine sites in which sharks are highly abundant residents [13]. However, to ensure that tourists are satisfied with their wildlife experience, tourism operators often use attractants and/or provisioning techniques to keep sharks within the designated observation area. In these cases, different methods of supplying either bait or attractants may be employed, which mainly entail chumming, baiting, or feeding. Chumming consists of releasing fish fluids and tissues into the water to attract sharks over large areas, whereas baiting consists of using real or artificial bait to attract sharks passively or actively either visually or by smell [10,14,15].

In Mexico, there are many opportunities for diving with different shark species, and some of these activities do not require provisioning the animals with either bait or attractants. Examples of shark tourism that do not require provisioning include swimming with whale sharks (*Rhincodon typus*) and diving with bull sharks (*Carcharhinus leucas*) in the Cabo Pulmo National Park (in the Gulf of California) and diving with various shark species in the Revillagigedo Archipelago National Park (in the central Mexican Pacific) [5]. Shark tourism activities that employ provisioning techniques are carried out in Los Cabos and Bahía Magdalena (both in Baja California Sur) with pelagic species, such as the blue shark (*Prionace glauca*), short-fin mako (*Isurus oxyrinchus*), scalloped hammerhead (*Sphyrna lewini*), smooth hammerhead (*Sphyrna zygaena*), and silky shark (*Carcharhinus falciformis*). In Guadalupe Island, located off the western coast of Baja California, tourists can cage dive with white sharks (*Carcharodon carcharias*) [5]. The white shark is currently listed as vulnerable to extinction by the International Union for Conservation of Nature (IUCN) and is listed in Appendix II of the Convention on International Trade in Endangered Species (CITES).

Despite the popularity of cage diving, this activity has been associated with negative effects on target shark species. These negative effects are varied and include the transmission of diseases due to contaminated bait and natural predation being reduced as sharks become conditioned to artificial feeding [6,17]. Furthermore, the potential for negative interactions and accidents between tourists, cages, and the sharks themselves has been known to increase due to cage diving, and incidents have been observed in Guadalupe Island on several occasions [16,17]. For both reef sharks and the white shark, previous studies have also found negative effects on metabolic activity as a consequence of the elevated consumption of food items used as attractants [18,19]. Moreover, an increase in white shark residence times (from 11 to 98 days) and short-term changes in behavior have been registered within areas in Australia and Guadalupe Island [14, 20, this paper]. However, these effects have not been found to influence natural shark behavior in either the mid- or long-term, and attractants appear to function solely as distractors within the specific tourism area and do not appear to modify natural life cycle activities or result in behavioral conditioning to shark tourism [14,17,21,22].

White shark cage diving has been recreationally conducted in Australia since the 1970s [17,20]. Currently, this activity is carried out in the Farallon Islands (US), Guadalupe Island, South Africa, the Neptune Islands (Australia), and Stewart Island (New Zealand) [18]. Among these locations, the use of attractants is only prohibited in the Farallon Islands [23]. In Guadalupe Island, white shark cage diving involves the use of yellowfin tuna (*Thunnus albacares*) to maintain the white sharks in front of the observation cages [16]. Due to the visibility of the water (~ 30 m) and the size and abundance of the white sharks present, Guadalupe Island is now recognized as the best place in the world for white shark cage diving [5]. Due to the characteristics of the site, the number of white shark cage diving vessels operating in Guadalupe Island increased (i.e., from 6 to 10 vessels) from 2014 to 2019, reflecting a substantial increase in the number of tourists that visited the island [24]. In fact, more than 2800 tourists visited Guadalupe Island during the 2019 season [24,25].

Cage diving can be a great tool to remove the stigma and bad reputation that the white shark has been given. Moreover, this activity can be used to generate a new conservation ethic for this species while functioning as a scientific platform. Cage diving can also be used to assign an economic value to living sharks that is much higher than that of sharks that are caught for consumption or as trophies [5,19]. From an anthropogenic standpoint, shark tourism has proven to play a crucial role in conservation efforts, aiding in the development of local communities that value the exponential increase in profits that they obtain from the utilization of live sharks in a virtuous cycle called the blue economy [5,14,26].

Each year from July to December, white shark cage diving at Guadalupe Island constitutes one of the most economically important non-extractive activities [16,17,25]. In 2019, white shark cage diving in Guadalupe Island grossed US$ 8,000,000 with only 113 photo-identified white sharks, which breaks down to ~ US$ 70,795 per white shark [5, 24]. To put this in perspective, fishing studies that have been carried out along the west coast of the Baja California peninsula [27,28] have estimated that a white shark with a total length (TL) of 4 m (350 kg eviscerated weight with a set of dry fins) is only worth US$ 470. Nevertheless, the white shark is a protected species in Mexico and no retention of its products is permitted [29].

In Mexico, public policies of environmental matters are outlined in the *Ley General de Equilibrio Ecológico y Protección al Medio Ambiente* (LEGEPA; General Law of Ecological Equilibrium and Environmental Protection), which establishes that ecosystems must only be used in an optimal and sustained manner [30]. Moreover, the *Programa de Acción para la Conservación del Tiburón Blanco* (Action Program for White Shark Conservation) outlines a comprehensive strategy for white shark protection and conservation that is based on strengthening management measures that ensure sustainable, non-extractive uses that serve to prevent and mitigate the potential threats to this species and its habitat [31]. As such, the activities involving white sharks in Guadalupe Island must be sustainable while being founded on the premise that they will not alter or disturb the natural behaviors or habitat use of these sharks or those of the other species that make up the marine ecosystem of the protected area.

The term carrying capacity has been widely used in a variety of disciplines [32] and is frequently applied to populations and is defined as the number of individuals per unit area [33]. The carrying capacity of a marine environment is established based on the maximum number of tourists that the site can support [34–37]. In the LEGEPA, carrying capacity is defined as the estimation of the tolerance of an ecosystem to the use of its components, such that it does not exceed its short-term capacity for recovery without the implementation of restoration or recovery measures to establish ecological equilibrium [30].

In 2007, the carrying capacity for white shark cage diving at Guadalupe Island was determined based on the minimum permitted distance between vessels (i.e., 450 m) and the bathymetry of the area, and a carrying capacity of 10 simultaneously operating vessels was established [29]. In 2010, this carrying capacity was reviewed in an internal study that was not published but that employed the same parameters as those used in 2007. As a result of that study, the carrying capacity was reduced to 7 simultaneously operating large vessels. After a carrying capacity is determined, tourism activities may be regulated and possible negative impacts may be mitigated or limited [34,38]. However, it is crucial to also consider the current protection or conservation status of a site (a biosphere reserve in the case of Guadalupe Island), the management entities, and the tourism industry [7–9]. In addition, Cifuentes-Árias et al. [39] suggest that the biological factors of the species and the management capacity of a protected area should also be considered when estimating the effective carrying capacity of a site.

Given that white shark cage diving in Mexico only takes place at Guadalupe Island, this site is crucial for the management and conservation of this species [5,25]. In 2015, CONANP summoned expert white shark researchers to evaluate and update the carrying capacity for white shark tourism in this site, taking into consideration the criteria of Cifuentes-Árias et al. [39], the capacity of the authorities to manage the protected area, and white shark behavior, which is how this study was first conceived.

This study analyzes and integrates all of the available scientific information to date, including information generated by the authors themselves, to estimate a carrying capacity that adequately reflects current white shark regulations in Mexico [40], the behavior of the cage diving fleet, the movements and aggregations of white sharks and their aggregation zones, and the management capacity of the Guadalupe Island Biosphere Reserve. This study presents the first carrying capacity analysis for Guadalupe Island that takes into consideration white shark behavior and the authorized cage diving area management. The results of this study may serve as a basis for future management actions aimed at regulating white shark cage diving in Guadalupe Island and in white shark aggregation areas in other parts of the world.

2. Materials and methods

2.1. Study area

Guadalupe Island is located 240 km off the western coast of the Baja California peninsula (28° 52′ N, 118° 13′ W) and measures 35 km along its north-south axis while its width varies between 6 and 12 km (Fig. 1) [41]. The island is influenced by the California Current, one of the most productive ocean currents in the world, which is characterized by its cold and nutrient-rich waters that interact with local winds to foster high biological productivity [41,42].

The northeastern region of Guadalupe Island, also known as Rada Norte, is made up of a vestigial caldera composed of igneous rock with an approximate diameter of 10 km [43]. Insular topography protects this region from northwesterly winds, which predominate [44], while its

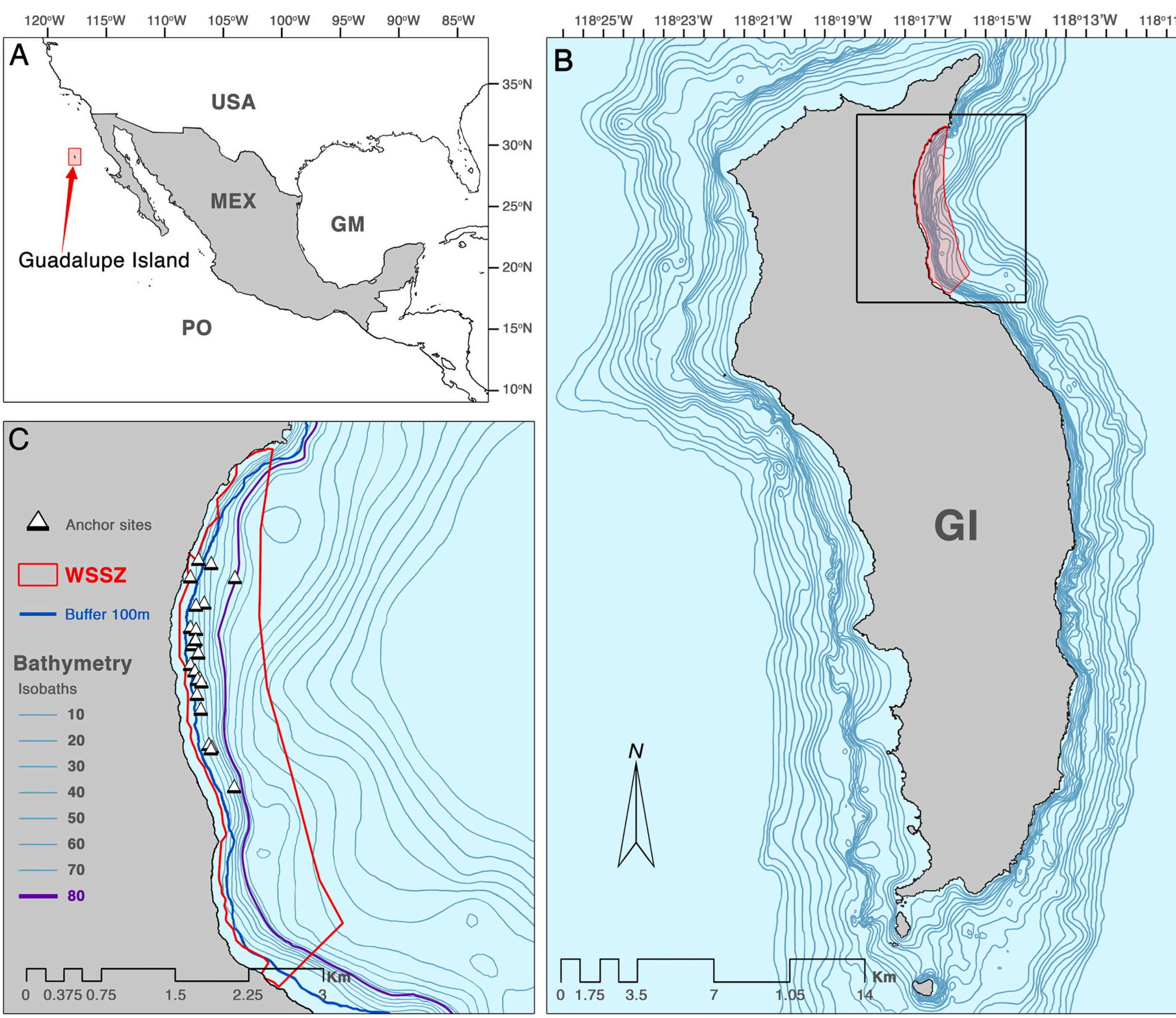

Fig. 1. The study area. A) The location of Guadalupe Island is shown in the red box. B) The designated cage diving area (red shaded region) and Guadalupe Island bathymetry. C) The black rectangular inset from panel B indicates the main aggregation area. The red polygon indicates the white shark sub-zone (WSSZ). The blue line shows the buffer zone or the maximum distance (100 m) at which the vessels can approach the coast. The purple line shows the 80-m isobath. The triangles indicate the anchor points recorded from 2014 to 2017. Abbreviations: GM, Gulf of Mexico; GI, Guadalupe Island; PO, Pacific Ocean; WSSZ, white shark sub-zone. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

abrupt bathymetry (0–200 m depth) prevents the resuspension of particulate organic matter [42]. Given that the northeastern region functions as a naturally formed roadstead, it has been designated as the area for white shark cage diving, which is carried out by surface-supplied diving using hookah [25].

2.2. Characterization of the white shark sub-zone

The white shark sub-zone polygon of Guadalupe Island was created using the coordinates referenced in the government management program of the Guadalupe Island Biosphere Reserve. Subsequently, a 100-m wide buffer zone was delimited that runs parallel to the coastline. This buffer zone serves to limit the approach of tourist boats to minimize disturbance to the resting pinnipeds that are found along the shore [45]. Within this zone, rules that have been agreed upon in the cage diving good practices must be followed, such as maintaining a minimum distance of 0.45 km between two vessels [46], which was fundamentally important for conducting this carrying capacity analysis. A total of 72 tourism vessel anchor points were recorded during the 2015–2017 seasons of the white shark biological observer program [24] and plotted to characterize anchoring dynamics within the white shark sub-zone.

2.3. Characterization of white shark movements

To characterize the area used by white sharks within the white shark sub-zone, a total of 21 white sharks were tracked by means of active acoustic telemetry using a small Robalo R220 boat (Georgia, United States) with an outboard motor equipped with a portable VR100 ultrasonic receiver (Vemco Ltd., Halifax, Canada) and a VH110 directional hydrophone (Vemco Ltd.). The sharks were fitted with V16TP-6x acoustic transmitters (Vemco Ltd.) attached with monofilament tethers and a plastic application dart. Tags were affixed to the sharks using a custom applicator and positioned on the dorsal musculature near the base of the dorsal fin. These transmitters were equipped with depth (0–680 m) and temperature (0–40 °C) sensors. Given that sub-adult (3–3.6 m TL for males, 3–4.8 m for females; Bruce and Bradford [47]) and adult white sharks interact with tourist boats more than sharks of other age classes [48], only individuals larger than 3 m TL were tagged. Ethics and tagging procedures followed an animal care protocol (Protocol number 16022, UC Davis Institutional Animal Care and Use Committee) and authorized by the research permits provided by the General Directorate of Wildlife (SEMARNAT; permit numbers SGPA/DGVS/6949/19, 07143/19, and 7913/19).

To detect and remove anomalies in white shark movements, spikes in the data were removed by low-pass filtering in MATLAB v. R2010a (Mathworks Inc., Natick, USA) using the community contributed script *despiking*. Temperature values lower than 0 °C and higher than 40 °C were eliminated from the acoustic data as well as all depths outside the range of 0–680 m. In addition, data with temperature values that did not correspond to acceptable values for a given depth based on the trend for the data series were eliminated. Finally, values that indicated speeds greater than 2.5 m/s (i.e., the average cruising speed of a white shark) were eliminated according to the variations in depth over time [49].

Geographic position data were plotted with ARC v.10.1 (ESRI Co., Redlands, USA) using the chronological representation of the coordinates and trajectories of the white shark movements recorded during each track. A kernel analysis was used to map the observation densities to determine the geographic areas in which the white sharks spent the most time. The kernel calculation was based on the distances between observations using the nearest neighbor method, and a 450-m bandwidth was used to estimate the probability density of encounters, which considered the established distance between boats. The kernel density results were associated with area measurements considering likelihood estimators and weight functions that were derived with a high degree of statistical reliability and reproducibility [50], and the frequency histograms were adjusted to reflect the probability of encounters per unit area [low (< 0.01) to high (1); 450 m]. Subsequently, a digital delineation was used to obtain the contour lines corresponding to each encounter probability contour interval and to evaluate overlapping areas. The contour lines were used to estimate the area that was most frequently used by tagged white sharks in three different scenarios: 1) when all data were pooled, 2) when only day or night data was included, and 3) when only the anchor points that were favored by cage diving operators were included. The area was calculated using two-dimensional cartesian mathematics with a precision of 1 m.

Finally, the accumulated interaction times between tourism boats and individual white sharks were determined for the 2015 and 2016 seasons. The interaction time was defined as the time during which an individual shark remained within a defined circular area (30-m radius) surrounding a given vessel. The times at which the individual shark entered this area (T1) and later left the area (T2) were used to determine the interaction time.

2.4. Monitoring and surveillance capabilities

To compare the management capacity of the Guadalupe Island Biosphere Reserve with those of other protected areas, the methodology proposed by Cifuentes-Árias et al. [39] was used, which indicates that this management capacity will depend to a great extent on the components of the protected area, such as its personnel, equipment, and infrastructure. In this sense, a comparative analysis of said components was conducted among the principal protected areas of the Baja California peninsula and northern Pacific region, namely the El Vizcaíno Biosphere Reserve; the Pacific Islands Biosphere Reserve; the Protected Area for Flora and Fauna Valle de los Cirios; the Cabo Pulmo National Park; the San Pedro Mártir National Park; the Revillagigedo National Park; and the Bahía de los Ángeles, Canales de Ballenas y Salsipuedes Marine Zone Biosphere Reserve.

Information on the personnel, infrastructure, and equipment of these protected areas was provided by their managing directors. Since the El Vizcaíno Biosphere Reserve presented the highest values for each of the three categories, it was considered as the base surveillance unit (i.e., percent coverage value of 100%) against which the percent coverage of each of the other seven protected areas was compared. The relative management capacity (MC) of each area was determined with Eq. (1):

$$MC = \frac{Infr + Eq + Pers}{3} \times 100, \tag{1}$$

where *Infr* is the infrastructure percentage, *Eq* is the equipment percentage, and *Pers* is the personnel percentage.

Finally, to characterize the percent coverage, the criterion of Cifuentes-Árias et al. [39] was used. In this categorization, a coverage percentage of $\leq$ 35% (0) was considered unsatisfactory, 36–50% (1) was considered not very satisfactory, 51–75% (2) was considered moderately satisfactory, 76–89% (3) was considered satisfactory, and $\geq$ 90% (4) was considered very satisfactory.

2.5. Carrying capacity calculation

In this study, the term carrying capacity was defined as the maximum number of vessels that could simultaneously be used for cage diving within the white shark sub-zone based on the available space, current regulations, tourism activities, and local white shark movements. Once data of the aforementioned variables had been gathered, a specific area was defined for the development of white shark cage diving, considering the relative management capacity of the Guadalupe Island Biosphere Reserve. To calculate the carrying capacity, this area was divided by the physical space required by each vessel, which was determined from the established courtesy distance between two vessels (i.e., 0.45 km diameter) [29], taking into consideration the core of the kernel distribution with encounter probabilities of $0.9 \geq 0.1$. For this, only data collected during the day (6 AM–6 PM) were used in order to exclude white shark use areas that were not affected by tourism activities (cage diving can only be performed during the day).

From the encounter probabilities, we established three different carrying capacity scenarios: 1) critical (encounter probability > 0.9), 2) optimal (encounter probability > 0.5), and 3) expanded (encounter probability > 0.1; Table 1). The area needed for each boat based on the courtesy distance was calculated from the area of a circle ($Area = \pi r^2$, where $r = 0.225$ km). The total area of physically available space was determined from the authorized observation area delimited by the 80 m isobath (maximum mooring depth) and the 100-m coastline limit established by the reserve.

3. Results

3.1. Characterization of the white shark sub-zone

The characterization of the white shark sub-zone aimed to identify the guidelines that should be used for white shark cage diving to ensure the protection of the species and the sustainable development of this wildlife tourism practice. The white shark sub-zone coordinates provided by the Reserve Management Program of CONANP, a polygon with an approximate area of 6.07 km^2 was generated (Fig. 2). The anchor points of the vessels allowed for a polygon to be generated that was used to identify a linear anchoring pattern that ran parallel to the coastline. This pattern was determined from the depth favored by boat operators (80 m), the locations of resting beaches for the different pinniped species [40], and the areas that were most protected from the wind. Considering the anchor points that were farthest from each other from north to south and those along the buffer line of the 80-m isobath, a preferential use polygon pattern for the vessels was recorded, which had an area of 1.1 km^2, a length of 3.4 km, and width of 0.34 km (Fig. 1).

3.2. Characterization of white shark movements

Data from 12 white sharks (7 females, 5 males) with TLs between 3 and 5.5 m (mean: 4.16 ± 0.61 cm SD) were obtained from 2015 to 2019. Taken together, these data were collected from a total of 21 active acoustic tracks with durations between 4 and 38 h (mean: 15.7 ± 9.36 h SD), yielding a total of 330 h of effective monitoring data (Table 1). These acoustic tracks provided 208,036 geo-referenced detections, which allowed for a kernel density calculation with observation percentages ranging from 1% to 100% [51]. In this way, a white shark use polygon was determined with a total area of ~ 160,073 km^2 and a critical area of ~ 3.49 km^2 in which the detections from all tracked sharks overlapped (Fig. 2). With regard to the interaction times between the sharks under observation and the tourism boats, the maximum and minimum accumulated interaction times, which ranged between 5 and 848 min (mean: 218 min), were recorded (Table 1).

3.3. Monitoring and surveillance capabilities

When comparing the relative management capacities of the protected areas evaluated in this study, it was found that the El Vizcaíno Biosphere Reserve presented the highest values in the personnel, infrastructure, and equipment categories. In particular, this protected area had 19 people in director (n = 1), deputy director (n = 1), department head (n = 1), social program operator (n = 4), and operational technician (n = 12) positions, in addition to land transport vehicles (cargo and personnel, n = 8), marine transport vehicles (small boats with outboard motors, n = 1), offices in the city closest to the reserve (n = 1), and stations within the reserve (n = 3; Table 2).

Considering that the El Vizcaíno Biosphere Reserve showed the highest management capacity, its relative management capacity was deemed to be 100% (very satisfactory), and the relative management capacities of the other areas were determined. The relative management capacity of the San Pedro Mártir National Park was determined to be 80.6% (satisfactory), followed by those of the Bahía de los Ángeles, Canales de Ballenas y Salsipuedes Marine Zone Biosphere Reserve (55%, moderately satisfactory), the Revillagigedo National Park (50%, not very satisfactory), the Pacific Islands Biosphere Reserve (48%, unsatisfactory), the Guadalupe Island Biosphere Reserve (34%, unsatisfactory), the Valle de los Cirios Flora and Fauna Protection Area (33%, unsatisfactory), and the Cabo Pulmo National Park (31.6%, unsatisfactory; Table 2).

3.4. Carrying capacity calculation

Considering the white shark sub-zone polygon, 100-m buffer, 80-m isobath, unsatisfactory relative management capacity, and central

Table 1
Acoustically tracked white sharks in the Guadalupe Island Biosphere Reserve (2015–2019). The code indicates the identification number of the tagged shark and the tracking year. Time indicates the total duration of the track. Interaction is the accumulated interaction time between the shark and tourism vessels.

Code	Date	TL (m)	Sex	Time (h)	Interaction (min)	Avg. Depth (m)	Avg. Temp. (°C)
T01-15	7–8 Sep-15	4	Male	14.3	175	17.2	21.8
	12- Sep -15			4	5	33	20
	14- Sep -15			7	38	24	21.7
	25- Sep -15			24	193	41.5	19.2
T02-15	13–14 Sep 15	4	Female	11.5	157	43	19.9
	13-Oct-15			24	464	14.1	22.5
T03-15	21- Sep -15	4.5	Male	24	329	47.9	19.6
T04-15	03-Oct-15	4	Male	16.3	476	46.9	18
	05-Oct-15			24	209	81	16.4
T05-16	24-Ago-16	4	Female	7.4	70	47.25	19.8
	3–4 Sep 16			14.8	105	22.39	20.8
	07- Sep -16			11.30	119	45.08	18.13
	18- Sep -16			4	45	5.7	21.28
	26–27 Sep 16			24.2	–	37.3	18.9
T06-16	14- Sep -16	4	Male	6.1	47	48.08	18.9
T07-16	28–30 Sep 16	5	Male	38	848	45	18.67
T08-17	15–17 Oct 17	4	Female	7	–	94	15.9
T09-18	16 Oct 18	4	Female	8	–	22	20
T10-18	14-Oct-18	3	Female	10	–	45	18
T11-19	26–28 Sep 19	5.5	Female	22	–	95	15.78
T12-19	4, 7–8 Oct 19	4	Female	28	–	16.05	20.22
Total 12		~ 4.16	7F/5M	330		~ 41.49	~ 19.37

Abbreviations: TL, total length; Avg. Temp, average temperature; Avg. Depth, average depth.

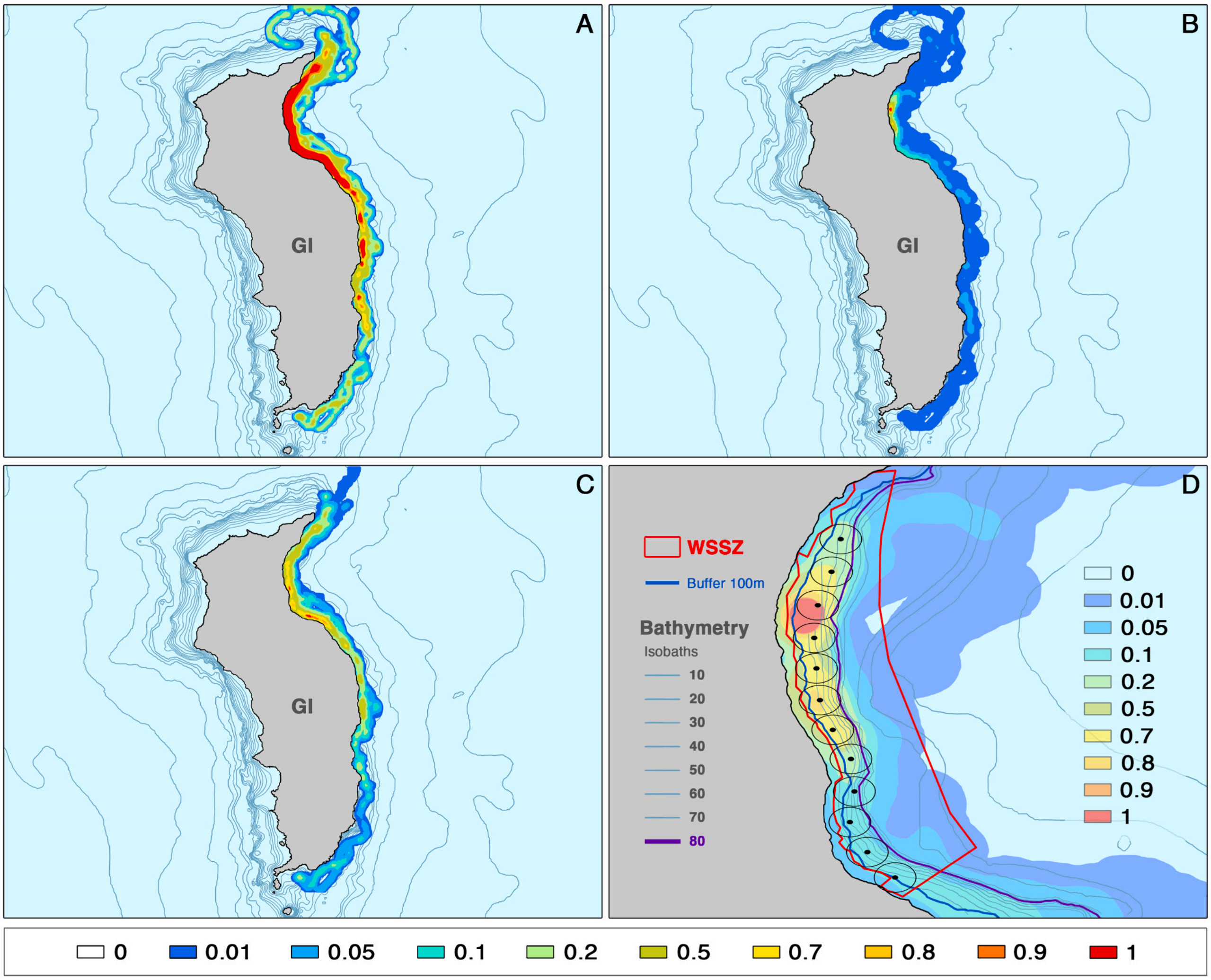

Fig. 2. Kernel densities showing the habitat use of the great white shark in the Guadalupe Island Biosphere Reserve. The color axes at the base of the graph and in panel D indicate the different contours and their respective probabilities. Panel A shows all acoustic tracking data; Panel B shows the data collected during the day (6 a.m.– 6 p.m.); Panel C shows the data collected at night. Panel D is an amplification of the white shark sub-zone (WSSZ) and shows daylight data and all the variables considered in the study. The WSSZ indicates the public use polygon decreed in the management program of the protected area. The blue line or buffer indicates a distance of 100 m from the coast, which is the maximum distance that tourist boats are allowed to approach. The purple line indicates the 80-m isobath, which is the maximum depth at which tourist boats can anchor. The black dots indicate the number of boats that fit within each contour, and the circle around each point indicates the 450-m courtesy distance that should be present between boats. What we wish to indicate visually with the circles (with center points) is the number of ships that could fit within each Kernel contour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 2
Relative management capacity of the eight principle protected areas of the Baja California peninsula. The main management components of the protected areas are presented based on the information provided by the different managing directors. The management capacity of the El Vizcaíno Biosphere Reserve was considered to be 100%.

PA	Terrestrial area (ha)	Marine area (ha)	Personnel	%	Infrastructure	%	Equipment	%	Management capacity
El Vizcaíno BR	2,259,002	287,787	19	100	4	100	9	100	100%
San Pedro Martir NP	72,910	0	10	52.6	4	100	8	88.9	80.6%
Bahía de los Ángeles, Canales de Ballenas y Salsipuedes Marine Zone BR	483	387,473	7	36.8	2	50	7	77.8	55%
Revillagigedo NP	15,518	14,793,261	10	52.6	3	75	2	22.2	50%
Islas del Pacífico BR	79,139	1,091,083	9	47.4	3	75	2	22.2	48%
Isla Guadalupe BR	26,276	450,694	4	21.1	1	25	5	55.6	34%
Protected Area for Flora and Fauna Valle de los Cirios	2,521,987	0	8	42.1	1	25	3	33.3	33%
Cabo Pulmo NP	38.86	7072	5	26.3	1	25	4	44.4	31.6%

Abbreviations: PA, protected area; BR, biosphere reserve; NP, national park.

contours generated by the kernel analysis (Fig. 2), three carrying capacity scenarios (i.e., critical, optimal, and expanded) were generated. Taking into account the mandatory courtesy distance of 0.45 km (total area of 0.15 km^2 per boat) and areas with different probabilities of shark encounters ranging from high to low based on the kernel analysis, it was determined that a critical scenario could allow for 1 boat with a sighting probability > 0.9, whereas the optimal and expanded management scenarios could allow for 6 and 13 boats with sighting probabilities of > 0.5 and > 0.1, respectively (Table 3).

4. Discussion

This study incorporates information on the bathymetry of the Guadalupe Island Biosphere Reserve, vessel anchoring points and operations, reserve regulations, white shark behavior, and management capabilities to generate a useful management tool for white shark cage diving [31]. Our acoustic tracking results suggest a critical white shark use area that clearly overlaps with the anchoring sites use by the cage diving vessels. Additionally, we provide a detailed comparison among the relative management capacities of the protected areas of Baja California, which highlights the current limited management capabilities of the Guadalupe Island Biosphere Reserve given its location, size, and complexity (i.e., having both terrestrial and marine protected areas). In addition, this study quantifies and strengthens the current working dynamics of the white shark cage diving tourism industry of Guadalupe Island. As of 2018, the operators of the cage diving vessels in this protected area have designed a travel calendar that prevents more than seven boats from simultaneously conducting activities [25].

4.1. The overlap of sharks and cage diving vessels

The observed trajectories of the acoustically tracked sharks were strongly related to the anchor positions of the tourism boats (even those within the white shark sub-zone). From the first acoustic tracking data collected during the 2015 season (4 sharks; 9 tracks; 149 accumulated h), it was observed that the area of greatest use overlapped with that of the polygon generated with the anchor points of the tourism vessels (white triangles in Fig. 1). As more acoustic tracking data were compiled, the total shark use area grew, covering a notable portion of the total area of the white shark sub-zone, the core of which was visited by all sharks (Fig. 2). This indicates the potential influence that tourism activities in the Guadalupe Island Biosphere Reserve may have on white shark behavior and the important overlap that exists between tourism activities and white shark home ranges [16,18,25,33].

With the acoustic tracking data, it was found that white sharks display different diurnal and nocturnal behavior patterns, which may be strongly influenced by cage diving activities. However, previous acoustic tracking studies that have ignored the influence of tourism activity have found the same pattern, namely that adult white sharks move offshore during the day and remain close to the coast at night [48]. This was the principle reason why only acoustic monitoring data collected during the day were included in our analysis. By excluding nighttime acoustic tracking data, we were able to exclude the areas that white sharks use at night, when the influence of tourist boats is minimal.

Table 3
Comparison of the carrying capacity scenarios based on all criteria.

Scenario/ Criterion	Shark encounter probability	Total area (km^2)	Area used per 1 boat (km^2)	Carrying capacity (# of boats)
Critical	> 0.9	0.13	0.15	1
Optimal	> 0.5	0.95	0.15	6
Expanded	> 0.1	1.95	0.15	13

4.2. White shark behavior in Guadalupe Island

From the acoustic tracking data, it was observed that not all sharks were equally attracted to each tourism boat. In particular, sharks showed different levels of interaction among the tourism vessels. While some sharks spent more time near the vessels, other showed only brief interactions (Table 1). This conclusion was corroborated by observations made during the concurrent biological observer program [see 25 for a detailed description of this program]. In particular, it was found that some sharks were only registered at certain vessels [24]. The same type of preferential behavior has been recorded in Australia, and it was concluded that the variation in the degree of interaction among individuals (e.g., presence, proximity to vessels, and bait attack) highlights the complexity of the effects that cage diving may have on white shark behavior [21]. In the case of Guadalupe Island, we believe that the abundance of individuals is such that a kind of micro-territorialism is generated that is based on the hierarchical status of each shark, with low-ranking sharks not being permitted to approach boats or areas by higher ranking sharks, as observed in previous behavioural studies [16].

The observations that have now been reported in two white shark aggregation sites indicate that it is necessary to better assess individual white shark preferences for particular cage diving attributes to determine those that serve to either attract or repel sharks, in addition to evaluating the often controversial provisioning approach to shark tourism. To some extent, these individualistic behaviors are beneficial to the white sharks of Guadalupe Island in that tourism activities may not necessarily affect all individuals equally [16,17]. However, future studies are required to evaluate the impacts of tourism activities on white sharks since cage diving has been shown to potentially affect the behaviors and energy budgets of individuals [18,25,31].

Although recent studies have suggested that tourism activities have a low impact on the behavioral conditioning of white sharks in Guadalupe Island [17], it is also important to assess white shark movements and behaviors in the absence of tourism activities. These comparisons are needed to fully assess how white sharks utilize the white shark sub-zone in the absence of attractants and humans. Moreover, the acoustic tracking data presented in this study were collected during periods when white shark cage diving activities were underway. In a previous study, Hoyos-Padilla et al. [48] observed individuals who also used the white shark sub-zone on a recurring basis during November in the absence of tourism activities. This study identified that the northern portion of the white shark sub-zone was used the most. This area also contains one of the main elephant seal (*Mirounga angustirostris*) colonies [45,46]. Despite these findings, the low number of individuals that were tracked and the time frame of this research precludes further speculation on white shark behavior and supports the need for future study.

4.3. Managing the cage diving activities at Guadalupe Island

In this study, three carrying capacity scenarios are proposed in which 1, 6, or 12 tourism vessels can simultaneously conduct their activities in the white shark sub-zone (Table 3), according to the management capacity of the protected area. Currently, 10 boats are authorized to conduct white shark cage diving in Guadalupe Island. However, an internally generated rotation schedule has been implemented so that no more than 7 boats are simultaneously operating within the white shark sub-zone. Based on this study, in which the management capacity of the protected area was found to be unsatisfactory, only one vessel should operate at a time. However, it is possible for the corresponding authorities and cage diving companies to work together to collaboratively finance the management and surveillance actions that are lacking within the white shark sub-zone and surrounding areas. Nevertheless, these scenarios should not be viewed as rigid, although they can function as useful reference points for future management decisions.

When answering the question we pose in the title of this paper, it is important to consider that as the number of boats that simultaneously conduct cage diving increases, the opportunity to see a white shark within a 450-m radius decreases, considering that sighting probabilities of > 0.9, > 0.5, and > 0.1 were found for the critical, optimal, and expanded scenarios, respectively. It is important to mention that white sharks arrive at Guadalupe Island in a staggered manner and that the period of September–November is when the greatest abundance of individuals has been registered [24,48]. As can be seen in Table 1, acoustic monitoring was carried out during August–October, and thus this study considers a period of peak abundance. Therefore, the probability of sighting a great shark before or after this period in each scenario is likely even lower than the value reported here. Given that this study does not consider the effects or impacts that white shark cage diving may have on the species in the mid- or long-term, it is useful to apply the precautionary principle when selecting the scenario as a preventive measure [9]. In this sense, the expanded scenario must be discarded, whereas the critical and optimal scenarios could serve as reference points to select an intermediate number of tourism vessels.

4.4. Management actions and conservation

The main objective of the action program for white shark conservation in Mexico is to develop strategies that generate information to conserve the species, including information on habitat use [31]. In this context, Guadalupe Island Biosphere Reserve managers have also expressed concern regarding the impact that cage diving activities could have on the white shark habitat and the other species present. In particular, there are concerns regarding the multiple anchor points that some vessels employ during a single trip, which may possibly affect the seabed and the associated benthic communities. In addition, the noise produced by the generators and engines onboard the cage diving vessels may be affecting the cetaceans in the area, while the night lights may be affecting the behavior of nocturnal birds, such as Leach's petrel (*Oceanodroma leucorhoa*) and the Mexican shearwater (*Puffinus opisthomelas*) [52]. From the results of this study, it is possible to determine fixed anchor points that will favor habitat protection and minimize the impacts of tourism activities on other species [5,22].

Shark tourism and its research at Guadalupe Island began nearly concurrently almost two decades ago [25]. Since then, managers at Guadalupe Island have strived to improve the management and sustainability of white shark cage diving [25,31], tour operators have incorporated environmental awareness in their tours [all authors, pers. obs.], researchers have aimed to assess the impacts of cage diving on white sharks [17,48], and members of the local community have begun to participate in the activity [25,45]. While several management challenges still exist, we consider that the combination of all of these efforts is taking white shark cage diving from a form of pure wildlife tourism to an activity with an ecotourism-focused approach, which not only benefits the conservation of this species but also the environment and the local community [2,3,5]. This study aims to provide valuable information that may eventually help white shark cage diving to become a form of ecotourism.

5. Conclusions and future research

The present study is the first carrying capacity assessment for white shark cage diving that incorporates encounter probabilities based on the spatial patterns of behavior at the Guadalupe Island Biosphere Reserve. These patterns revealed critical sites in which diving vessel regulations may be implemented to better manage this threatened top predator. The results of this study highlight the need to define a new vessel rotation schedule for the island and to designate fixed anchorage sites. These anchorage sites will not only favor tourism activities while reducing the impacts on white shark behavior but may also contribute to reducing the yet unevaluated potential damage to the seabed and associated fauna [45,53]. On the other hand, it is necessary to continue researching the white shark (e.g., energy expenditure studies) to help characterize the impacts that tourism activities could be having on this species [31]. In addition, when selecting a carrying capacity scenario, the precautionary principle should be considered as a measure to prevent irreversible negative impacts [8,10].

The analysis of the management capabilities of the protected areas evaluated in this study highlights the substantial lack of personnel and equipment. These are necessary to ensure the adequate preservation of marine and terrestrial resources of the Guadalupe Island Biosphere Reserve and of other key areas for marine conservation like the Cabo Pulmo National Park and Pacific Islands Biosphere Reserve. Improvements of the working conditions of the personnel of each protected area are urgently needed. Successful conservation actions depend on such factors and on effective responses to other threats like illegal fishing, unsustainable or damaging tourism practices, and natural or anthropogenic events related to climate change, forest fires, and pollution.

The present study represents an effort to integrate available scientific information on the spatio-temporal distribution and individual behaviors of the white sharks at Guadalupe Island. In addition, it provides information to improve the operational dynamics of cage diving to determine the carrying capacity of this marine ecosystem and the degree of compliance with the public policies for ecosystem protection and conservation delineated in Mexican laws. Likewise, the results of this study support the aims of the Action Program for White Shark Conservation [31] and may be used as a tool to define limits for the use of white shark habitat in Guadalupe Island. Finally, this study will contribute to improving the environmental management capabilities of the protected areas evaluated and possibly of other white shark aggregation sites in the world.

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Author statement

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript.

CRediT authorship contribution statement

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Declarations of interest

None.

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Glossary

acoustic tracking:: technique employed to follow animals tagged with ultrasonic transmitters using a unidirectional hydrophone to obtain fine-scale continuous movement data.
biological productivity:: amount and rate of production in a given ecosystem over a given time period, although this term may apply to a single organism, population, or entire community.
biological observer program (of the white shark):: long-term monitoring that focuses on photo-identification and recording white shark behavior during cage diving operations.
biosphere reserve:: a geographical area representative of the different ecosystems of the planet, which may be both terrestrial and marine, and that is part of the Man and Biosphere Program (MAB) that was initiated by UNESCO in 1970 with the aim of reconciling the conservation and use of natural resources and outlining the current concept of sustainability.
buffer zone:: an area surrounding or adjacent to the core area(s) of a reserve that is used for activities that are compatible with sound ecological practices related to scientific research, monitoring, training, and education.
carcharhinids:: any member of the shark family Carcharhinidae (also called **requiem sharks**), which includes ∼ 12 genera and 50 species worldwide. Carcharhinids are found primarily in warm and temperate ocean waters, although a few species inhabit fresh or brackish water. Carcharhinidae is one of the largest shark families.
carrying capacity:: maximum number of people that may visit a tourist destination simultaneously without resulting in the destruction of the physical, economic, socio-cultural environment or an unacceptable decrease in the quality of visitor satisfaction
cartesian mathematics:: geometry describing every point in an n-dimensional space by means of n coordinates referred to within n-coordinate axes.
eviscerated weight:: fresh weight of an animal once it has been stripped of all of the internal organs of the abdominal cavity.
isobath:: line running connecting points with identical depth values.
kernel analysis:: a kernel density estimation, which is a non-parametric method to estimate the probability density function of a random variable.
protected area:: a clearly defined geographical space, recognized, dedicated and managed, through legal or other effective means, aimed to achieve the sustainability and long term conservation of natural resources with associated ecosystem goods and services as well as social and cultural values [39].
national park:: a park that is used for conservation purposes and that is created and protected by national governments.
pinnipeds:: an infraorder of carnivorous mammals of the caniform suborder. Pinnipeds have long tails, short legs, flat hands, and clapped feet in the shape of flippers. They tend to be gregarious and feed on fish, mollusks, and crustaceans. Pinnipeds are present in all seas.
provisioning:: when an attractant, typically food-related, is used to aggregate target species and ensure consistent, up-close encounters for tourists.
reserve management program:: a plan to implement a set of rules in order to ensure good practices with regard to the activities that are carried out within the framework of the reserve.
white shark sub-zone:: the area in which white shark cage diving and observation is allowed.
wildlife (shark) tourism:: a set of tourism activities focused on observations and interactions with plant and animal life (sharks in the current study) in their natural habitat [54].