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## Marine spatial planning provides a comprehensive framework for building evidence-based shark risk management policies with sea-users

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### Abstract :

Marine spatial planning (MSP), a process aimed at negotiating the spatial allocation of human activities at sea, has to integrate new challenges arising from growing human activities and their impacts on threatened marine ecosystems. Yet, human–wildlife interactions that result in threat to humans are rarely explicitly addressed in planning and almost not at all in MSP. Rare events of unprovoked shark bites can significantly impact local economies while leading to polarized social debates that often hinder the development of evidence-based shark risk public policy. Here, we suggest an approach for integrating shark risk and its management into MSP. The method addresses simultaneously the spatial, social, and ecological components of shark risk and its inherent uncertainties. The approach is applied on Reunion Island case study where shark risk management is implemented as a response to a rapid increase in the frequency of shark bite events over the past decade. Similar to other countries where shark risk management is implemented, sharks' removal is in the heart of social debate in Reunion Islands (3860 shark fishing operations in 5 years) and data gaps provide a fertile ground for alternative discourses and social conflicts about shark risk. Through a structured public consultation involving 200 stakeholders we demonstrate how MSP can be used to address shark risk while considering multiple sea-uses and conservation objectives. The results suggest that the approach is ideal, both for integrating shark risk as a driver to the MSP process, and for developing a transparent, sustainable and evidence-based shark risk public policy as it places shark risk management within a broader social-ecological spectrum of stakes.

### Highlights

► MSP is an effective platform for addressing human-shark related conflicts. ► MSP contributes to the development of shark risk management policies. ► Suggested planning approach highlights risk-related data gaps.

**Keywords** : Marine spatial planning, Shark risk management, Human–wildlife interactions

52 **1. Introduction**

53 Marine spatial planning (MSP) is a political process that aims to bring multiple ocean  
54 users to negotiate informed and coordinated decisions about the sustainable future use  
55 of marine resources (Ehler and Douvère, 2009). Being useful for realizing the ecosystem  
56 approach by analyzing and allocating human activities in the marine space, MSP  
57 initiatives are applied in about 70 countries around the world, which face multiple and  
58 various challenges (MSP Programme IOC-UNESCO, 2019; Santos et al., 2019). Moreover,  
59 MSP mechanisms and principles has been integrated within the legal framework of  
60 several countries including the EU member states (EC, 2014).

61 The theory and practice of MSP have significantly developed in the past decade and  
62 adapted to new challenges. The growing concern to marine ecosystems and impacts of  
63 climate change, along with increasing human activity at sea, drove this evolution and  
64 demonstrated the adaptability of the MSP framework (e.g., Gissi et al., 2019; Santos et  
65 al., 2016; Young, 2015; Zanuttigh et al., 2016). The ability of MSP to adapt to new  
66 challenges might therefore be useful also for planning the management of specific  
67 human-wildlife interactions at sea.

68 Although most of those interactions result in threat to wildlife, some interactions such  
69 as shark bites on humans receive significant attention. Shark bite events in the past 30  
70 years were recorded in more than 50 countries, most of them (83%) in United States,  
71 Australia, South Africa, Brazil, and Reunion Island (ISAF, 2019). Despite being a global  
72 phenomenon, fatality rates of unprovoked shark bite are relatively low (average of <10  
73 people per year globally) (ISAF, 2019). Yet, public response to these events is often  
74 impacting local economies due to following reduction in marine recreation activities and  
75 tourism (Lemahieu et al., 2017; Simmons and Mehmet, 2018). In addition, shark risk  
76 management that involves shark removal often triggers disputes regarding  
77 management's effectiveness and its impact on marine ecosystems. Therefore, shark risk  
78 and its related management should be addressed from holistic perspective within an

79 interdisciplinary framework that considers the ecological and social aspect of it  
80 (Lagabrielle et al., 2018a).

81 In the present study, we use MSP as a backbone structure to frame shark risk and its  
82 related management within the wider scope of managing multiple human activities in  
83 the marine space. We suggest an approach for integrating shark risk into MSP-related  
84 spatial analyses, consultation processes, and decision-making. The approach identifies  
85 the social and ecological issues related to spatial overlap between humans and sharks,  
86 and supply a solid ground for negotiations regarding shark risk management allocation.  
87 We first explore how human-wildlife interactions are referred to in spatial planning and  
88 how shark risk is managed, to prescribe an adjusted and relevant MSP approach that  
89 addresses shark risk within a broader social-ecological scope. Then, we apply the  
90 prescribed methodology on an MSP process in Reunion Island (France, Indian Ocean),  
91 where the rate of lethal shark bite events is one of the world's highest (ISAF, 2019).

92

## 93 **2. Integrating shark risk management into MSP**

### 94 *2.1 Human-wildlife interactions and spatial planning*

95 Threats to humans as a result of human-wildlife interactions are rarely addressed  
96 through spatial planning and especially not in the marine environment. In most cases,  
97 planning considers human impact on wildlife and not the other way around. As evidence  
98 are the numerous tools and approaches developed in the past decade to use planning  
99 for mitigating threats to wildlife caused by human activities and to ensure ecosystem-  
100 based management (Lombard et al., 2019; Pınarbaşı et al., 2017). Therefore, using MSP  
101 to address threat to humans as a result of human-wildlife interactions, may require  
102 adoption of perspective that captures both the ecological and social dimensions of  
103 those interactions, across time and spatial scales.

104 A key step towards understanding the complexities of conflicting human-wildlife  
105 interactions, is exploring their related social factors .Dickman (2010) suggests that

106 human-wildlife conflicts represent conflicts between social groups with antagonistic  
107 opinions. Planners and authorities who direct MSP and who are usually familiar with  
108 social conflicts in general but less with specific human-wildlife conflicts, can therefore  
109 use their skills to investigate social factors related to human-wildlife interaction, to  
110 initiate conflict's mitigation process.

111 Stakeholders and public participation in MSP processes is an opportunity to investigate  
112 social conflicts about human-wildlife interactions. A broad-scoped public consultation  
113 can reach beyond antagonistic debates about these interactions and develop an  
114 understanding of the mental representations involved. The consultation process can  
115 also be used to estimate the extent and intensity of the conflict which is needed to  
116 determine whether sufficient grounds for negotiation exist (The Consensus Building  
117 Institute, 2000). Thus, understanding the stakes and history of the conflict, and  
118 identifying social groups in early stages, may direct the organization of stakeholders'  
119 interactions within the MSP process at later stages.

## 120 *2.2 Shark risk management*

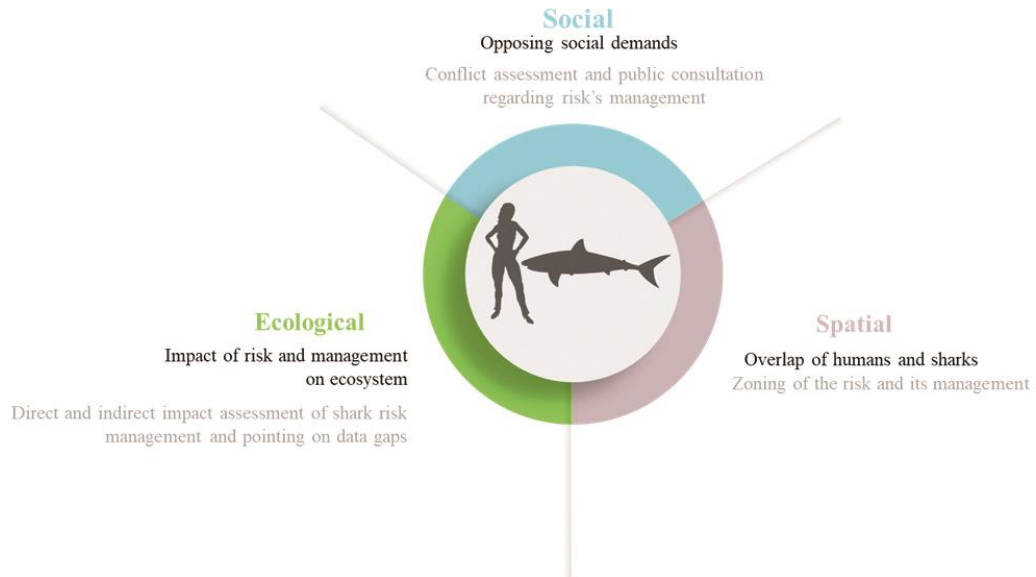
121 Shark risk management is applied where events of unprovoked shark bite occurred  
122 several times, in attempt to reduce the probability of their occurrence. Management  
123 measures include warning and education, surveillance, at-sea devices such as lethal  
124 shark nets and drumlines, exclusion shark nets, and personal electromagnetic devices  
125 for sea users. The effectiveness of these measures is still unclear despite their constant  
126 assessment by scientists and management authorities (Clua and Linnell, 2019; CSR,  
127 2017; Curtis et al., 2012; Guyomard et al., 2019). Especially controversial is whether  
128 management effectiveness in terms of reducing risk to humans worth its impact on  
129 marine ecosystems (Atkins et al., 2016; EPA, 2014; Gibbs and Warren, 2015). Moreover,  
130 impacted by the reaction of people to the risk, management is often an adaptive,  
131 sometime erratic, process that responds to random variations in locations of shark bite  
132 events, changing legislations, instruments availability, social tolerance to the risk, and  
133 social acceptance of the management (Gibbs and Warren, 2015; Pepin-Neff and Wynter,

134 2018; Pepin-Neff, 2019; Simmons and Mehmet, 2018). Therefore, shark risk  
135 management is often applied under condition of uncertainty and remains a matter of  
136 social controversies.

### 137 *2.3 Addressing shark risk through marine spatial planning*

138 The random character of the risk and the ad hoc, emotion-driven, character of shark risk  
139 management policies is a challenge for MSP which is a long and wide process that  
140 considers multiple marine uses, their long-term development stakes and environmental  
141 impacts at once. Still, the integration of shark risk management into MSP may  
142 contribute to better conceptualizing and contextualizing the risk, its management, and  
143 the associated social representations.

144 We suggest that shark risk and related management should be conceptualized within a  
145 three components framework (Figure 1). The first component is the ecological system,  
146 its structure and dynamics that might influence shark presence and might be impacted  
147 as a result of shark risk management. The second component is the social system with  
148 stakeholders and social groups of opinions, building up representations of the issue and  
149 competing to influence shark risk management. The third component is the geographic  
150 area of interaction where the ecological system and the social system meet. In this  
151 geographic area human-shark interactions may result in a threat to people, sharks, or  
152 ecosystems as a whole. The management of this area is a stake of negotiations in the  
153 social system and therefore in the MSP process. At the same time, MSP can be  
154 conceptualized as a framework to shape shark risk management public policy, and  
155 address social demand in a sustainable way. MSP which is embedded within a robust  
156 legal framework, might also enable the public policy to be negotiated and implemented.

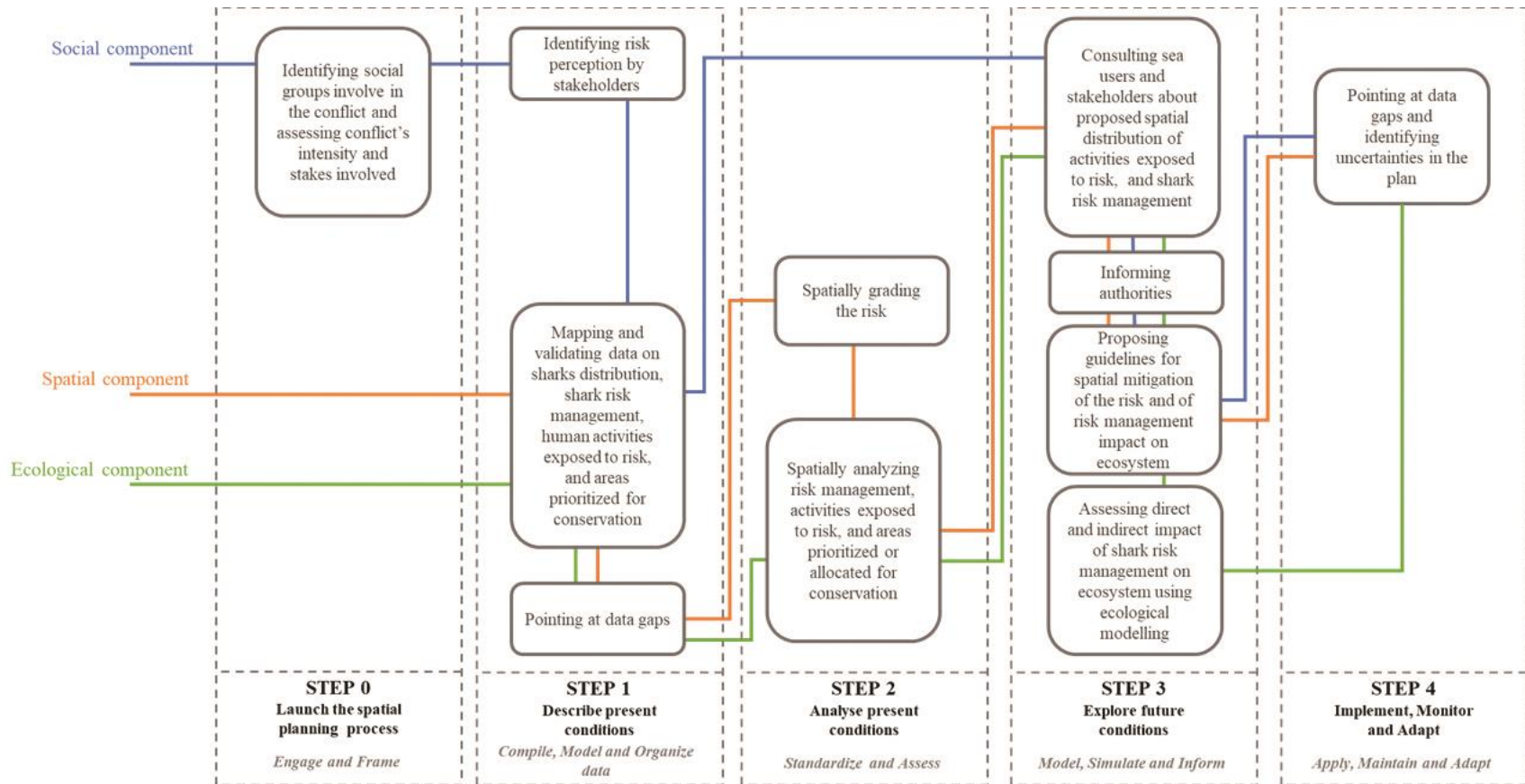


157

158 **Figure 1.** The three components of socioecological interaction, the challenges they pose  
 159 for MSP (black text) and how they are addressed through MSP (gray text).

160

161 The three components of the interaction can be addressed using tools and consultation  
 162 processes that are often being used in MSP as presented in Figure 2. Directing those  
 163 tools towards shark risk and related management, will advance the understanding of  
 164 the multicomponent nature of the shark-risk issue and the dependencies that may exist  
 165 between these components. Sharks play an important ecological role in marine  
 166 ecosystems and therefore human activities primarily designed for sharks' removal, have  
 167 considerable potential for negatively impacting marine ecosystems (Ferretti et al.,  
 168 2010). Therefore, impact assessment in the MSP process should include an overlap of  
 169 shark risk management with areas prioritized for marine conservation and direct impact  
 170 of shark risk management on sharks' populations and other taxa (e.g. bycatch of shark  
 171 control operations or wildlife entangled in shark nets, see Atkins et al. 2013). Ideally, the  
 172 indirect impact on the ecosystem should be assessed as well. Ecological modelling and  
 173 especially food-web modelling could be highly useful for these assessments (Shabtay et  
 174 al., 2018).



177 **Figure 2.** Tools and consultation processes that can be used throughout the marine spatial planning process to address the social,  
 178 spatial, and ecological components of human-shark interaction. Simplified version of marine spatial planning stages (Ehler and  
 179 Douvère, 2009) is adopted from Lagabrielle et al. (2018b).



180 **3. Case-study: Integrating shark risk and related management into MSP in**  
181 **Reunion Island**

182 *3.1.1 Study site*

183 Reunion Island is a French volcanic island in the Southwestern Indian Ocean  
184 (21°07'S/55°32'E) with an overall area of 2512 km<sup>2</sup>. After rapid population growth since  
185 1980, the island inhabits today about 860,000 people. The majority of the population  
186 resides along the coasts of the island and especially along the most urbanized northern  
187 and western coasts.

188 *3.1.2 Shark risk management*

189 Shark bite events have been known throughout the history of Reunion Island. However,  
190 the frequency of these events has increased dramatically by a factor of 23 since 2010  
191 with 25 events of shark-bite that resulted in 11 fatalities up to this day (CSR, 2019a;  
192 Lagabriele et al., 2018a). The majority of bite events was of surfers (i.e. wave-based  
193 activities) and caused by bull sharks (*Carcharhinus leucas*) and tiger sharks (*Galeocerdo*  
194 *cuvier*). The causes for the increased frequency of shark-bite events are still unclear to  
195 scientists.

196 Yet, studies suggested that among the potential causes are changes in sea water  
197 temperature, increased freshwater and sewage discharge along the west coast, and  
198 changes in shark's behavior due to degradation of prey populations including depletion  
199 of reef sharks by overfishing (Chapman and McPhee, 2016; Lagabriele et al., 2018a).  
200 Furthermore, Guyomard et al. (2020) suggest that ban on sharks' finning and sharks'  
201 meat selling due to ciguatera concern, decreased sharks' fishing and therefore increased  
202 potentially dangerous sharks' abundance along the coasts. (see also Guyomard, 2016; Le  
203 Manach et al., 2015). In addition, Thiann-Bo Morel (2019) presented social groups  
204 debated ideas about the causes of this increased frequency that include the  
205 establishment of a coastal marine protected area (MPA) in 2007.

206 Following a series of shark bite events in 2011, shark risk management measures were  
207 developed to reduce the risk. In 2013, the local government released a prefectural  
208 decree (Arrêté préfectoral n°222 du 15 février 2018, 2018) that bans bathing and wave-  
209 based activities along most of the island's coasts up to a distance of 300 m from the  
210 shore. The ban is excluding areas of shallow lagoons, coastal pool, and areas of  
211 surveillance. Since 2014, preventive shark control is operated and targeting individuals  
212 of bull shark and tiger shark that approach the coast. Control operations include lethal  
213 horizontal longline and SMART drumline devices (Guyomard et al., 2020). Later, in 2015,  
214 two large shark exclusion nets totalizing ~1km length were placed at two locations to  
215 allow surfing and bating activities, but are no longer operational due to unsustainable  
216 maintenance costs. Yet, 3 smaller nets for bathing remained operational.

217 At the same time, an innovative in-situ surveillance program was launched along the  
218 west coast of the island. Surveillance operations include in-water observers, water  
219 crafts, and a beach-based team that provides emergency response in case of shark  
220 observation or shark bite event. Both, exclusion nets and surveillance operations are  
221 located in 5 designated areas named ZONEXs (zone for experimental shark risk  
222 management measures) and are distributed along the west coast of the island.

223 Since 2016, shark risk management in the island is developed and coordinated primarily  
224 by Le Centre Sécurité Requin (CSR), which is a boundary organization placed under the  
225 authority of the state, regional council and municipalities. Daily information on shark  
226 management are accessible on <http://www.info-requin.re>, but no spatially explicit long-  
227 term analysis and synthesis of this information has been developed and released to the  
228 public so far.

### 229 *3.1.3 Marine Spatial Planning process: The Ocean Metiss project*

230 In Reunion Island, the on-going MSP process, named Ocean Metiss (see  
231 <https://www.oceanmetiss.re>, 2019), aims to develop a sustainable, integrated, long-  
232 term maritime development strategy and to implement it through a marine spatial plan  
233 of the exclusive economic zone of the island. Ocean Metiss is a partnership project co-

234 funded by the European Maritime and Fisheries Fund, France state, and Reunion Island  
235 regional council. The interdisciplinary project is associating with the University of  
236 Reunion for its implementation, and the Indian Ocean Commission as a technical  
237 partner. From a European Commission perspective, Ocean Metiss is a pilot-project  
238 aiming to investigate innovative MSP processes, tools and methods that will facilitate  
239 the implementation of the European Directive on MSP (EC, 2014).

## 240 **3.2 Methods**

241 The Ocean Metiss project serves as a backbone structure for developing and testing our  
242 approach for addressing shark risk in MSP and designing MSP-based shark risk  
243 management, throughout the five planning stages as presented in Figure 2 and Table 1.

244 **Table 1.** Applying the integrative approach for marine spatial planning and shark risk in Ocean Metiss project, following Ehler and  
 245 Douvere (2009) planning stages.

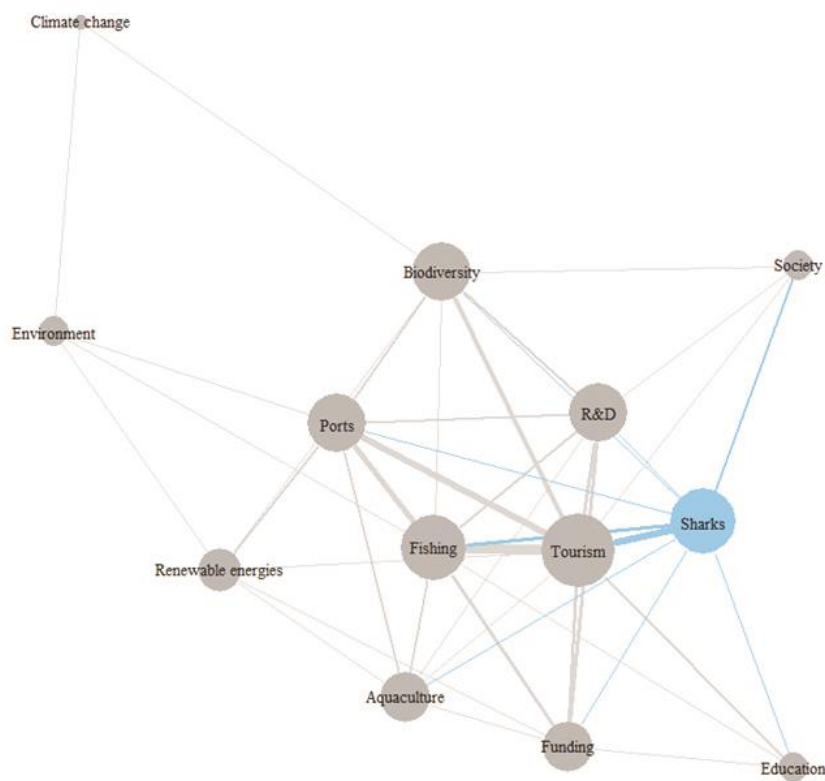
<b>Planning stage</b>	<b>Objectives</b>	<b>Methods</b>	<b>Tools</b>
Stage 0- Launch the spatial planning process	0.1. Formulate vision, goals, and objectives for the planning process. 0.2. Identify and describe conflicts related to shark risk.	Three stakeholders' meetings (200 participants each) were organized. Stakeholders from various marine sectors discussed opportunities and challenges relating to their sectors in several working groups. Meetings transcription was analyzed following statistical methods described in Kuckartz (2019) to identify major topics discussed and their links with specific sectors. This was also used to examine how stakeholders perceive shark risk in relation to other topics and sectors driving the MSP process. A literature review provided further information about shark risk management and related conflicts as it is today.	igraph package (Csardi and Nepusz 2006) for R (R Core Team 2014)
Stage 1- Describe present conditions	1.1. Collect spatial data on habitats, species and human activities including those exposed to shark risk <sup>a</sup> , shark risk management <sup>b</sup> , and marine protected areas. 1.2. Identify data gaps relating to shark risk and shark risk management.	Data layers were collected from multiple sources. An exhaustive list of data layers and data sources is available in Appendix A1. (see also <a href="https://www.oceanmetiss.re">https://www.oceanmetiss.re</a> 2019, <a href="https://www.seasketch.org">https://www.seasketch.org</a> 2019). All data layers were gridded and mapped in planning units of 100x100 m and 1x1 km each from the coastline to 4 nautical miles.	ArcMap version 10.2

Stage 2- Analyze present conditions	2.1. Analyze spatial relationships (overlap and proximity) between human activities, species and habitats.	Spatial analysis was used to calculate spatial overlap of shark presence <sup>c</sup> , human activities, and spatial management zones (both for conservation and shark management purpose). The relative high exposure of surfers to shark risk (see Arrêté préfectoral n°222 du 15 février 2018, 2018; Lagabrielle et al., 2018a), was represented by areas where surfing is practiced within and outside risk management areas <sup>d</sup> in a 1x1 km grid.	ArcMap version 10.2
Stage 3- Explore future conditions	3.1. Develop and negotiate a spatial plan for shark risk management (among a set of optional spatial plans) in the broader framework of a multi-sectorial marine spatial plan. 3.2. Propose guidelines for spatial mitigation of the risk and of risk management impact on ecosystem.	Stakeholders explore alternative management options, using an online tool for collaborative planning. This stage is expected to be finalized at the end of the consultation process in August 2020. Limited biomass data and planning resources did not allow using ecological modelling in the current planning cycle.	Seasketch
Stage 4- Implement, manage and assess	4.1. Implement shark risk management spatial plan as part of the broader marine spatial plan. 4.2. Assess spatial plan.	This stage is expected to be executed from September 2020.	ArcMap version 10.2 Policy instruments
<p><sup>a</sup> Activities exposed to shark risk were assumed to be any type that includes the immersion of the human body in the water, meaning bathing, diving, wave-based activities (hereafter = surfing), and wind-based activities. Freediving and spearfishing were also considered as activities exposed to risk, yet they were not investigated due to lack of updated data on their spatial distribution around the island. All activities exposed to risk are operated from the coast or from small boats.</p> <p><sup>b</sup> Shark risk management include ZONEXs (where shark nets and surveillance operations are implemented), and preventive shark control (drumlines and longlines).</p> <p><sup>c</sup> Due to limited data on sharks' species distribution around the island, we assumed sharks' presence in the entire area of interest.</p> <p><sup>d</sup> Preventive shark control operations were excluded from this analysis due to high level of uncertainty associated to its impact on the risk.</p>			

247 **3.3 Results**

248 *3.3.1 Stage 0*

249 Along the cycle of MSP conferences, the “sharks” theme, was identified by the  
250 stakeholders as one of the major themes of the MSP process. (Figure 3). The theme was  
251 found to be linked to several other themes by 17 causative or impacting factors. Out of  
252 all the linked themes, the greatest number of links to the “sharks” theme was to tourism  
253 (6) and fishing (3).



254

255

256 **Figure 3.** Thematic analysis of MSP drivers as viewed by the stakeholders. Each node  
257 represents a theme and lines represent link between themes in the form of cause or  
258 impact. The size and position of the node represent the number of other nodes linked to  
259 it (the larger and central the node, the more links it has). The width of the line  
260 represents the number of links that were identified between two nodes. The node that

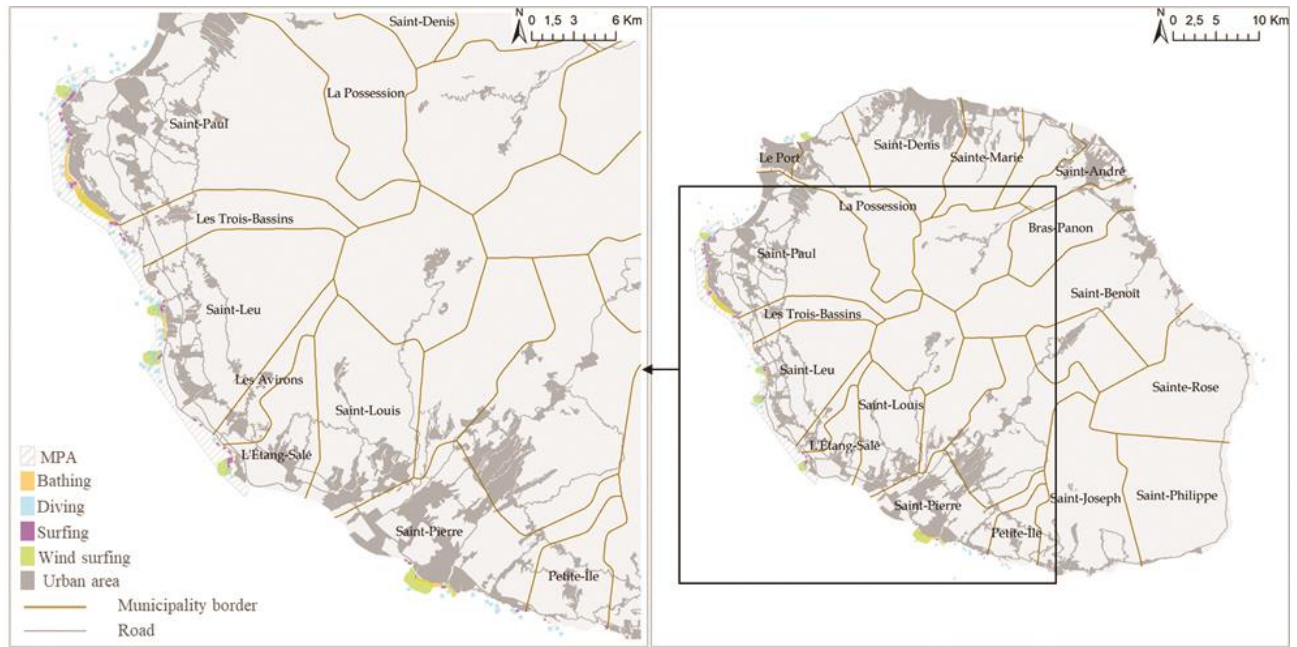
261 represents the “sharks” theme and the links between shark’s theme and other themes  
262 are highlighted in blue.

263

264 Identification of social groups involved in the shark risk debate significantly profited  
265 from the study of Thiann-Bo Morel (2019). She identifies surfers and their supporters in  
266 Reunion Island as a social group claiming sharks’ removal in addition to other  
267 management measures. The study also sheds light on the complex context of the  
268 conflict to ethno-racial issues in a post-colonial community and environmental  
269 inequalities. The results of this study are also echoed by a survey which follows the work  
270 of Gibbs and Warren (2015) and is currently being processed by Lagabrielle (2019,  
271 unpublished) with support from the CSR. The preliminary results confirm that the main  
272 disagreements are between surfers and other sea users and revolve around shark  
273 removal policy. This study also shows the consensus among groups of users about other  
274 non-lethal shark management measures, including unanimous opposition against the  
275 decree that bans bathing around the island. The social component of shark risk and  
276 shark risk management in Reunion Island was also translated by Dupéré (2019) into  
277 legal basis for integrating shark risk into marine spatial planning.

### 278 *3.3.2 Stages 1 and 2*

279 In spatial terms, all activities exposed to shark risk besides freediving and spearfishing  
280 take place in an overall area of 23 km<sup>2</sup>, most of it along the west coast of the island.  
281 About 60% of this area is within an MPA (Figure 4).



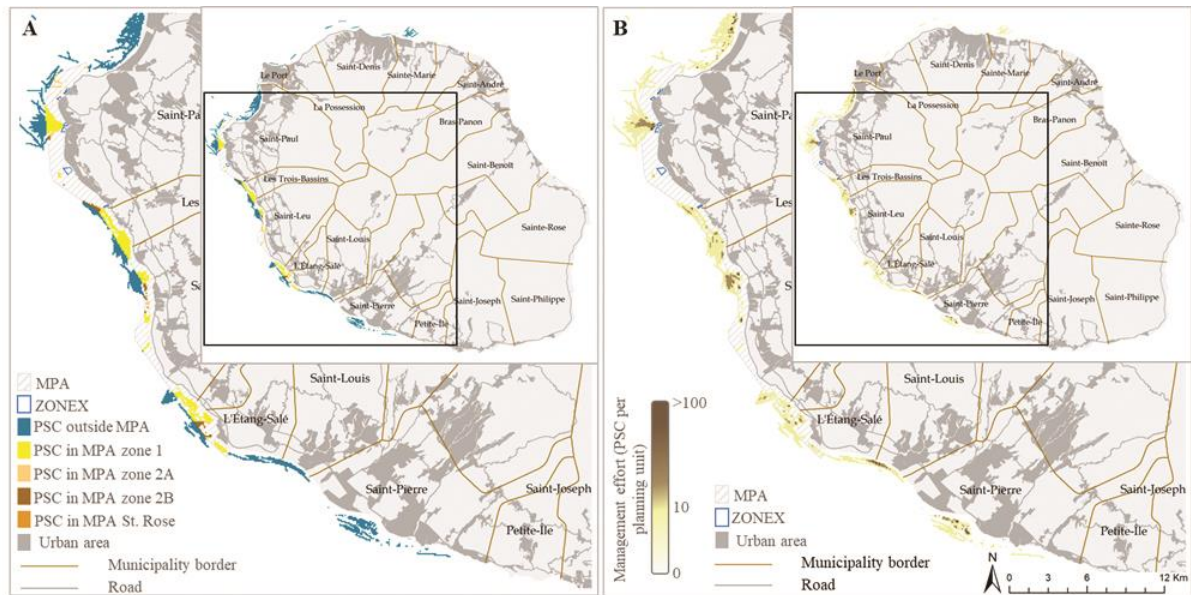
282

283 **Figure 4.** Recreation activities exposed to shark risk in Reunion Island

284 Regularly, shark risk management is applied in ZONEXs areas which include surveillance,  
 285 and shark nets, in an area of 1.1 km<sup>2</sup>. In addition, preventive shark control is applied  
 286 regularly but in changing locations, and concentrated along the west coast of the island.  
 287 The latest preventive shark control program was released in May 2018 and lists areas  
 288 where preventive shark control is regularly applied. In the first seven months of the  
 289 program 155 bull sharks and tiger sharks were removed (CSR, 2019b). Since the  
 290 beginning of preventing shark control operations in January 2014 until November 2019,  
 291 a total area of 31.3 km<sup>2</sup> was used, 28% of it within MPA. Out of the 9559 drumline and  
 292 longline devices which were deployed during that period, 3121 were deployed within  
 293 zones 1 and 609 within zone 2B of the MPA where professional fishing including  
 294 preventive shark control is permitted. Deployments of devices at the edges of zones 2A  
 295 of the MPA where fishing is prohibited are recorded as well (130 devices), yet are  
 296 assumed to be unintentional or due to unprecise location reporting (Figure 5A). Along  
 297 this period, the number of devices per planning unit (100x100 m) where preventive  
 298 shark control was applied varied between 1 and 376 (Figure 5B). Most (70%) of the  
 299 devices were deliberately located within 1 km of activity exposed to risk, which reflects



300 management objective of targeting sharks that frequent areas of activities exposed to  
301 risk.

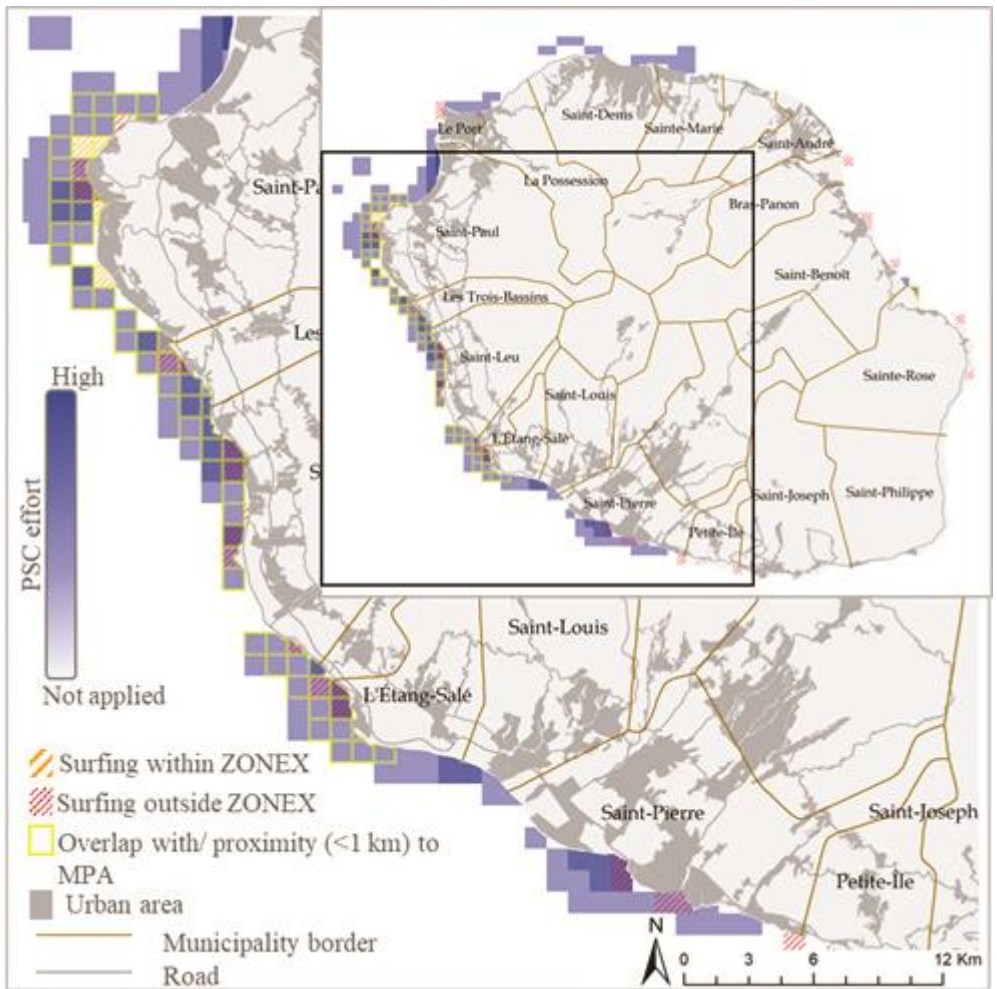


302

303 **Figure 5.** Shark risk management around the island and along the west coast. **A.**

304 Location of ZONEXs and preventive shark control devices deployed between January  
305 2014 and November 2019 in relation to MPAs. **B.** PSC effort (per 100x100 m planning  
306 unit). MPA= marine protected area, ZONEX= area where shark risk management is  
307 constant and includes bathing nets and surveillance. PSC= preventive shark control  
308 device (drumlines and horizontal longlines).

309 Surfing activity which is considered to be most exposed to shark risk is practiced along  
310 3.2 km<sup>2</sup>, 24% of this area is within ZONEXs (Figures 4 and 6). Therefore, 2.4 km<sup>2</sup> (76% of  
311 the surfing area) is still being used for surfing in an area banned for surfing by the  
312 prefectural decree (yet, at least 10 times less frequently than before 2011; see  
313 Lagabrielle et al. 2018a).



314

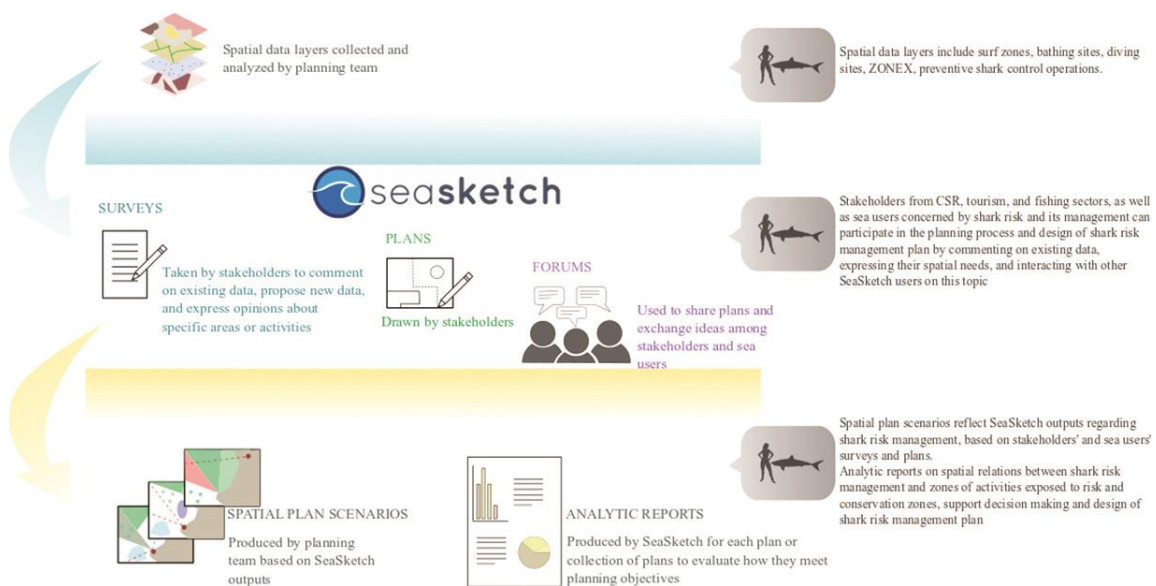
315 **Figure 6.** Preventive shark control (PSC) effort, overlap with MPA, and surfing within and  
 316 outside ZONEXs, presented in 1x1 km grid around the island.

317

318 Attempts to identify and assess the ecological impact of shark risk management faced  
 319 difficulties due to significant data gaps. Most gaps are related to the biology, ecology,  
 320 and behavior of bull sharks and tiger sharks in the area. However, others relate to the  
 321 impact of management on the ecosystem and the effectiveness of the management in  
 322 decreasing the risk. While some gaps are a consequence of data scarcity, others might  
 323 emerge from poor synthesis or lack of data communication. Table 2 presents the main  
 324 data gaps which were identified in this study and the implications they might have on  
 325 planning.

326 3.3.3 Stage 3

327 Stage 3 of the planning process is currently being implemented and is expected to be  
328 completed by August 2020. Seasketch online zoning negotiation platform is currently  
329 being used (<http://reunion.seasketch.org>, 2019). The platform allows participation of  
330 stakeholders and sea users that can comment on existing data and propose spatial  
331 management planning scenarios (Figure 7). Those scenarios involve alternative zoning  
332 options for nautical activities exposed to shark risk and shark risk management  
333 measures. The platform includes more than 100 data layers of various environmental  
334 features and marine uses. The CSR aims to use Seasketch to design territorial  
335 management of shark risk. They expect it to improve the zoning of their actions, and to  
336 facilitate interactions and negotiations with stakeholders being impacted by shark risk  
337 management.



338

339

340 **Figure 7.** Using Seasketch tool in marine spatial planning to promote collaborative  
341 process and address shark risk.

342 **Table 2.** Data gaps and sources for uncertainty identified when addressing shark risk and its management through MSP in Reunion  
 343 Island. Available and missing data refer to local data only.

Topic	Available data	Missing data	Uncertainty to account for in MSP	Data sources
Sharks' biology and ecology	<ul style="list-style-type: none"> <li>• Partial data on bull shark population and their presence along the island west coast and along the year.</li> <li>• Partial data on trophic ecology, reproductive biology, population genetics, population dynamics, and behavioral ecology of bull sharks and tiger sharks.</li> <li>• Bull and tiger sharks are both considered apex predators, yet they demonstrate different foraging niches.</li> </ul>	<ul style="list-style-type: none"> <li>• Sharks' population size and structure (sex ratio, average age etc.) *.</li> <li>• Sharks' species distribution around the entire island.</li> <li>• Trends in sharks' distribution and use of habitat*.</li> <li>• Drivers of distribution trends (e.g. water quality, climate change, prey population).</li> <li>• Trends in consumption and production* (biomass, prey, and predators).</li> </ul>	<ul style="list-style-type: none"> <li>• Exposure of users to sharks' presence in an area.</li> <li>• Cumulative long-term impact of uses on marine ecosystem.</li> </ul>	<p>The CHARC program (2015)            The ECoReCo-Run program (2017)            Blaison et al. (2015)            (Trystram et al., 2016)            (Pirog et al., 2017)            (Pirog et al., 2019a)            Pirog et al. (2019c)            Pirog et al. (2019b)</p>

Shark risk management impact on ecosystem	<ul style="list-style-type: none"> <li>• SMART drumlines are suggested to have the lowest impact on non-target species compared to longlines and gill nets. In addition, a link was found between variables such as hour of device deployment and the catch ratio of targeted versus non-targeted species.</li> </ul>	<ul style="list-style-type: none"> <li>• Impact of shark risk management on target shark populations (structure, dynamic, and behavior).</li> <li>• Indirect impact of target shark capturing on the marine ecosystem (structure and dynamics).</li> <li>• Impact of bycatch capturing by shark removal devices on bycatch populations.</li> </ul>	<ul style="list-style-type: none"> <li>• Existence and/or extent of conflict between uses objectives (shark risk management and MPAs, see Figure 5).</li> <li>• Ability of spatial alternatives and management plans to enhance ecosystem-based management.</li> </ul>	<p>Guyomard et al. (2019) Guyomard et al. (2020)</p>
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Impact of shark risk management on the risk	<ul style="list-style-type: none"> <li>• Evaluation of shark risk management performed by the authorities expressed lack of satisfaction from the performance of shark nets that protect surfing zones due to poor resistance to sea condition.</li> <li>• Shark nets that protect bathing areas were found more effective yet require high maintenance.</li> <li>• Experimental surveillance programs were found to be somewhat effective yet further evaluation of the program is required.</li> <li>• Preventive shark control was found to be effective in decreasing the risk, yet require further assessment.</li> <li>• Warning and prevention measures were found highly effective.</li> <li>• Population of sea users exposed to the risk is defined and partially mapped.</li> </ul>	<ul style="list-style-type: none"> <li>• The degree in which shark risk management of all types reduces shark risk.</li> <li>• Complete and updated spatial data on the distribution and intensity of activities exposed to risk.</li> </ul>	<ul style="list-style-type: none"> <li>• Identifying ideal locations and effort of management.</li> </ul>	<p>CSR (2016)          CSR (2017)          Lagabrielle et al. (2018)          Lemahieu et al. (2017)          Guyomard et al. (2019)</p>
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344 \* Data is unavailable due to an ongoing processing, lack of processing, or lack of data communication.

345 **4. Discussion**

346 The increased use in MSP framework to promote sustainable development around the  
347 world, reveals various interactions between human and marine ecosystems. In our study  
348 we disassembled the human-shark interaction that is primarily described as potentially  
349 dangerous for human, and acknowledged its multicomponent nature. We demonstrate  
350 that the MSP framework has the ability of addressing shark risk when it reaches beyond  
351 spatial solutions to the conflict. The MSP process can then be used in that case to design  
352 public policies related to shark risk through comprehensive, inclusive, and transparent  
353 consultation processes.

354 Targeting social debates within the framework of MSP, could be constrained by time  
355 and other planning resources such as knowledge and funding. Especially, intense social  
356 conflicts related to shark risk may require use of conflict mitigation tools which are not  
357 commonly applied in MSP (e.g. Hanssen et al., 2009; Peltonen and Sairinen, 2010). In  
358 this case, the contribution of MSP to conflict's mitigation might be hindered but could  
359 initiate and drive forward a process of mitigation that use social-conflict-oriented tools  
360 as a preparatory step for MSP (Lecourt and Baudelle, 2004; Oteros-Rozas et al., 2015).  
361 Alternatively, instead of trying to mitigate the conflict, effort could be directed towards  
362 providing the practice and institutions that allow conflicts to take an agonist form and  
363 make the conflicts explicit in the process as management issues (Albrechts, 2015;  
364 Nursey-Bray, 2016). This radical planning approach that was originally suggested as an  
365 urban planning approach by Grabow and Heskin (1973), is not common in MSP process,  
366 but it may benefit from the significant driving force of conflicts to enhance social  
367 capacity as suggested by Nursey-Bray (2016).

368 Understanding the ecological impact of shark risk management could also be a  
369 challenge under the constrains of planning resources. The lack of sharks' ecological data  
370 results in high uncertainty regarding the effectiveness of management measures. The  
371 ability of MSP to account for the ecological dimension of the conflict is therefore  
372 depended on the existence of environmental data, how data reflect the

373 interconnectivity between ecosystem components, and how it is translated into policy if  
374 at all.

375 In cases where shortfalls in data exist, we suggest that data gaps and related  
376 uncertainties should be strongly emphasized in the MSP process. This could direct  
377 resources towards biological and ecological research, which can be used for plan  
378 adaptation in the next planning cycles. We also suggest that those research products  
379 can be used for shark risk management strategy design in cases where the MSP is also  
380 used as a platform to construct shark risk public policy.

381 The results of this study suggest that MSP process is an opportunity to set guidelines for  
382 conflict mitigation when proposing a spatial marine plan (Table 3). Overall, those  
383 guidelines highlight the need to zone shark risk management, define target of each  
384 zone, and assure that areas developed for recreation will include the spatial  
385 requirements of shark risk management. Zoning of shark risk management can also be  
386 used to minimize or avoid overlap with other uses in cases of uncertainty such as  
387 overlap with MPAs. Evaluation of the marine plan can refer to the degree in which those  
388 guidelines are met.

389 Reunion Island case study demonstrates a rapid evolution of shark risk management  
390 that responded to sudden increase in a number of shark bite events in an unplanned  
391 environment. Shark risk management strategy that was and still being developed in “as-  
392 we-go” mode was spatially oriented mostly by the locations of activities exposed to risk  
393 and of shark bite events (see Section 3.2 and CSR, 2017; Guyomard et al., 2019). As a  
394 result, management measures such as preventive shark control and shark nets are  
395 located in or in proximity to an MPA which hosts most of the area of recreational  
396 activities around the island and which was primarily allocated to protect coral reef  
397 ecosystem. Although lack of evidence of a conflict between the MPA and shark risk  
398 management was found, significant data gaps were identified regarding the impact of  
399 shark risk management on the marine environment (see Table 2). Therefore, we suggest



400 that the coexistence of these uses should be carefully considered in light of this high  
401 uncertainty.

402

## 403 **5. Conclusions**

404 The first attempt to address shark risk and its management through the MSP process,  
405 suggests that significant weight should be given to shark risk when considering  
406 development of sectors and designing public participation in decision makings. Framing  
407 of the risk and of the management in terms of space, people, and impact on ecosystem  
408 is a big step towards mainstreaming shark risk into transparent and participative  
409 decision making. This may balance both social responses to shark risk and the impact of  
410 management on the marine ecosystem.

411 The ability of MSP to adapt to new challenges and shed light on issues that are more  
412 than merely spatial overlaps of uses, allows the process to effectively address  
413 socioecological conflicts such as human-shark interactions. Even if complex decision  
414 support tools or analysis tools are not being used in the process, MSP can still reveal  
415 social and ecological aspects of uses and suggest systematic solutions. These solutions  
416 eventually contribute to sustainable development and ecosystem-based management  
417 which are in the heart of the recent worldwide legislations such as the European  
418 Directive for MSP (EC, 2014).

419 We suggest that the approach proposed in this study could be adopted by other MSP  
420 initiatives worldwide where shark risk management is applied, and that it could  
421 encompass various management measures and social groups. Yet, we suggest that local  
422 knowledge and personal as possible consultation process would best promote  
423 sustainable solutions to shark risk and therefore, when applied to large marine areas or  
424 to heavily populated regions, the approach should be adapted accordingly (for example,  
425 by graduating the process or applying it to sub-regions).

426 **Table 3.** Guidelines for spatially mitigating human-shark conflict in MSP

	<b>Guidelines</b>	<b>Examples</b>
<b>Zoning shark risk management</b>	Setting management targets. Each zone should address specific target or risk. Management type and intensity should differ from one zone to another according to zone’s targets.	<ul style="list-style-type: none"> <li>- Protection of bathing or surfing zone by nets/ surveillance.</li> <li>- Removing specific individuals (such as adults vs. juveniles, males vs. females, daily vs. nightly catches, bull vs. tiger sharks, etc.) in attempt to control the presence of sharks or reduce immediate threat to sea users while minimizing impact on population or ecosystem.</li> </ul>
<b>Coupling recreation activities and shark risk management</b>	Development of zones for recreational activities should include consideration and perhaps allocation of shark risk management.	<ul style="list-style-type: none"> <li>- Allocating multiuse areas of activities and shark risk management (e.g. surveillance or shark nets in bathing or surfing sites).</li> <li>- Creating buffer zones dedicated to shark risk management around popular areas of recreation activities while considering management limitations (e.g. depth and currents).</li> <li>- Allocating coastal zones for warning against shark risk (signs, alerts etc.) and preparedness for shark bite events, such as medical cabin in popular recreation sites.</li> </ul>

427

<b>Minimizing impact on ecosystem</b>	Uncertainty regarding impact on ecosystem should prevent or at least restrict and minimize allocation of shark risk management in proximity to vulnerable habitats.	<ul style="list-style-type: none"><li>- Excluding preventive shark control and shark nets from MPA areas.</li><li>- Expanding, reallocating, adapting the regulation or rezoning MPA</li></ul>
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