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Conservation and economic potential of the whale shark (*Rhincodon typus*) in Boa Vista, Cabo Verde

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Abstract

The whale shark (*Rhincodon typus*) is an Endangered species for which information regarding its behaviour and distribution remains limited. This thesis aims to assess the spatiotemporal distribution of whale sharks in Cabo Verde, especially around Boa Vista, and to determine the degree of overlap between whale shark occurrence areas and existing Marine Protected Areas (MPAs) and Important Shark and Ray Areas (ISRAs). In addition, explores the potential economic dimension of whale shark tourism. Satellite tracking data from seven whale sharks were analyzed. Different maps were produced in order to analyse spatial patterns, identify core-use and broader utilization areas, and assess their overlap with MPAs and ISRAs. The economic component was based on a review of studies that reported economic values related with whale shark tourism. Instead of assigning a monetary value to whale sharks in Boa Vista, this review was used to examine the economic benefits reported in established whale shark tourism destinations and to provide context for discussing if similar kind of tourism could be explored in Boa Vista in the future. The results showed a strong concentration of whale shark space use in Cabo Verde's EEZ, since approximately 78% of all the positions recorded from the seven individuals were in this area. Focusing in Boa Vista, where the core-use area is, spatial protection focused on sharks is limited. Indeed, only 3% of the whale shark utilization distribution overlaps with existing MPAs, and only 2% of the core-use area is currently protected. The economic review showed that whale shark tourism can generate economic benefits in established destinations, although the magnitude of these benefits varied considerably among locations and cannot be directly extrapolated to Boa Vista. Further ecological, social and economic research is needed to assess the viability of whale shark tourism in Boa Vista.

Keywords: Whale shark; Endangered; Cabo Verde; Spatiotemporal distribution; Marine Protected Areas; Important Shark and Ray Areas.

Resumo

O tubarão-baleia (*Rhincodon typus*) é uma espécie classificada como Em Perigo, sobre a qual informação relativa ao seu comportamento e distribuição continua a ser limitada. Esta tese tem como objetivo avaliar a distribuição espaço-temporal dos tubarões-baleia em Cabo Verde, com foco Boa Vista, e determinar o grau de sobreposição entre as áreas de ocorrência desta espécie e as Áreas Marinhas Protegidas (AMPs) e Áreas Importantes para Tubarões e Raias (ISRAs). Explora também o potencial da dimensão económica do turismo relacionado com o tubarão-baleia. Foram analisados dados de localização de sete tubarões-baleia. Foram elaborados mapas com o objetivo de analisar padrões espaciais, identificar diferentes áreas de utilização, e avaliar a sua sobreposição com as AMPs e as ISRAs. A componente económica baseou-se numa revisão de estudos que apresentam valores económicos sobre o turismo com o tubarão-baleia, para examinar os benefícios económicos relatados em destinos onde já existe este tipo de turismo e para fornecer contexto para discutir se, no futuro, um turismo semelhante poderia ser explorado na Boa Vista. Os resultados revelaram uma forte concentração do uso do espaço pelos tubarões-baleia na ZEE de Cabo Verde, uma vez que aproximadamente 78% de todas as posições registadas se situavam nesta área. Em torno da Boa Vista, onde se concentra a área de utilização principal, a proteção espacial é limitada: apenas 3% da distribuição de utilização se sobrepõe às AMPs existentes e apenas 2% da área de utilização principal se encontra protegida. A análise económica revelou que o turismo relacionado com o tubarão-baleia pode gerar benefícios económicos em destinos já estabelecidos, embora a magnitude desses benefícios varie consideravelmente entre locais e não possa ser diretamente extrapolada para a Boa Vista. Desta forma, são necessárias mais investigações ecológicas, sociais e económicas para avaliar a viabilidade do turismo relacionado com o tubarão-baleia na Boa Vista.

Palavras-chave: Tubarão-baleia; Em Perigo; Cabo Verde; Distribuição espaço-temporal; Áreas Marinhas Protegidas; Áreas Importantes para Tubarões e Raias.

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List of Acronyms

MPA - Marine Protected Area

ISRA - Important Shark and Ray Areas

IUCN - International Union for Conservation of Nature

EEZ - Exclusive Economic Zone

KDE - Kernel density estimation

TEV - Total economic value

WTP - Willingness to pay

1. Introduction

The whale shark (*Rhincodon typus*) is the largest living fish and a highly mobile species with a circumtropical distribution (Pierce et al., 2025; Rowat & Brooks, 2012). Despite its capacity for long-distance movements, individuals often show repeated use of specific areas, especially where favourable feeding conditions occur (de la Parra Venegas et al., 2011; Guzman et al., 2018; Putra et al., 2026). This species is currently classified as Endangered, reflecting continued population declines and ongoing anthropogenic pressures (Pierce et al., 2025).

Various anthropogenic factors threaten whale sharks (Guzman et al., 2022; Stewart & Wilson, 2005). In the past, fishing has been one of the major causes of whale sharks mortality, whereas current threats include bycatch, ship strikes, marine pollution, habitat destruction and poorly regulated tourism interactions (Capietto et al., 2014; Chen et al., 1997; Fossi et al., 2017; Rowat et al., 2021; Rowat et al., 2021; Womersley et al., 2022). Its slow growth makes it more vulnerable, while its highly migratory behaviour makes effective conservation particularly challenging (Rowat et al., 2021).

Various conservation strategies have been developed to protect whale sharks, including measures to regulate fisheries and international trade, reduce bycatch and mortality, and promote cooperation in the management of this species (Convention on the Conservation of Migratory Species of Wild Animals [CMS], 2024; Convention on International Trade in Endangered Species of Wild Fauna and Flora [CITES], 2015; Pierce et al., 2021). Besides, nowadays, the practice of tagging and tracking the movement and residence of whale sharks has become one of the most important tools that provides data about their habitats and that also helps to identify spatially significant areas and possible gaps within conservation (Guzman et al., 2022). This may lead to the development of spatial conservation planning through tools such as Marine Protected Areas (MPAs) and Important Shark and Ray Areas (ISRAs) (Guzman et al., 2022). MPAs can help mitigate human impacts in regions that are ecologically important, although their effectiveness depends on their design, management, and implementation (Chin et al., 2023; Putra et al., 2026; Sala & Giakoumi, 2018). Therefore, their effectiveness in protecting highly mobile species will depend upon their ability to include regions that are routinely used for used for feeding, aggregation, reproduction or movement. (Grorud-Colvert et al., 2021; Valsecchi et al., 2021). At the same time, although ISRAs are

not protected areas, they are important because they represent regions of high ecological importance for sharks and rays (Hyde et al., 2022; IUCN SSC Shark Specialist Group, 2022; Rohner et al., 2025). In this way, the identification of ISRAs can support the development of conservation measures by highlighting zones that are associated with processes such as feeding, aggregation, reproduction and movement patterns (Hyde et al., 2022).

Cape Verde is rich in marine biodiversity, and to protect it, conservation efforts such as the creation of Marine Protected Areas (MPAs) and the identification of Important Areas for Sharks and Rays (ISRAs) have been made (Hyde et al., 2022; Larrea et al., 2023; Orejas et al., 2026). Nevertheless, conservation measures specifically targeting sharks and rays are still limited (Rosa et al., 2023). Moreover, there is very limited information about the occurrence and habitat use of most shark species in the archipelago (Rosa et al., 2023). This lack of information makes it difficult to identify the areas of importance and to assess whether existing conservation measures adequately account for these species (Hyde et al., 2022; Whiting et al., 2026). Improving this knowledge is therefore essential to better evaluate the current conservation context for sharks in Cabo Verde and to identify potential gaps in protection (Varela et al., 2025).

In addition to being ecologically valuable, whale sharks also have economic value (Catlin et al., 2012). Nowadays, the main economic value of whale sharks comes from the so-called non-consumptive uses, mainly wildlife tourism (Catlin et al., 2012; Davis et al., 1997). Other than the direct uses, this species can also have values that relate to future use of the species as well as non-use values (Moreno-Gutiérrez et al., 2026). Nevertheless, these latter components remain far less studied and are more difficult to quantify than tourism-related values (Moreno-Gutiérrez et al., 2026; Pagiola et al., 2004). Although the Total Economic Value framework includes several use and non-use components, this study focuses only on reported direct economic values associated with whale shark tourism. Whale shark tourism is now established in various locations across the world, with predictable aggregations supporting the development of this activity (Rowat & Brooks, 2012; Ziegler & Dearden, 2021). Economically, whale shark tourism has the potential to provide economic benefits beyond the direct income received by tour operators since visitors spend money on services such as accommodation, restaurants, transports, retail, and other local businesses, while creating job opportunities in the area (Cagua et al., 2014; Djunaidi et al., 2021; Moreno-Gutiérrez et al., 2026). In addition to financial gains, tourism with these gentle giants can contribute to conservation by generating funds for research, monitoring, and management

and by promoting environmental education (Davis & Tisdell, 1999; Graham, 2003). However, these benefits depend strongly on how tourism is managed (Graham, 2003). At the same time, whale shark tourism also presents risks to the species if it is poorly managed or conducted at high intensity (Catlin et al., 2012). High vessel densities, inappropriate swimmer behaviour and repeated interactions may alter whale shark behaviour, increase energy expenditure and increase the risk of injury (Davis et al., 1997; Reynolds et al., 2025). Thus, the development of whale shark tourism demands an appropriate balance between economic opportunities and the protection of the animals on which the activity depends (Ziegler & Dearden, 2021).

This way, this thesis focuses on whale sharks in Cabo Verde, paying particular attention to Boa Vista Island. The main objectives are analysing the spatiotemporal distribution of tagged whale sharks and evaluate the adequacy of existing MPAs and ISRAs, particularly the ones established around Boa Vista, for the protection of these species. In addition reported economic values from established whale shark tourism destinations were reviewed to provide context for considering the potential for non-consumptive whale shark tourism in Boa Vista. By combining ecological, conservation, and economic approaches, this thesis seeks to provide information to support future whale shark conservation and to inform discussions about the possible development of sustainable tourism in the island.

2. Framework

2.1 Whale shark ecology and conservation

2.1.1 Biology and ecology of the whale shark

The whale shark (*Rhincodon typus*), the biggest fish in the world reaching lengths of 18-20 meters, is a planktivorous elasmobranch harmless to humans (Motta et al., 2010; Pierce et al., 2025; Rowat & Brooks, 2012; Womersley et al., 2024). This species presents a characteristic morphology with a broad and flattened head, a big and nearly terminal mouth and large gill slits, which are specialized for this filter feeder (Figure 1) (Stewart & Wilson, 2005). It has a robust body, which tapers towards the end where the tail is, and a "pattern of light spots, horizontal stripes and vertical bars against a dark background" which can be very useful for photo identification (Brooks et al., 2010; Graham & Roberts, 2007; Stewart & Wilson, 2005, p.184).

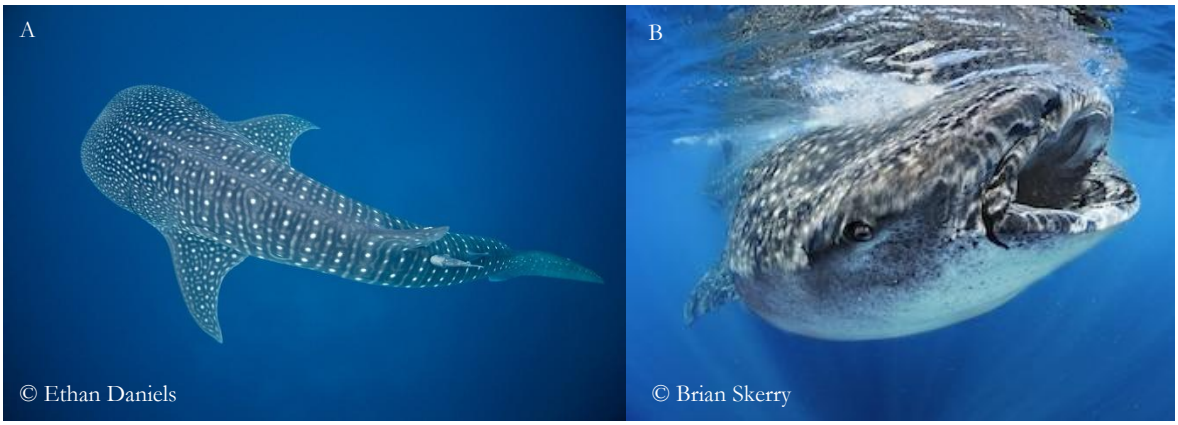


Figure 1. A- Dorsal view showing the characteristic body shape and distinctive pattern of spots and stripes; B- Whale shark feeding at the surface with the mouth open, illustrating its filter-feeding strategy.

The *Rhincodon typus* has complex migratory patterns and can be found in costal or pelagic environments and is distributed in tropical, subtropical and temperate waters, however it is important to mention that there is still very little information regarding movement patterns and how habitats are selected by this species (Colman, 1997; Guzman et al., 2022; Sequeira et al., 2012; Womersley et al., 2024). Different studies have shown that whale sharks demonstrate both horizontal and vertical movements in the water column, although they have a preference for the upper layers (Arrowsmith et al., 2021; Wilson et al., 2006). They

also spent a significant amount of time in the surface waters, with D'Antonio et al. (2024) reporting that tagged individuals passed 50% of the time at a 10 m depth. According to Sequeira et al. (2012), the distribution of this species is influenced by different variables such as the sea surface temperature, chlorophyll concentration and water depth, being these the ones with more impact, while bathymetry appears to have a minor importance. Moreover, the movement of the whale sharks has been related to climatic changes and plankton blooms which affect the availability of food (Compagno, 1984; Reynolds et al., 2024).

In addition, the whale shark is a filter feeder that consumes vast amounts of biomass from the lower levels of the food chain, so it has a very important role in plankton control, for example (Motta et al., 2010; Rowat & Brooks, 2012). Although the ecology knowledge of the whale shark is very limited, the study by Ibarra-García et al. (2017) showed that the whale shark has an important role in the resilience and in the stability of the ecosystems since (as a planktivorous filter feeder) it links lower and higher trophic levels, facilitating the flow of energy across the food chain (Colman, 1997). Although specific information on the whale shark's role in nutrient cycling is still lacking, marine megafauna is known to play a major part in these processes (Estes et al., 2016). Therefore, as a member of this group, and due to its extensive migratory behaviour, the whale shark is also likely to contribute to nutrient cycling within marine ecosystems (Colman, 1997; Estes et al., 2016). It is also an indicator of marine productivity, as its presence is often associated with high food density (Rohner et al., 2018).

2.1.2 Threats and conservation status of the whale shark

2.1.2.1 Anthropogenic pressures and population decline

The scientific and conservation growing interest in the whale shark is partly due to the recognition that populations of this species are declining in various regions because of different factors such as fishing, marine pollution and maritime traffic along with ship collisions (Guzman et al., 2022; Putra et al., 2025; Stewart & Wilson, 2005).

Studies shown that interactions between fishing boats and whale sharks can get them entangled during commercial fishing operations, especially when purse seine are used in fisheries that targets tuna shoals, where this large animal is often found (Capietto et al., 2014; Rowat & Brooks, 2012). While mortality levels recorded may be small, the incidence of bycatch in certain regions can be considered highly threatening, especially since post-release

mortality levels remain unknown and the impact of that on the animal may be sublethal (Capietto et al., 2014).

Besides fishing, the increase in maritime traffic has become another global threat facing whale sharks since over time, commercial shipping routes have increased along with the number of vessels (Rowat et al., 2021; Schoeman et al., 2020). This has led to an overlap between the shipping routes and the areas where the whale sharks are present as demonstrated by Womersley et al. (2022), that showed that whale sharks exhibit a high degree of spatial overlap with maritime traffic, with around 92% of horizontal space use and 50% of vertical space use occurring in areas with large vessels activity, which means that the risk of collisions is very high. This type of collisions is of special concern since they can lead to mortality that in many cases go undetected because of the tendency of such animals to sink (due to their negative buoyancy), leading to an underestimation of the actual number of deaths (Rowat et al., 2021; Womersley et al., 2022).

Also, marine pollution, especially ingestion of plastics, has become an emerging issue (Fossi et al., 2017). While marine pollution may not be considered one of the major anthropogenic stressors, the effect that it may have on whale sharks' wellbeing cannot be underestimated, since they may lead to mortality and population decline (Abreo et al., 2019; Rowat et al., 2021). Given the fact that whale sharks are filter feeders and feed often at the water surface level, their contact with floating plastic is quite high (Fossi et al., 2017; Rowat et al., 2021).

Cases of whale sharks becoming stranded have been reported in many locations around the world, for example in Australia, Indonesia, Philippines, China and in the Eastern Cape and Western Cape and different studies show that this can happen for the factors mentioned above (Abreo et al., 2019; Beckley et al., 1997; Gao et al., 2025; Putra et al., 2025; Speed et al., 2009). According to Abreo et al. (2019) in August 2018, a live whale shark was found stranded in Tagum City but a few hours later died, and a post-mortem test showed the presence of marine debris lodged in its gills, as well as plastic fragments inside the stomach of the whale shark. Although it was not clear whether the consumption of the plastic caused the whale shark death, the research shows the potential risks that marine pollution can pose to this species and highlights the increasing exposure of marine megafauna to anthropogenic debris (Abreo et al., 2019).

2.1.2.2 Conservation status and legal protection

Although whale sharks have inhabited the world's oceans for millions of years, increasing human pressure threatens the survival of this gentle giant that is now classified as Endangered, according to the International Union for Conservation of Nature (IUCN) Red List. Due to its ecological importance and intrinsic value by simply existing, it is extremely important and our responsibility to protect this species (Ibarra-García et al., 2017; Rowat et al., 2021; Ziegler & Dearden, 2021) .

Although there is growing international awareness of the conservation status of whale sharks, adequate protection of this species at an international level has proven difficult (Pierce et al., 2025; Putra et al., 2025). As said before, this species has a highly migratory behaviour and broad distribution, so their conservation requires coordinated management efforts at an international scale (Pierce et al., 2021; Womersley et al., 2024).

As a result, this species has been incorporated into several global conservation frameworks aimed at reducing human-induced threats and promoting long-term population recovery (Pierce et al., 2021). The whale shark is included in Appendix II of the Convention on International Trade in Endangered Species of Wild Fauna and Flora, which according to World Wildlife Fund (n.d.) control or ban international exchange of species under threat in order to prevent overexploitation, and in Appendix I of the Convention on Migratory Species of wild animals, which encourages international collaboration for the conservation of migratory species and their habitats (CITES, 2015; CMS, 2024). Additionally, the United Nations Convention on the Law of the Sea (UNCLOS) and the International Plan of Action for Sharks (IPOA-Sharks) also contribute to whale shark conservation, recognizing this species as highly migratory, highlighting the need for international cooperation in their management and encourages the development of management measures to reduce shark mortality and bycatch (Pierce et al., 2021).

In spite of all the efforts that have been made towards protecting whale sharks through legislation and other methods of conservation, this endangered species still faces many anthropogenic threats (Gao et al., 2025; Stewart & Wilson, 2005). Thus, a range of research and monitoring techniques have become essential tools for informing conservation actions and management decisions (Andrzejaczek et al., 2021). Methods like photo-identification, acoustic telemetry and satellite tracking have helped to understand more about the movement patterns of whale sharks, their preferred habitats, and their spatial ecology

(Acuña-Marrero et al., 2014; Brooks et al., 2010; Guzman et al., 2022). Such information can be used in the implementation of evidence-based conservation initiatives for this species by establishing where they aggregate, migrate, and interact with potential anthropogenic threats (Berumen et al., 2014; Sequeira et al., 2012; Womersley et al., 2022).

2.1.3 Spatial ecology and conservation planning

2.1.3.1 Tracking studies and spatial ecology

Several tracking studies have been conducted on whale sharks from different locations across the globe to generate insights on their spatial ecology (Andrzejaczek et al., 2021; Berumen et al., 2014; Queiroz et al., 2019; Rohner et al., 2018; Womersley et al., 2022). Through tracking, it has been proven that whale sharks have the capacity to migrate over vast distances across oceanic basins, connecting distant aggregating grounds and even crossing national borders (Robinson et al., 2017; Sequeira et al., 2012). According to Berumen et al. (2014), even though the majority of the tagged whale sharks in the Red Sea stayed there, some exhibited wide-ranging movements to the Gulf of Aden and northern Indian Ocean. In addition, Robinson et al. (2017) noted that all tagged whale sharks, crossed international maritime boundaries and some dispersed over considerable distances, with one female travelling more than 2,600 km crossing five international maritime boundaries. These results highlight the need for international and regional collaboration to ensure the conservation of the species, since the existing legal protection in individual territorial waters may not be very effective alone considering such large-scale movements (Bradshaw et al., 2008; Robinson et al., 2017).

Having identified large scale movements, tracking has been equally essential in identifying important habitats that support key ecological roles such as feeding, residency, and seasonality aggregation for whale sharks (Guzman et al., 2022; Rowat & Brooks, 2012). Several important habitats have been established across the Indian Ocean, which form important aggregation sites for juvenile whale sharks (Andrzejaczek et al., 2021; Berumen et al., 2014). Another hotspot is Al Shaheen in the Arabian Gulf which has been identified as an important seasonally aggregating area for whale sharks who feed on tuna spawn (Robinson et al., 2017). The Mozambique Channel has been described as one of the most significant habitats for whale sharks in the Indian Ocean, offering highly suitable environmental conditions that functions as a key hotspot, where individuals may remain for extended periods or even revisit

after extensive oceanic migrations (Pierce et al., 2010; Sequeira et al., 2012). The Ningaloo Reef in Western Australia, is also a whale shark hotspot and is one of the most intensively studied aggregations in the world, however, long-term observations have shown a decline in the abundance of this specie (Bradshaw et al., 2008; Catlin et al., 2012; Davis et al., 1997).

There are also other important habitats for whale sharks in the Pacific and in the Atlantic Ocean (Cárdenas-Palomo et al., 2025; Guzman et al., 2022). In Panama, Coiba National Park and Las Perlas Archipelago have been identified as important foraging grounds and Darwin Island, in the Galápagos Archipelago has been found to be an important environment for adult females, with movement analyses suggesting that it may function as a migratory stop potentially related with reproduction (Acuña-Marrero et al., 2014; Guzman et al., 2022).

Regarding the Atlantic Ocean, the "El Azul" in the Mexican Caribbean and the Gulf of Mexico have already been established as being of great importance, since these locations provide an area for whale sharks that aggregate seasonally due to increased food availability (Cárdenas-Palomo et al., 2025). Additionally, beyond being a foraging area, Saint Helena may also represent a territory of reproductive importance (Clingham et al., 2016). This is supported by the fact that the aggregation includes adult females (supposedly pregnant individuals) mature males and juveniles, and because potential mating behaviour has been observed (Clingham et al., 2016).

Together, these studies indicate that the whale sharks depend on different areas spread out across various oceanic systems, each one serving different ecological roles for this species, such as feeding, residence and migration (Cárdenas-Torres et al., 2007; Guzman et al., 2022; Pierce et al., 2010). However, identifying these areas alone does not necessarily mean that they will be protected, and the main challenge is how to use this information to create effective spatial conservation measures capable of conserving habitats that are essential to whale sharks (Guzman et al., 2022).

2.1.3.2 Spatial conservation measures: Marine Protected Areas (MPAs)

A protected area, according to the International Union for Conservation of Nature (IUCN), is "a clearly defined geographical space, recognised, dedicated and managed, through legal or other effective means, to achieve the long-term conservation of nature with associated ecosystem services and cultural values" (Dudley, 2008, p. 8). Marine Protected

Areas (MPAs) are one of the most common types of spatial conservation mechanisms used to conserve marine biodiversity (MacKeracher et al., 2019; Trotman & Berggren, 2026).

MPAs are created in order to ensure the conservation of marine ecosystems for the long-term (Day et al., 2019). They are not only concerned with the conservation of biodiversity but also with maintaining the integrity of ecosystems, providing ecosystem services, and sustainable use of natural resources (Chin et al., 2023; Sala & Giakoumi, 2018). By regulating human activities such as fishing, coastal development, tourism, and maritime transport, MPAs aim to reduce pressure on ecosystems and contribute to their continued functioning, while conserving biodiversity and meeting human needs (Driedger et al., 2023; Putra et al., 2026).

According to the IUCN, there are six categories of protected area management (Ia–VI), which are distinguished based on their primary management objectives (Dudley, 2008). Thus, different zones can be classified as strictly protected areas, where human intervention is highly limited, to areas where biodiversity conservation is combined with the sustainable use of natural resources (Dudley, 2008; Sala & Giakoumi, 2018). In marine systems, this distinction is particularly relevant, since MPAs can include zones with different levels of protection, ranging from areas where entry or fishing is prohibited to multiple-use zones, depending on the conservation objectives established for each site (Day et al., 2019; Driedger et al., 2023; Frisch & Rizzari, 2019; Gill et al., 2017).

Consequently, the category of a marine protected area will affect the level of protection that marine animals will receive; when it comes to whale sharks, the conservation role of MPAs is based on the protection of the habitats repeatedly used during the different phases of their life cycle (Grorud-Colvert et al., 2021; Valsecchi et al., 2021). Protecting these sites can reduce the anthropogenic pressures in the individuals' and at the same time ensure protection of habitats that are crucial for vital phases of their life cycle (Harvey-Carroll et al., 2021; Putra et al., 2025).

Some MPAs have been established around areas where whale sharks are frequently gathered, serving as a good example of how spatial protection plays an important part in the conservation of this species (Pierce et al., 2021). The establishment of South Ari Atoll Marine Protected Area (Maldives) aims to protect one of the known year-round aggregations of juvenile whale sharks and the Gladden Spit Marine Reserve (Belize) was created in order to protect predictable seasonal aggregations, associated with food availability (Harvey-Carroll et al., 2021; Heyman et al., 2001; Pierce et al., 2021). Besides helping in the conservation of

the whale shark, these areas also serve to protect marine ecosystems that are home to many other species (Heyman et al., 2001). For this very reason, the whale shark can be considered an umbrella species, since protecting its habitats indirectly helps other species that share the same areas (Ibarra-García et al., 2017; Rowat, et al., 2021)

However, while being an important instrument for marine conservation, the effectiveness of MPAs depends largely on how they were implemented (Galveia & Macusi, 2025). In most cases, there is a considerable gap between the legal guarantees provided and the reality (Chung & Zheng, 2026; Galveia & Macusi, 2025). The lack of funds, monitoring system, and mechanisms to enforce management measures can lead to breaches of management plans; that is why some areas can become "paper parks," which is a term used for protected areas that exist legally but provide no protection (Galveia & Macusi, 2025; Gill et al., 2017; Pieraccini et al., 2017; Pierce et al., 2021).

Moreover, the success of MPAs depends not only on their legal establishment but also on how they are received and implemented at the local level (Enthoven, 2025). If these areas place restrictions on fishing or other activities connected with the use of the sea, conflicts may emerge in case the communities that will be affected by these restrictions are not taken into account (Beuret et al., 2025; Dudley, 2008).

It is also necessary to emphasize that MPAs have limitations for the protection of highly migratory species (Breen et al., 2015; MacKeracher et al., 2019). Therefore, while a MPA may be effective in protecting vital areas, much of the lifetime of the individuals will take place outside the protected areas, making them vulnerable to different forms of human threats (Pierce et al., 2021). Furthermore, assessing the effectiveness of MPAs is another challenge, since whale sharks grow slowly and reach sexual maturity late, so the positive effects of conservation measures may take years to become evident (Colman, 1997; MacKeracher et al., 2019; Pierce et al., 2021). Given the difficulty in assessing short-term population outcomes, it is necessary to evaluate the spatial overlap between the animals' locations and existing conservation areas in order to understand the effectiveness of current Marine Protected Areas and, subsequently, identify gaps in the protection of highly migratory species (Cochran et al., 2026; Conners et al., 2022; Putra et al., 2026).

2.1.3.3 Identification of priority areas for shark conservation (ISRAs)

Given the limitations of traditional conservation approaches and the global decline of many shark and ray species, new tools have been developed to support the conservation of this species (Kyne et al., 2023; MacKeracher et al., 2019). The Important Shark and Ray Areas (ISRAs) are "discrete, tri-dimensional portions of habitat, important for one or more shark species, that have the potential to be delineated and managed for conservation" (Hyde et al., 2022, p.3). Such areas have been established in an attempt to cover some of the gaps in marine spatial planning and the current protected areas, which don't necessarily consider the spacial ecological requirements of such animals (Hyde et al., 2022).

The primary goal of ISRAs is to support spatial conservation through the identification of areas that carry out vital roles in the ecology of species (Cochran et al., 2026; Gonzalez-Pestana et al., 2026; Hyde et al., 2022). Instead of only represent places where the sharks and rays appear, ISRAs are supposed to be areas that provide an important role in the survival of the animals, including areas where they can feed, reproduce, rest, or aggregate (Rohner et al., 2025). Through such an approach, it is possible to ensure that spatial conservation planning is not focused only on the size of an area, but more focused, on its ecological significance (Mouton et al., 2025).

An ISRA is identified through a scientific procedure that involves proposing potential sites that are important for sharks and rays based on ecological data, which are then evaluated according to specific criteria (Cochran et al., 2026; IUCN SSC Shark Specialist Group, 2022). Some of the criteria used include the vulnerability of the species present in the areas, the presence of species with a restricted geographic distribution, whether the areas are essential to the life cycle of these animals, and whether there is high biodiversity at the proposed sites (Hyde et al., 2022).

This way, ISRAs provides useful scientific information to support decision-making processes, and can contribute to the review of boundaries for the existing protected areas and to guide the creation of new ones (Armstrong et al., 2025; Gonzalez-Pestana et al., 2026; Mouton et al., 2025; Rohner et al., 2025). It is important to note that ISRAs differ from MPAs since ISRAs do not have any form of legal protection; they are simply areas that provide scientific information and identify where conservation is needed (IUCN SSC Shark Specialist Group, 2022; Rohner et al., 2025).

The ISRA framework has already been used in various parts of the European Atlantic region, such as in Cabo Verde, where some critical areas for sharks and rays were recently

identified, making possible (through spatial overlap between ISRA and MPAs) to determine if the existing conservation measures there cover the habitats of highly migratory species, such as the whale shark (Guzman et al., 2022; Jabado et al., 2025; Rohner et al., 2025).

2.1.4 Conservation context in Cabo Verde and Boa Vista

2.1.4.1 Marine biodiversity and spatial conservation in Cabo Verde and Boa Vista

Cabo Verde is an archipelago that is known for its high marine biodiversity, containing a mix of tropical and subtropical species (Freitas et al., 2019; Larrea et al., 2023).

The marine environment of Cabo Verde is characterized by the presence of several mobile species that have conservation significance such as sharks, rays, marine turtles, and cetaceans (Marco et al., 2012; Orejas et al., 2026; Rosa et al., 2023). In the archipelago, the island of Boa Vista stands out as an important region for marine biodiversity because it offers habitat to some threatened species (Marco et al., 2012; Whiting et al., 2026). Some of its beaches serve as one of the main nesting sites for the loggerhead turtles (*Caretta caretta*) in the eastern Atlantic Ocean and its shallow coastal waters are also important for sharks (Marco et al., 2012; Ramalho et al., 2026). For example, in Sal Rei Bay was identified as a potential shark nursery, where species such as the scalloped hammerhead (*Sphyrna lewini*), blacktip shark (*Carcharhinus limbatus*) and nurse shark (*Ginglymostoma cirratum*) have been recorded (Rosa et al., 2023; Whiting et al., 2026)

The national network of protected areas is one of the major conservation approaches, that include terrestrial, coastal and marine areas that are important habitats and important for conservation of the species (Orejas et al., 2026; Sena et al., 2023). Apart from legally recognized protected areas, Important Shark and Ray Areas (ISRAs) also offer a complementary way of recognizing habitats that are especially important for chondrichthyan species (Hyde et al., 2022; Rohner et al., 2025). Some ISRAs, such as Sal Rei Bay, Sal Rei Reef and João Valente Shelf are located close to Boa Vista (Jabado et al., 2025). Sal Rei Bay has been identified due to its importance for several threatened shark species, as was said before, and Sal Rei Reef is an important habitat for the Critically Endangered sand tiger shark (*Carcharias taurus*) (Jabado et al., 2025; Orejas et al., 2026; Rosa et al., 2023; Varela et al., 2025). João Valente Shelf, situated between Boa Vista and Maio, is recognised for the occurrence of the endemic Cape Verde skate (*Raja herwigi*) (Jabado et al., 2025).

The presence of ecologically important habitats, species and areas of conservation importance around Boa Vista highlights the island's relevance for marine conservation in Cabo Verde (Larrea et al., 2023; Orejas et al., 2026; Rosa et al., 2023).

2.1.4.2 Knowledge gaps for sharks in Cabo Verde

Despite the ecological importance of Cabo Verde for sharks and rays, there is little knowledge regarding the chondrichthyan species in the archipelago (Rosa et al., 2023). Specifically, there is a lack of information on the movement, behaviour and the use of space by those species, which complicates the identification of essential areas and makes it difficult to assess whether current protection measures are effective (Hyde et al., 2022; Whiting et al., 2026). Spatial ecology data obtained through satellite tagging of sharks has recently been available for Cabo Verde, showing not only localized movements, but also connectivity at a larger spatial scale (Coelho et al., 2020; Santos & Coelho, 2018; Seymour et al., 2026). For example, Coelho et al. (2020) showed through tracking that blue sharks and shortfin makos are highly mobile in Cabo Verde, which helped to identify spatial and seasonal patterns of habitat use within and beyond the Cabo Verde region. More recently, Seymour et al. (2026) revealed movement patterns of tiger sharks ranging from movements within the Cabo Verde archipelago to movements towards the African coast and across the Atlantic Ocean. Nonetheless, the amount of data is still quite small and remains available for only a limited number of species (Seymour et al., 2024; Varela et al., 2025; Varela et al., 2026).

2.2 Economic valuation: Theoretical framework and application to whale sharks

2.2.1 Total Economic value

Biodiversity and natural ecosystems contribute to our lives in various ways, most of which are not traded on traditional markets and therefore do not have an observable market price (Millennium Ecosystem Assessment, 2005). Consequently, assessments based on traditional market transactions may fail to account for a significant portion of the benefits associated with natural resources and biodiversity conservation (Millennium Ecosystem Assessment, 2005). The Total Economic Value (TEV) approach, used in environmental economics, offers a way to identify and, in some cases, estimate the market and non-market values of natural resources and biodiversity (Loomis & White, 1996; TEEB, 2010). TEV takes into account different types of values (Figure 2), making it an important approach, especially in the case of endangered species, whose extinction results in losses involving not only ecological consequences but also significant economic and social losses (Loomis & White, 1996; Plottu & Plottu, 2007; Richardson & Loomis, 2009). TEV is generally organized in use and non-use values, even though the exact classification and placement of specific elements may differ in some ways (Pagiola et al., 2004; Turner et al., 2010).

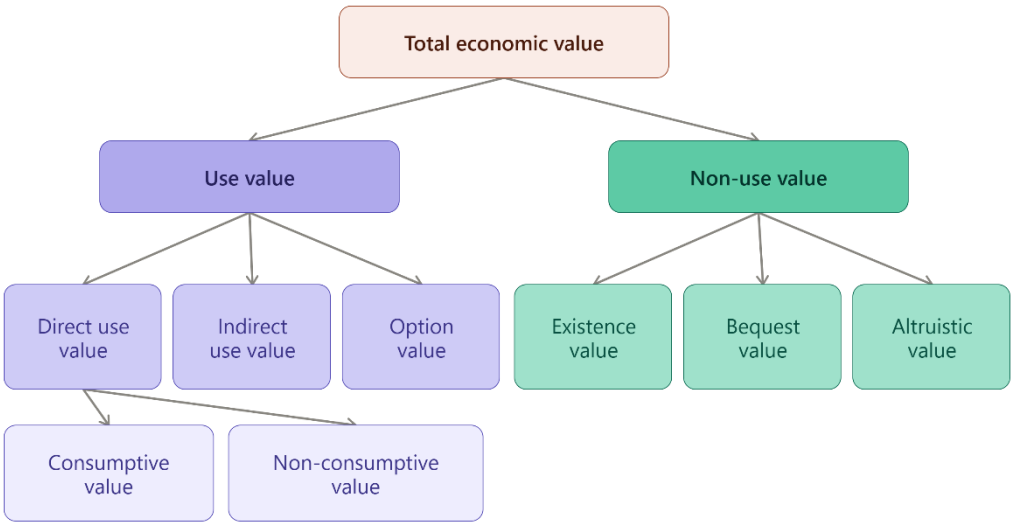


Figure 2. Components of Total Economic Value (TEV), including use and non-use values and their respective subcategories. Adapted from TEEB (2010).

Use values are associated with the actual or potential use of an environmental resource and include direct use, indirect use, and option values (TEEB, 2010). Direct use values are based on the direct contact with natural resources and can be classified into consumptive and non-consumptive values (TEEB, 2010). Consumption ones arise from the extraction or consumption of natural resources, while non-consumptive values are related with the direct use of the natural resource without its removal or consumption (Department for Environment, 2007; Millennium Ecosystem Assessment, 2005; TEEB, 2010). This way, it is possible for a single natural resource to derive economic value while remaining accessible (Pagiola et al., 2004). The indirect use values, however, are related to the ecological roles and processes of an ecosystem that generate benefits, even if we do not use them directly (Department for Environment, 2007; Pagiola et al., 2004; TEEB, 2010). Examples of this use values include the regulating role of an ecosystem in the form of climatic regulation, sequestration of carbon or even the purification of water (Millennium Ecosystem Assessment, 2005). Measurement of indirect use value tends to be challenging in an economic sense since the value obtained is associated with ecological functions rather than the direct use of the resource (Millennium Ecosystem Assessment, 2005; Pagiola et al., 2004). Another type of use values is the option one, that reflects the value associated with preserving an environmental resource and the possibility of using it at some point in the future (Millennium Ecosystem Assessment, 2005; Plottu & Plottu, 2007). The concept is particularly important where environmental degradation or species loss may be irreversible, as conservation preserves the possibility of future uses and benefits that may not yet be fully known (Plottu & Plottu, 2007).

The non-use values refers "to the value humans place on knowing that a natural asset exists, even if they never plan to see or use it" (Catlin et al., 2012, p.94) and can be divided into existence value, bequest value and altruistic value (TEEB, 2010). This type of value is usually measured using the contingent valuation method, which is a technique that uses surveys to create a hypothetical market, with the aim of measuring the willingness to pay (WTP) of different individuals to preserve a natural asset (Loomis & White, 1996; Richardson & Loomis, 2009). The existence value is related to the value of knowing about the existence of the resource, regardless of whether the individual uses the resource or not (Pagiola et al., 2004). Bequest value refers to the value individuals place on the preservation of natural resources and ecosystem services, so that they remain available to future generations (Pagiola et al., 2004). Altruistic value, in turn, reflects the value individuals derive from knowing that other people from the same generation can benefit from those resources or services (TEEB,

2010).

The values discussed above are especially important to biodiversity and for conservation of species because the absence of direct use of a species does not mean an absence of economic value (Loomis & White, 1996; Plottu & Plottu, 2007). In fact, studies about threatened and endangered species show that people may attribute value to their preservation through a combination of use, option, existence and bequest motivations (Loomis & White, 1996).

2.2.2 Economic values associated with whale sharks

Within the Total Economic Value framework, whale sharks can be associated with different forms of economic values (Catlin et al., 2012; Rowat et al., 2021). Historically, the species has been exploited through targeted and incidental fisheries, particularly in parts of Asia, where whale sharks were captured for products including meat, fins and liver oil (Cagua et al., 2014; Chen et al., 1997; Rowat et al., 2021). These activities represent a consumptive direct-use value, as the economic benefit depends on the permanent removal of individuals from its habitat (Cagua et al., 2014; Moreno-Gutiérrez et al., 2026).

In contrast, whale sharks can also generate non-consumptive direct-use value while remaining alive in their natural environment, through tourism (Catlin et al., 2012). Davis et al. (1997), for example, showed that whale shark tourism is highly profitable and showed that the local economies in Exmouth and Coral Bay (two areas that are part of Ningaloo Park in Australia) had a direct injection of 4.7 million australian dollars two years after the whale shark tourism began. In addition, the results of a study in South Ari Atoll, Maldives, showed that the whale shark centred tourism had a significant economic impact, with tourist spending increasing by approximately 1.8 million dollars from 2012 to 2013 (Cagua et al., 2014).

Beyond these uses, whale sharks can also have option and non-use values (Moreno-Gutiérrez et al., 2026). However, compared with tourism related values, these components remain considerably less studied and more difficult to quantify (Moreno-Gutiérrez et al., 2026; Pagiola et al., 2004).

Overall, the economic value that whale sharks have cannot be summed up as merely one price in the market (Moreno-Gutiérrez et al., 2026; Richardson & Loomis, 2009). As already mentioned, whale sharks have economic value in terms of the benefits gained from different types of use, as well as values associated with potential future uses, their continued existence, and their preservation for others and future generations (Cagua et al., 2014;

Loomis & White, 1996; Plottu & Plottu, 2007). Nevertheless, the growth of whale shark tourism has made the direct value of non-consumptive use quite evident, showing how the continued presence of the species can generate a continuous source of economic benefits (Anna & Saputra, 2017; Jones et al., 2009). This can be particularly relevant for decision-makers when considering measures to ensure the protection of suitable habitats for the species (Anna & Saputra, 2017; Jones et al., 2009).

2.2.3 Marine wildlife tourism and ecotourism

In recent decades, tourism has increased in many countries, and several studies show that this has been accompanied by economic growth (Ashley et al., 2007; Ceballos-Lascuráin, 1996; Jin & Gao, 2025; Nguyen & Le, 2026). With the increase in tourism, there has also been a greater offer of jobs in different areas, since tourism stimulates various sectors of the economy, leading to job creation not only in hotels and transports, but also in agriculture and construction (Ashley et al., 2007; Jin & Gao, 2025).

The nature-based tourism is a sector that started to gain a lot of attention in the literature in the late 1980s and has continued to expand ever since then, and besides helping the country's economy, it also helps with conservation (Ceballos-Lascuráin, 1996; Donici & Dumitras, 2024). There are different types of nature-based tourism such as the ecotourism and the wildlife tourism, both of which are growing in different parts of the world (Donici & Dumitras, 2024; Jin & Gao, 2025).

According to Roe et al. (1997, p.11) wildlife tourism can be described as a "tourism that includes, as a principle aim, the consumptive and non-consumptive use of wild animals in natural areas. It may be high volume mass tourism or low volume/low impact tourism, generate high economic returns or low economic returns, be sustainable or unsustainable, domestic or international, and based on day visits or longer stay".

Ecotourism is different, and although is one of the most studied forms of tourism nowadays, there are still different ways to describe it (Donici & Dumitras, 2024; Samal & Dash, 2023). As stated by The International Ecotourism Society (2015), it can be defined as "responsible travel to natural areas that conserves the environment, sustains the well-being of the local people, and involves interpretation and education". With the growth of ecotourism, marine environments have started to play an increasingly important role, resulting in the development of marine ecotourism (Ressurreição, 2025). This term is related to sustainable

activities that include the observation of marine ecosystems and species while contributes to environmental protection and generation of revenues for local communities (Rosmiza et al., 2025; Sakellariadou, 2014; Sidqi et al., 2026). This type of ecotourism integrates different activities such as, whale watching and scuba diving, that by providing direct contact with the ocean can raise awareness of the need to preserve the marine ecosystems (O'Halloran, 2025; Ressurreição, 2025; Sakellariadou, 2014). Marine tourism has been identified as having significant potential to generate economic value at the global and local levels and can be an important economic income earner for a destination (Kuba et al., 2024; Spalding et al., 2017). This value is created through different ways such as visitor spending and the consumer surplus, all of which contribute to economic flow (Deely, 2022; Spalding et al., 2017; Zulpikar et al., 2018). Besides these direct economic impacts, marine tourism can also have multiplier effects on the economy (Amanda et al., 2024; Ressurreição, 2025). Some studies have shown that there are increases in income from tourism and the creation of new business and employment opportunities, which in turn improves revenue and services in the area (Amanda et al., 2024; Rosmiza et al., 2025).

2.2.4 Whale shark tourism

2.2.4.1 Whale shark tourism worldwide

Whale shark tourism emerged in the late 1980s when it started to develop in areas where the existence of the species was predictable, like Ningaloo Reef in Australia and South Ari Atoll in the Maldives (Davis el al., 1997; Ziegler & Dearden, 2021). Since then, it has expanded to different parts of the world, being one of the most popular forms of shark tourism (Reynolds et al., 2025; Ziegler & Dearden, 2021).

Ningaloo Reef continues to be one of the best-known cases of such development, where a seasonal aggregation of whale sharks contributes to a well-developed tourism industry (Catlin et al., 2010; Davis et al., 1997; Davis & Tisdell, 1999; Jones et al., 2009). In 2006, whale shark tourists spent an estimated US$4,51 million at the Ningaloo Coast, including direct spending for the whale shark tour as well as for accommodation, meals, transport, and other tourist expenditures (Jones et al., 2009). In South Ari Atoll, Maldives, whale shark sightings have become an integral part of the marine tourism industry of the country (Cagua et al., 2014; Harvey-Carroll et al., 2021; Valsecchi et al., 2021). According to Cagua et al. (2014), about 72,000–78,000 people went on whale shark tours annually in South Ari Marine

Protected Area, generating direct expenditures of approximately US$7.6 million in 2012 and US$9.4 million in 2013.

The development of this kind of activity may be quite fast when there is a known aggregation close to tourist locations and the case of Holbox Island in Mexico is an example of this (Dearden et al., 2008; Ziegler et al., 2012). Although fishing has been the common occupation of this island for many years, people have started exploiting the aggregation of whale sharks in the area to promote tourism, and right now swimming with the whale sharks there, is one of the main attractions (Ibarra-García et al., 2017; Ziegler et al., 2012).

It can also be shown from Ziegler et al. (2021) that this species can have an impact on the destination choice as well since in this case, tourists that came to observe whale sharks spent more money compared to other tourists that used this service additionally during their stay. Plus, Jones et al. (2009) further found that tourists for whom whale shark encounters were an important motivation for visiting the region tended to spend more, illustrating the capacity of charismatic wildlife to act not only as an attraction but also as a primary destination driver.

The economic impact of this industry varies significantly among locations, depending on factors such as the number of visitors, the seasonality of whale sharks, and the existing tourism model, however, despite the differences, the studies show that whale shark tourism can be a significant economic activity (Cagua et al., 2014; Moreno-Gutiérrez et al., 2026; Prudnikov & Robles-Zavala, 2022; Rowat & Engelhardt, 2007; Ziegler et al., 2019; Ziegler et al., 2021; Ziegler & Dearden, 2021).

This way, it is evident that there has been a significant growth in whale shark tourism, which now extends beyond just a few regions of the world (Prudnikov & Robles-Zavala, 2022; Reynolds et al., 2025). It has grown into a significant industry that has substantial economic value (Anna & Saputra, 2017; Cagua et al., 2014; Ramírez-Macías et al., 2026). Nevertheless, the development of this sector has raised certain questions in relation to the potential benefits for conservation (Ramírez-Macías et al., 2026; Ziegler et al., 2012; Ziegler & Dearden, 2021).

2.2.4.2 Benefits and risks of whale shark tourism

Whale shark tourism can generate important economic, social and conservation benefits, but these advantages are closely linked to the way tourism activities are developed and

managed (Cagua et al., 2014; Davis et al., 1997; Harvey-Carroll et al., 2021; Ziegler et al., 2012; Ziegler et al., 2019).

One clear benefit of whale shark tourism is its economic contribution at local and regional level (Cagua et al., 2014). This type of tourism not only provides economic benefits in terms of direct expenditure but also creates employment chances for the locals as well (Djunaidi et al., 2021; Sidqi et al., 2026). Moreover, besides spending their money on tours, tourists spend money on other services like accommodations and transportation (Cagua et al., 2014; Moreno-Gutiérrez et al., 2026). Apart from the economic effects, the activity may also find application in the domain of environmental education and creation of perceptions regarding how people perceive this animal (Graham, 2003; Ziegler & Dearden, 2021). In many cases, for many people, coming across whale sharks in their natural habitat becomes an unforgettable experience, that can spark curiosity and a desire to learn more about them (Graham, 2003; Ziegler & Dearden, 2021). When this activity is done in an ethical way, it can help visitors leaving with a better understanding and appreciation for this animal (Graham, 2003). Whale shark tourism can also support conservation more directly by generating resources for research, monitoring and management as seen at Ningaloo, where a visitor levy has been used to finance whale shark research, management and education (Davis & Tisdell, 1999).

However, these close encounters could also be disturbing for the animals. Swimming activities and vessels could change whale shark movement and behaviour especially when the animals are disturbed too often (Davis et al., 1997; Reynolds et al., 2025). In Bahía de La Paz, Mexico, about 77% of identified whale sharks had boat-related injuries in 2016 (Ramírez-Macías et al., 2026). Likewise, at Botubarani, Indonesia, 74% of observed whale sharks had visible injuries, with abrasions being usually caused by their interaction with tourism boats (Yasir et al., 2024). Also, at Ningaloo, some whale sharks were more active during their encounter with tourists, meaning that they were spending more energy than the usual (Reynolds et al., 2025).

These threats can be addressed through management strategies that regulate how tourists and boats interact with whale sharks (Ziegler & Dearden, 2021). These strategies should focus on controlling the number of swimmers and boats allowed to engage with a single whale shark, setting distances from the sharks, limiting encounter durations, and making sure there is no physical contact or hindering of the movements of the animals (Davis et al., 1997; Legaspi et al., 2020). This way, the sustainability of whale shark tourism lies in

making sure that all the gains made do not compromise the health of these amazing animals (Ziegler & Dearden, 2021).

3. Methods

3.1 Study area

This study was conducted in Cabo Verde, an archipelago located in the Atlantic Ocean, with a focus on the island of Boa Vista. This is one of the easternmost islands in the archipelago and is characterized by extensive coastal and marine habitats that are home to various species of marine megafauna, including the whale shark. This location was selected as the primary study area because whale sharks were tagged here, providing the spatial context to assess the movements of whale sharks, their habitat use, and whether existing conservation measures take this species into account.

At the national level, the Cabo Verde's Exclusive Economic Zone (EEZ) served as a marine spatial reference for the analysis of the distribution and conservation coverage of whale sharks (Figure 3A). In order to get a more detailed picture of whale shark spatial use near the archipelago, the outer limit of Cabo Verde's territorial sea was used as an additional tool for defining the spatial extent. In this study, this referred to a single polygon defined by the outermost 12-nautical-mile boundary encompassing the entire Cabo Verde archipelago, with all waters enclosed within this boundary (Figure 3B). The maritime boundaries data were sourced from Marine Regions (Flanders Marine Institute, 2023).

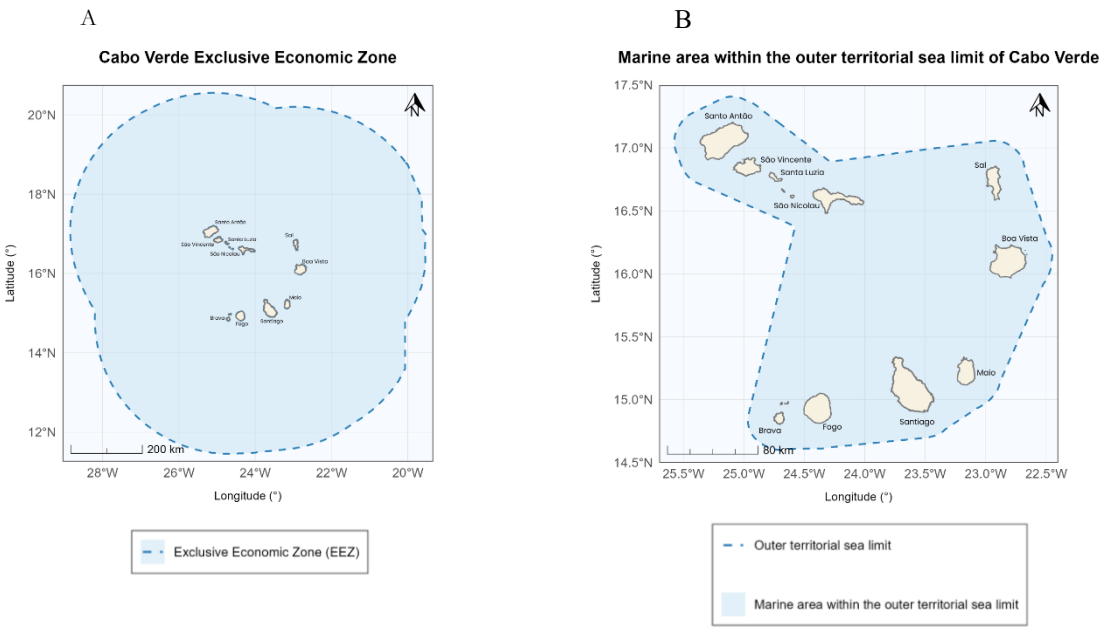


Figure 3. Study area in Cabo Verde. (A) Cabo Verde's Exclusive Economic Zone (EEZ). (B) Marine area enclosed by the outer limit of the territorial sea

3.2 Satellite tracking data

Satellite tracking data were obtained from whale sharks tagged in the waters surrounding Boa Vista Island. In total, eight individuals were tagged between 2024 and 2025 using SPOT satellite transmitters. However, one individual was excluded from this analysis because it provided less than five locations, resulting in a final dataset of seven whale sharks: three males, three females and one individual of unknown sex. The tracking period analysed in this study started in September 2024 and ended in March 2026. The initial dataset consisted of locations obtained by the Argos system, which included date, time, latitude, longitude, and location class (LC 3, 2, 1, 0, A, B, and Z). Since this data was received in raw form, it was processed before spatial analysis. The cleaning, filtering, and interpolation procedures were performed in RStudio and are described in the following section.

3.3 Argos data processing and interpolation

An R script was developed to process the dataset, and the first step was to filter the data by individual and by the validity of the coordinates and the class of the ARGOS locations. Individuals with fewer than five valid locations were excluded from the analysis, as they did not provide sufficient data for accurate movement modelling. Locations with invalid coordinates and all locations belonging to Argos Location Class Z (which represents invalid locations with no information or accuracy) were also removed. Next, the aniMotum package version 1.2.14 (Jonsen et al., 2023) was used for modelling, and the "Move persistence model" was fitted to the trajectories, taking into account the temporal autocorrelation of consecutive locations and the irregularity of Argos transmissions. The tracks were standardized to a 24-hour time interval, creating a matrix of one estimated location per individual per day. The maximum swimming speed was set as 2 m/s to exclude biologically impossible movements. Following this, the time interval between positions was analysed, and in cases where the gap between two consecutive locations exceeded three days, no interpolation was performed. This was done to ensure consistency in the trajectories of the daily positions, in order to avoid unrealistic movement segments. Next, the trajectories were reviewed to check for any positions located on land or unrealistic movement segments that crossed land.

Whenever necessary, the trajectories were re-routed to avoid crossing land. This correction was performed using the pathroutr package version 0.2.1 (London, 2020) with land polygons used as barriers, so that land-crossing segments were adjusted rather than manually

moved. Initial positions located on land were also removed before the final dataset was selected for subsequent analysis. Only the final validated daily positions per individual were kept and used in other analyses such as descriptive mapping, kernel density estimation and spatial overlap analysis with Marine Protected Areas and Important Shark and Ray Areas.

3.4 Descriptive mapping of whale shark positions

3.4.1 Global and zoomed visualisation

Once data processing and track standardization were done, the final positions were plotted on a global map to visually inspect the general spatial distribution of the tagged whale sharks. A second map was then created after plotting the data on a smaller extent covering the main range of all the individuals. This provided a better visualization of the areas used by the whale sharks. The same mapping procedure was also applied by month and by season to describe temporal variation in spatial use. The monthly analysis was conducted by calendar month, grouping the positions across the years of the study. Because the tracking periods did not have equal temporal coverage across the years, some calendar months were represented in more than one year, while others were represented in just one year. The seasonal and monthly analyses were interpreted descriptively rather than as standardized estimates of proportional use, as individuals contributed different numbers of tracking days, resulting in unequal temporal effort among individuals, months and seasons. The dry season was defined as November to June, and the wet season as July to October (Varela-Lopes & Molion, 2014). All maps were created in RStudio using spatial and graphics packages such as sf version 1.1.2 (Pebesma, 2018) and ggplot2 version 4.0.3 (Wickham, 2016), and the whale shark locations were plotted as spatial point data using their longitude and latitude coordinates in WGS84.

3.4.2 Cabo Verde scale mapping

Descriptive maps at the Cabo Verde spatial scale involved the initial mapping of the locations of whale sharks at the larger national level with reference to the Exclusive Economic Zone (EEZ) of Cabo Verde. The map gave an overview of the spatial distribution of within Cabo Verde waters and provided a way of visualizing the locations across the archipelago. To create a more detailed depiction of the space use around the archipelago, another map was created using the outer boundary of Cabo Verde's territorial sea as the spatial

reference. Together, these maps helped to create a visual representation of the distribution of whale sharks at two complementary spatial scales, from the broader EEZ scale to a finer coastal scale.

3.5 Conservation layers and point-based overlap

Spatial conservation layers were included in this study to determine the connection between the positions of whale sharks and the Marine Protected Areas (MPAs) as well as the Important Shark and Rays Areas (ISRAs). The MPAs shapefile was provided by the team members, and the ISRAs shapefile was obtained from the official ISRA website. In these maps, the EEZ was used as a reference and, once again, the external boundary of Cabo Verde's territorial sea was included as a spatial layer for a better visualization of the overlap between the positions and the MPAs and ISRAs.

The layers were all imported into R studio as polygon data, which were then transformed to a common geographic coordinate system and validated geometrically before proceeding to further analysis. For the layer with MPAs, we retained the areas that had a marine part.

For Cabo Verde, the overlap based on whale shark locations was assessed using the daily final positions of the individuals. Spatial overlap tests were conducted to see if the positions were inside or outside an MPA or an ISRA. In this case, the location was classified into either "inside MPA" or "outside MPA", and "inside ISRA" or "outside ISRA". These classifications were used to calculate the number and percentage of whale shark positions occurring inside and outside MPAs and ISRAs.

3.6 Movement and temporal summary metrics

Additional temporal and movement summary measures were calculated to complement the spatial analysis. More specifically, latitude was analysed to describe north-south variation in the positions of whale sharks over time, and the cumulative distance travelled was measured to provide a minimum descriptive measure of the extent of each individual's movement during the analysis period. The cumulative distance was measured individually as a sum of the distances between successive daily positions However, to avoid overestimating

movement during long periods with no available positions, distances between consecutive positions separated by more than three days were not included in the cumulative distance. These gaps were shown as breaks in the cumulative-distance plot.

This measure provided an estimate of minimum cumulative distance travelled by each individual. Because cumulative distance is influenced by tracking duration, this measure was interpreted descriptively and in relation to the number of tracking days available for each individual. The cumulative distance was plotted by individual along a chronological monthly time axis to assist in the analysis of temporal and individual differences in travel distances. These variables were used as auxiliary descriptors of the satellite telemetry dataset.

3.7 Grid-based spatial use and kernel density estimation

To determine the spatial use of the whale sharks within the EEZ of Cabo Verde, only the final positions falling inside that area were selected for the grid analysis process.

A regular fixed grid consisting of 25 × 25 km cells was created within the spatial area covered by the Cabo Verde's EEZ. The same grid was kept identical for all the individuals and subsequent temporal analyses to allow direct spatial comparison. All the final daily positions of the whale sharks were allocated to the corresponding grid cell. For each of the seven whale sharks, the number of final daily positions recorded in each grid cell was counted separately. When cells had no positions, a position count of zero was assigned. This resulted in seven individual grids, in which the cell values represented the number of daily final positions recorded for each shark.

Individual grid maps were produced to show the distribution of position counts across the 25 × 25 km grid. Subsequently, an aggregated grid map was also created, in which the positions of all individuals in each cell were summed, representing the total number of final daily positions recorded per 25 × 25 km cell. The mean spatial use grid was then determined based on the counts per cell per individual. For each cell, the sum of the positions of all seven individuals were obtained, and the average was calculated by dividing the sum of the positions by the number of individuals (n = 7). Individuals who did not use any specific cell contributed a count of zero to the average for that particular cell. Only cells with a mean position count greater than zero were included as weighted input points in the subsequent KDE analysis. The KDE was therefore calculated from the centroids of the 25 × 25 km cells, weighted by their respective mean position counts, rather than directly from the final

daily positions. However, the exclusion of cells with a mean position count of zero should not be interpreted as indicating unavailable habitat.

The same grid-based procedure was repeated separately for the dry season and for the wet season. Seasonal mean cell use was then calculated by summing the individual position counts in each cell and dividing by the seven tracked individuals, as all seven whale sharks had tracking data during both seasons. The monthly spatial use by the individuals was calculated through the same fixed grid, with locations grouped according to their respective calendar months. However, since the number of individuals with available data varied from one month to another, the mean was calculated by dividing the sum of the individual position counts within each cell for the number of individuals with tracking data on the respective calendar month. The individuals who had available tracking data on the respective month were included in the calculation even if none of their positions occurred within the Cabo Verde's EEZ, in which case they contributed a value of zero to all EEZ grid cells. On the other hand, the individuals who lacked any tracking data on that month would not be included in the denominator of the monthly mean. In summary, an individual was included in the monthly mean calculation whenever tracking data was available for that individual during the respective month and excluded only when no tracking data was available for that individual in that month.

Weighted kernel density estimation maps (KDEs) were then created based on the overall, seasonal and monthly mean grids. For each grid, the cells with an average number of positions greater than zero were represented by their geometric centroids, using the corresponding average number of positions as the weight for each centroid. The KDE analysis was conducted utilizing the packages spatstat.geom version 3.6.0 and spatstat.explore version 3.5.3 (Baddeley et al., 2015). A continuous utilization density surface was obtained for the KDE indicating the relative level of spatial use in the study area. Utilization isopleths for 50%, 80%, 95%, and 99% were determined based on the obtained density estimates, and these were turned into polygons. The 50% isopleth was used to describe the core-use area for the whale sharks, while the 95% isopleth was considered to be the utilization distribution for them. Isopleths of 80% and 99% were kept in order to have more information about the spatial utilization distribution. In addition, a 100% minimum convex polygon (MCP) was determined from the final daily whale shark positions which represented the largest total area covered by all the recorded positions of the whale sharks. A sensitivity test was conducted to determine the effect of different bandwidths on the outcome of the KDEs (Kie, 2013).

This involved the use of fixed bandwidths of 5, 8, 10, 15 and 20 km, and a reference bandwidth (href*)*. The bandwidth reference value was calculated based on the coordinates of the centroids of the grid cells included in each KDE. First, the variance of the x and y coordinates of all centroids was calculated; then the mean of these two values was calculated and the square root was taken (which corresponds to the spatial standard deviation of the centroids). This value was then multiplied by a factor based on the total number of centroids, with larger numbers of centroids resulting in a smaller adjustment factor. This was calculated separately for the overall dataset, for each season, and for each month. Smaller bandwidths resulted in more fragmented utilization distributions, and bigger bandwidths produced more spatially coherent isopleths. The 20 km bandwidth was selected for the final analyses because it produced less fragmented utilization distributions while preserving the main spatial patterns observed across the alternative bandwidths.

Some descriptive metrics were calculated for the overall, monthly and seasonal KDEs such as the areas of the 50% core-use area and the 95% utilization distribution, the percentage of the Cabo Verde's EEZ represented by each of these spatial estimates, and the number of individuals with positions inside the 50% core-use area and the 95% utilization distribution.

3.8 KDE overlap and spatial coverage metrics

Prior to the overlap analysis, the overall KDE that was created in an earlier step was clipped to the marine area enclosed by the outer limit of Cabo Verde's territorial sea. Although the KDE was calculated using all final positions within Cabo Verde's EEZ, only the portion of the KDE falling within this outer-limit area was used for the analysis of the spatial relation between the space used by whale sharks and the conservation areas. The resulting intersection was then used to calculate the percentage of the utilization distribution and core-use area that were overlapping with the MPAs and with ISRAs. The same overlap metrics were also calculated at the Boa Vista scale, focusing on overlap with Boa Vista MPAs and ISRAs. Other spatial metrics were also calculated including the proportion of the 50% core-use area and 95% utilization distribution located within the marine area enclosed by the outer limit of Cabo Verde's territorial sea, the % of that marine area occupied by each spatial estimate, the % of that marine area covered by MPAs and ISRAs, and the percentage of the Cabo Verde's EEZ covered by MPAs and ISRAs.

3.9 Economic assessment approach

In order to evaluate the possible relevance of whale shark tourism for Boa Vista, an economic assessment was carried out using scientific literature. Such an assessment reported monetary values related to whale shark tourism at other destinations. Given that whale shark tourism has not yet been developed in Boa Vista, and no local economic study had been carried out, this study was not designed to estimate the current income from tourism on the island. The assessment was only conducted to collect and analyse economic data related to other destinations hosting whale shark tourism, providing context for a preliminary discussion of whether similar tourism could be possible in Boa Vista in the future. The economic assessment consisted in four stages: literature research and selection of studies, data extraction of tourism and economic variables, currency conversion to USD, and an interpretation of the values reported in the reviewed studies.

3.9.1 Literature search

A structured literature review was carried out using Scopus and Web of Science databases to find articles which provide monetary values related to whale shark tourism. The database search was conducted in May 2026, and only studies published in Portuguese, English and Spanish were considered. Given the limited literature specifically addressing the economic value of whale shark tourism, broad eligibility criteria regarding publication type were adopted to capture as much relevant evidence as possible. Therefore, peer-reviewed journal articles, conference papers, institutional reports or case studies, doctoral theses, and preprints were eligible for inclusion. The search strategy included a combination of three sets of keywords: whale shark-related keywords, tourism/recreation-related keywords, and economic valuation-related keywords; the same combinations were used in each of the two databases. The full search strings used in each database are listed in Appendix A.

After the database search, the duplicates were removed and the titles, abstracts and keywords were used to evaluate the relevance of the articles. Studies that provided primary monetary values (original economic values generated by the study itself), related to whale shark tourism were selected. These included values per tourist for only whale shark tourism activity or for the whole tourist trip, as well as annual direct income or expenditure (again, whether these are expenses specific to the activity or more general travel-related expenses).

The studies were then selected for data extraction. In addition, snowballing was

conducted to extract references from the selected articles and identify additional sources that might be relevant for providing primary monetary data on whale shark-related tourism.

The screening process was conducted by the author and to help better understand this process a flowchart was created (Figure 4).

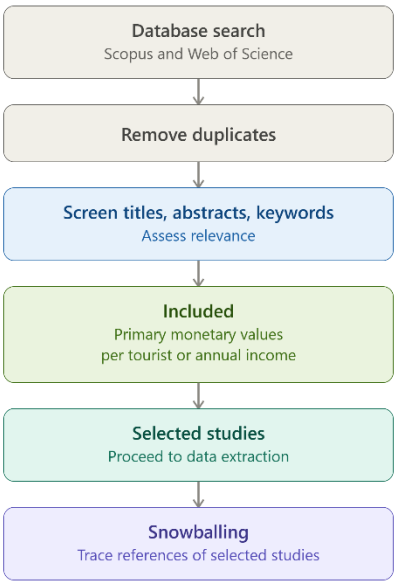


Figure 4. Flowchart of the literature review process for identifying studies with monetary values related to whale shark tourism data.

3.9.2 Data extraction

Data from the chosen studies were extracted manually using an Excel spreadsheet for data analysis. The excel sheet was divided into six main categories: study identification, study location, whale shark biology and ecology, tourism characteristics, methodological approach and economic data. Subsequently, a simplified sheet was developed, based on the variables that are more important for the objectives of this study. In this final sheet, the study identification included the author and year of publication. Location variables included the country, specific study location, whether the site was island-based or continental, and national GDP per capita (current US dollars), that was obtained from the World Development Indicators of World Bank. The reference year corresponded to the year in which the economic data used in each study were collected. For studies covering more than one year, GDP

per capita values for the corresponding years were considered. Ecological variables included the type of whale shark aggregation and the reported number of whale sharks associated with each study site. Depending on the information available in each study, this represented either an estimate of local aggregation size or the number of identified individuals, rather than an estimate of the overall whale shark population. Tourism variables included the annual number of whale shark tourists, the reference period of the tourism data, and the average whale shark tour price in USD. Economic variables were extracted according to the type of monetary value reported. These included the reference year of the monetary value, value per tourist and annual direct economic values associated with whale shark tourism (always in USD).

These values were categorized in two groups, which were activity-based values and total trip values. The activity-based values were directly associated with the whale shark tourism activity itself; and the total trip values were associated with whale shark tourism beyond the activity itself. However, in the case of total trip values, there was variation across articles regarding the exact components included in this category. In some cases, total trip values included accommodation, food, transport, souvenirs or other local expenditure, whereas in other cases only some of these components were reported.

In certain cases, annual direct economic values were not provided in the studies but could be determined through the data given by the authors. If the annual number of whale shark tourists and the value per tourist were presented for the same study site and referred to the same year, annual economic values were calculated by multiplying these two factors. This was done separately for activity-based values and total trip values:

Annual direct value **(activity only) =** annual number of whale shark tourists × value per tourist (activity only)
Annual direct value **(total trip-related) =** annual number of whale shark tourists × value per tourist (total trip-related)

Values calculated in this study were clearly identified in blue to distinguish them from values directly reported in the original studies. Missing or unavailable information was recorded as not reported.

3.9.3 Currency conversion

All monetary values presented in the table are expressed in USD, and refer to the original year reported in each study. If values were reported in currencies other than USD, then they were converted to USD based on the exchange rate in the year of reference for the monetary value, obtained from the World Development Indicators of World Bank (Official exchange rate, LCU per US$, period average). This approach was used to ensure that all monetary values were represented in the same monetary unit. However, no discount adjustment was performed.

3.9.4 Contextual interpretation for Boa Vista

The data sourced from literature were used to set the context for the discussion of possible future development of whale shark tourism activities in Boa Vista. Rather than presenting economic scenarios, the analysis focused on identifying the monetary values recorded at other destinations related to this type of tourism and on assessing how those examples might contribute to the debate on developing this type of tourism in Boa Vista. Values based on activities alone were treated separately from those based on the entire trip and the values per tourist were also distinguished from annual direct economic values. The interpretation considered the context in which the values of whale shark tourism had been described as well, specifically whether the study sites were situated on an island or in a continental setting, whether there was any seasonal occurrence of whale sharks, and whether the site had any conservation status. This was not intended to imply that the exact economic impacts would arise in Boa Vista, but rather to consider if this type of tourism could be a possible non-consumptive use of the species. The interpretation was therefore limited to the monetary values considered in this review and did not encompass other dimensions of economic value, such as option and non-use values.

4. Results

4.1 Satellite tracking dataset and data processing

In total, there were seven whale sharks included in the final dataset, with their tracking periods varying from September 2024 to March 2026. According to Table 1 the tracking duration of individual sharks varied from 127 to 417 days with an average tracking duration of about 274 days. In total, there were 2542 initial Argos positions in the database considering all the individuals. However, the number of the Argos positions was quite different for each shark, varying from 67 to 810.

After processing and modelling the Argos data and removing interpolated locations associated with gaps exceeding the specified threshold of three days, 991 final daily positions remained for subsequent spatial analyses. The number of final positions per shark varied from 40 to 188, reflecting differences in tracking duration and data availability (Table 1).

Table 1. Summary of whale shark tracking data.

Shark ID	Sex	Tracking start	Tracking end	Tracking duration (days)	Raw Argos positions	Final positions
202934	Male	14/03/25	28/11/25	258	145	96
202935	Female	28/09/24	22/06/25	266	382	172
205138	Female	15/01/25	07/01/26	357	67	40
205139	Unknown	08/01/25	01/03/26	417	468	188
205140	Female	14/04/25	27/01/26	288	289	185
205143	Male	05/05/25	28/11/25	207	381	185
205144	Male	17/09/25	22/01/26	127	810	125
				TOTAL:	**2542**	**991**

4.2 Spatial distribution of whale shark positions

4.2.1 Global distribution and movements

Tracked whale sharks exhibited a wide-ranging distribution in the North Atlantic Ocean over the study period (Figure 5). Most positions were recorded in the eastern part of the North Atlantic Ocean, particularly near the Cabo Verde archipelago. Nevertheless, two individuals moved farther north and had positions near Azores.

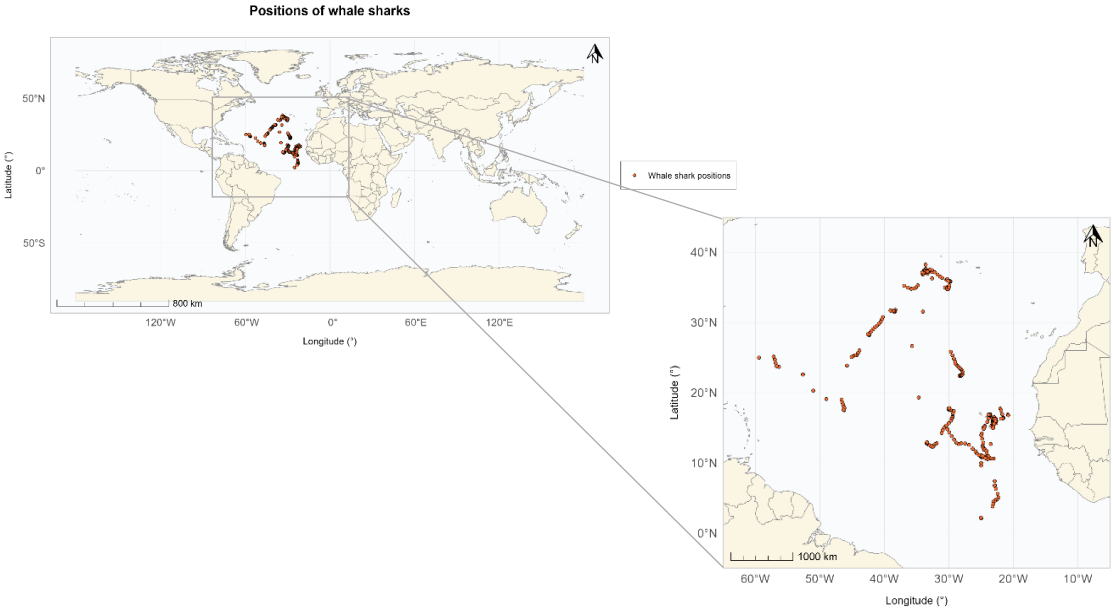


Figure 5. Positions of the seven tagged whale sharks.

The number of positions was quite different from month to month (Figure 6). The same figure shows the maximum number of positions occurred in November when there were 156 positions recorded by seven individuals. On the other hand, the minimum number of positions recorded was in February and September, when there were 52 and 53 positions contributed by two and five whale sharks, respectively.

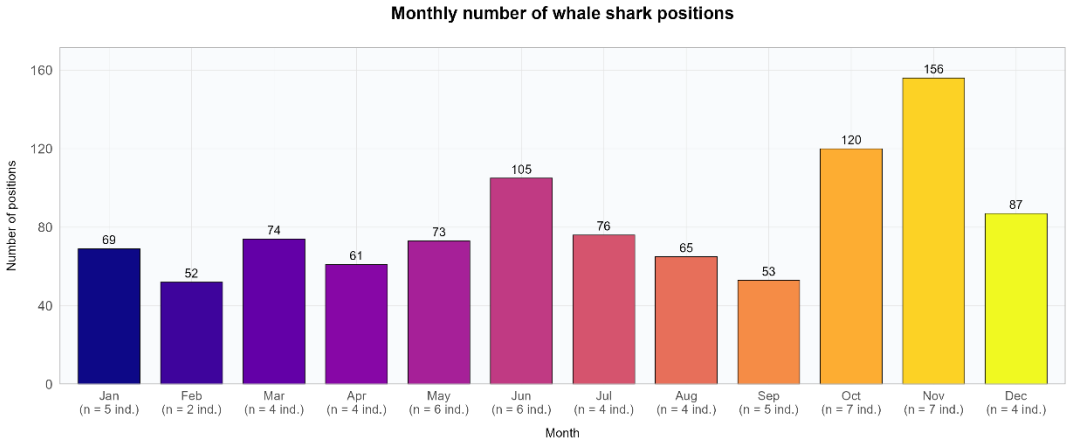


Figure 6. Monthly number of whale shark positions and individuals, pooled across years.

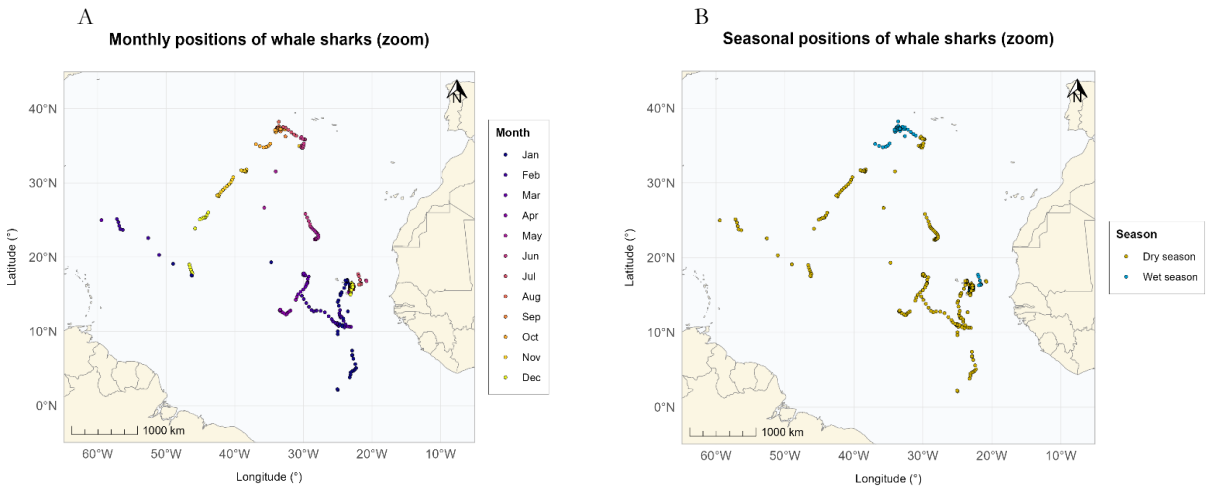


Figure 7. Monthly (A) and seasonal (B) positions of the seven tagged whale sharks.

Regarding the seasonal analysis, the seven whale sharks in the study were present during both seasons. Figure 7B showed that more positions were recorded during the dry season, with 677 positions, compared to only 314 during the wet season.

Nevertheless, the variations between the number of positions per month and season need to be interpreted with caution, as temporal sampling effort was uneven. The whale sharks were tagged at different times, and the periods of tracking were different between individuals. Moreover, positions were categorized according to calendar month over the whole period of research, which means that some months were represented in more than one year, while others were sampled only once (Figure 8). Thus, months and seasons with more locations can reflect more data availability and not differences in the occurrence or spatial use of whale sharks.

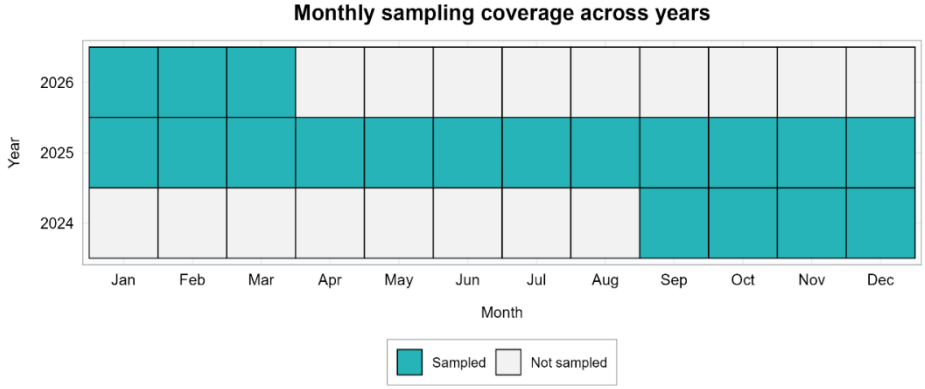


Figure 8. Temporal sampling coverage by month across the study period, indicating months represented by a single year and those represented by multiple years.

4.2.2 Distribution and point-based conservation overlap within Cabo Verde

Considering the Exclusive Economic Zone (EEZ) of Cabo Verde, 771 positions of the seven whale sharks were recorded there, indicating that most of the positions were in that area (Figure 9). Since most of the positions were concentrated between the islands, specifically near Boa Vista it was decided to zoom in using the outer limit of the territorial sea of Cabo Verde to provide a clearer view of the distribution of positions and their spatial relationship with Marine Protected Areas (MPAs) and Important Shark and Ray Areas (ISRAs) (Figure 10 and Figure 11).

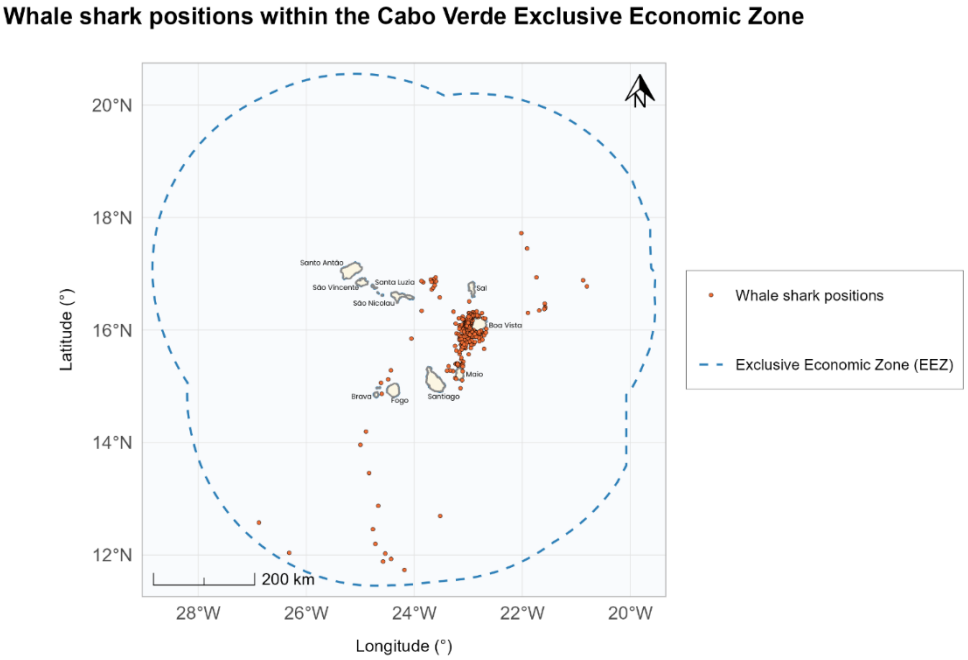


Figure 9. Whale sharks' positions within the Cabo Verde's Exclusive Economic Zone.

Overlap analysis based on point data indicated that 21 positions, representing 2.7% of all positions recorded in the Cabo Verde's EEZ, overlapped an MPA (Figure 10). Five out of seven tagged whale sharks had at least one position inside a protected area. Regarding overlap with ISRAs and the positions, 180 (23.3% of all positions within the Cabo Verde's EEZ) occurred within ISRAs, with six individuals having at least one position there (Figure 11). Among the MPAs where whale shark positions were recorded, the Tartaruga Natural Reserve in Boa Vista had the highest number of positions (n = 12), involving three of the tracked individuals. Among the ISRAs containing whale shark positions, João Valente Shelf,

located between Maio and Boa Vista islands, had the highest number of positions (n = 138), representing positions of six whale sharks.

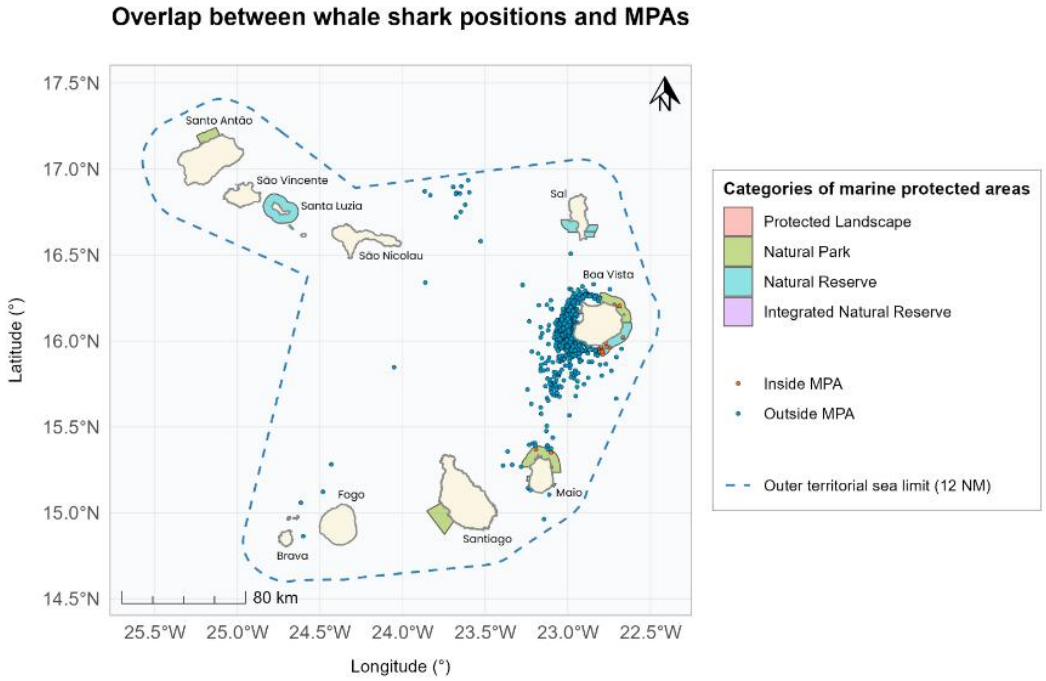


Figure 10. Spatial distribution of whale shark positions and their overlap with Marine Protected Areas within the area displayed using the outer limit of Cabo Verde's territorial sea.

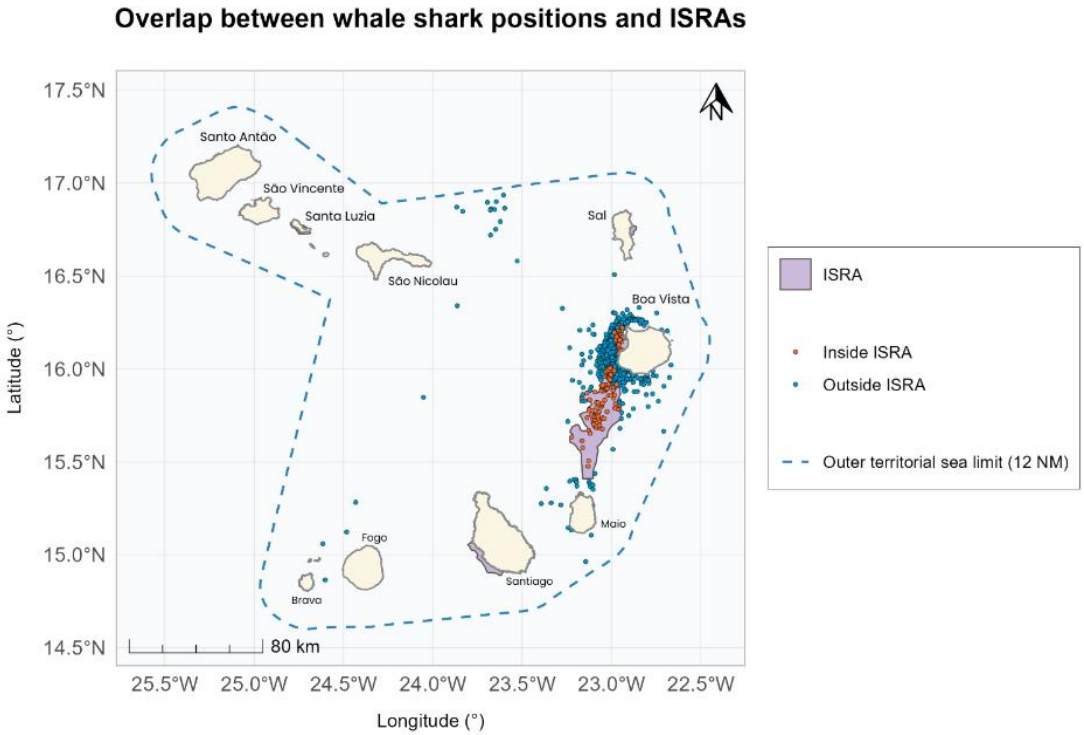


Figure 11. Spatial distribution of whale shark positions and their overlap with Important Shark and Ray Areas within the area displayed using the outer limit of Cabo Verde's territorial sea.

4.3 Movement and temporal patterns

The cumulative movement distance differed between the seven tagged whale sharks (Figure 12). The highest cumulative movement distance was recorded for individual 205139, where it exceeded 4,000 km within the tracking period, while the second highest was recorded for individual 205144, reaching approximately 2,000 km. For the other individuals, their total movement distances were much lower, remaining below 1,500 km.

Mean latitude during the dry and wet seasons also varied widely for different individuals (Figure 13). For the majority of tagged whale sharks, the average latitude was broadly similar between seasons, generally remaining around 16° N. Really small differences was observed in latitude between seasons for individuals 202934, 202935, 205140 and 205143. However, individual 205144 shifted its latitude further north, moving from approximately 14° N during the dry season to 16º N in the wet season. The clearest seasonal difference was observed for whale sharks 205138 and 205139. In both cases, a marked increase in the mean latitude occurred during the wet season, from about 20º N and 22° N during the dry season, to 37° N during the wet season. The individual that had the highest cumulative movement distance, also showed the highest mean latitude during the wet season. However, this observation is descriptive, as the relationship between cumulative movement distance and seasonal differences in latitude was not formally tested.

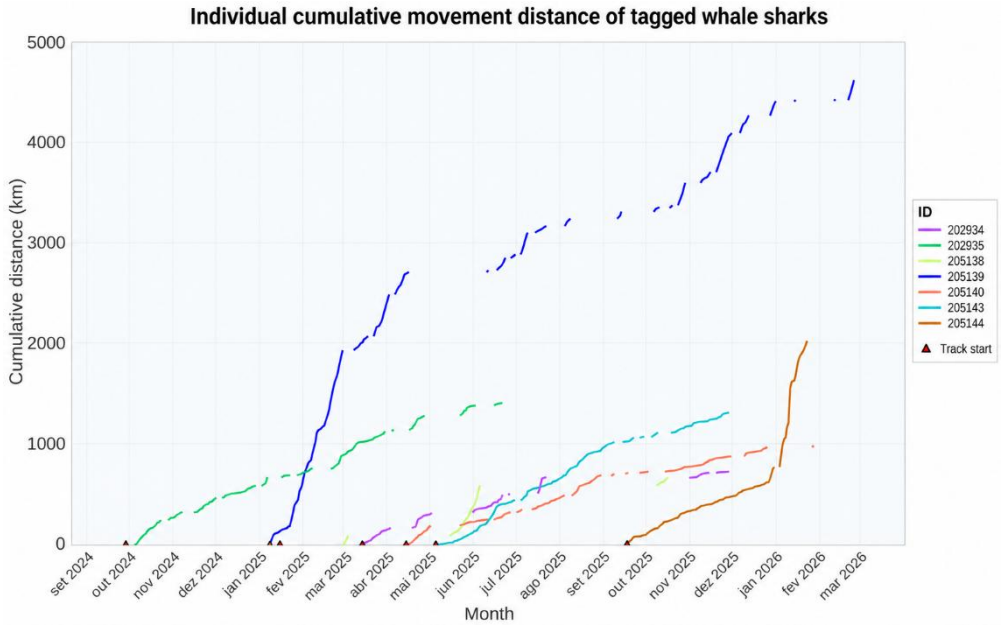


Figure 12. Individual cumulative movement distance of tagged whale sharks over time. Distances between consecutive positions separated by more than three days were excluded from the cumulative calculation and are therefore shown as gaps in the lines.

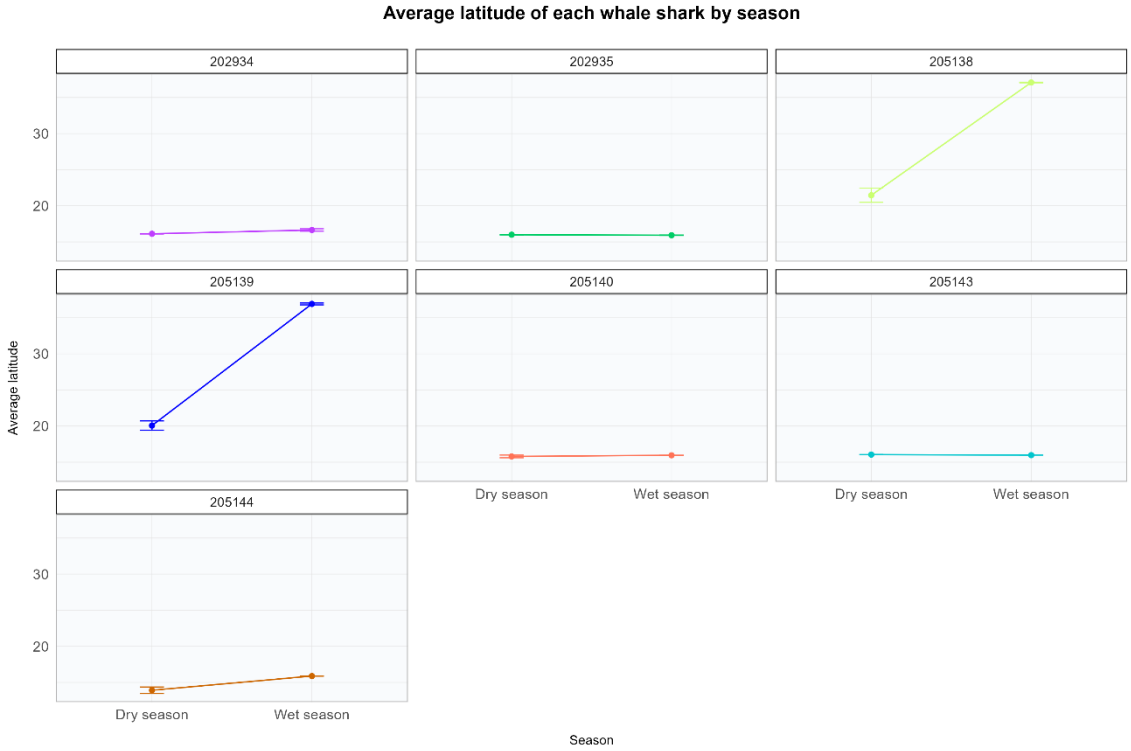


Figure 13. Average latitude of each tagged whale shark in each season.

4.4 Kernel density estimation of spatial use

4.4.1 Overall spatial use

The overall kernel density (KDE) estimation showed a concentration of spatial use in the eastern region of the archipelago, particularly around Boa Vista (Figure 14). The 95% utilization distribution was concentrated in the eastern region of the archipelago, extending between the islands of Boa Vista, Sal, and Maio, and covered an area of 27,514.95 km², which represented 3.42% of Cabo Verde's EEZ. However, when we analysed the 50% core-use area, it showed a more concentrated distribution around Boa Vista. The 50% core-use area covered 2,693.22 km², which represents only 0.33% of the EEZ (Table 2).

All seven whale sharks with position data within the Cabo Verde's EEZ had at least one position within both the 50% core-use area and the 95% utilization distribution. The 50% core-use area represented 9.79% of the area encompassed by the 95% utilization distribution, indicating a strong concentration of estimated use within a relatively small area. The other isopleths helped describe the overall spatial distribution. The 80% isopleth

extended beyond the 50% core-use area, encompassing a broader area around Boa Vista, whereas the 99% isopleth encompassed a broader and more spatially dispersed distribution across the Cabo Verde's EEZ. Regarding the 100% minimum convex polygon (MCP), it linked the outermost recorded positions, providing a complementary representation of the maximum spatial extent represented by the recorded positions.

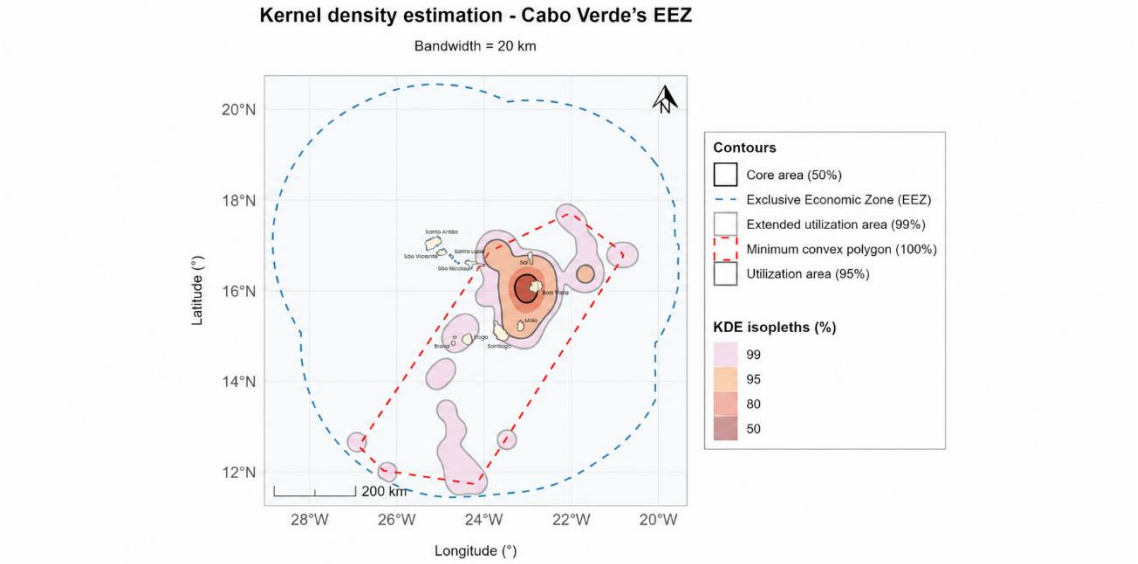


Figure 14. Kernel density estimation of whale shark space use within Cabo Verde's Exclusive Economic Zone.

Table 2. Spatial metrics of whale shark kernel density estimation within Cabo Verde's Exclusive Economic Zone.

Spatial estimate	**Area (km²)**	**% of Cabo Verde's EEZ**	**No. of individuals with positions inside**
50% KDE – Core-use area	2693.22	0.33	7
95% KDE – Utilization distribution	27514.95	3.42	7

4.4.2 Seasonal variation in spatial use

Figure 15 showed clear differences in the spatial extent and distribution of whale shark use between seasons. Although in both seasons the 50% core-use area was centred around Boa Vista, during the dry season, spatial use extended across a larger portion of the Cabo Verde's EEZ, and in the wet season, spatial use was more restricted and remained predominantly concentrated around Boa Vista, with an additional extension towards the northeast.

The 95% utilization distribution during the dry season was 30,588.96 km², which represents 3.80% of the Cabo Verde's EEZ, and in the wet season was 14,607.13 km², accounting for 1.81% of the EEZ (Table 3).

In relation to the 50% core-use area, it remained centred around Boa Vista in both seasons, although its spatial extent also differed slightly between periods. During the dry season, the 50% core-use area had a total area of 2,657.99 km², equivalent to 0.33% of the EEZ, whereas during the wet season it had an area of 2447.08 km², corresponding to 0.30% of the EEZ. The 50% core-use area represented 8.69% of the 95% utilization distribution during the dry season and 16.75% during the wet season. The tracking data were available for all seven whale sharks during both the dry and wet seasons. In the dry season, all seven individuals were recorded within the Cabo Verde's EEZ, while in the wet season, only five individuals had positions within the EEZ. All the individuals that had positions in the EEZ (during both seasons) had at least one position within both the 50% core-use area and the 95% utilization distribution.

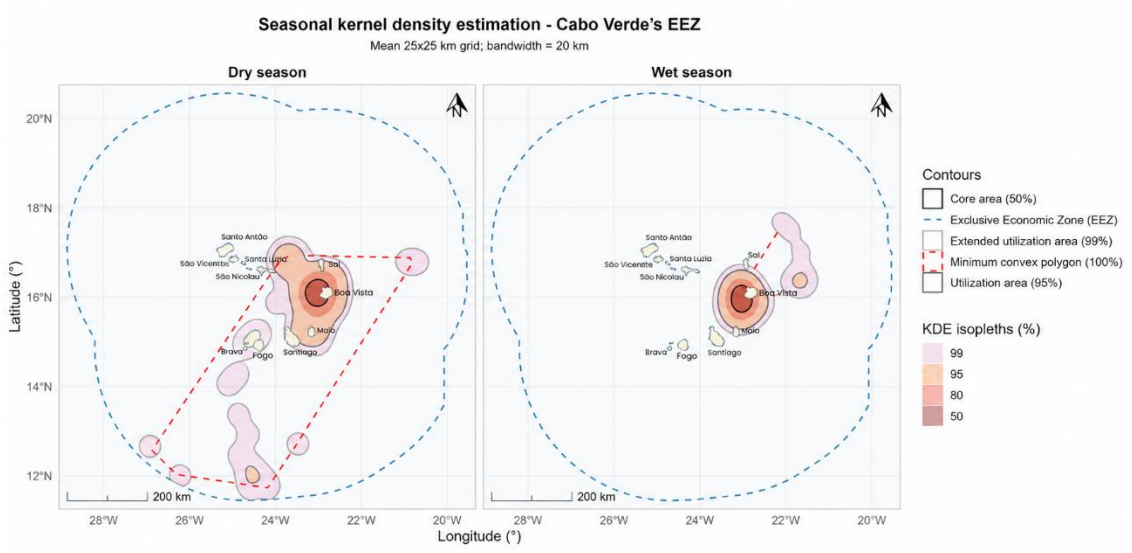


Figure 15. Season kernel density estimation of whale shark space use within Cabo Verde's Exclusive Economic Zone.

Table 3. Spatial metrics of seasonal whale shark kernel density estimation within Cabo Verde's Exclusive Economic Zone.

Season	**Spatial estimate**	**Area (km²)**	**% of Cabo Verde's EEZ**	**No. of individuals with positions inside**
Dry season	50% KDE – Core-use area	2657.99	0.33	7
	95% KDE –Utilization distribution	30588.96	3.80	7
Wet season	50% KDE – Core-use area	2447.08	0.30	5
	95% KDE –Utilization distribution	14607.13	1.81	5

4.4.3 Monthly variation in spatial use

There were differences in the geographical extent and pattern of whale shark use across the months of the year, despite the central zone of use being consistently associated with Boa Vista (Figure 16). Larger extents of space use were found during January and February, when the 95% utilization distribution extended past the surrounding waters of Boa Vista into other areas southwards and westwards of the archipelago. From March until May, there was a contraction in the 95% utilization distribution that was primarily centred around Boa Vista. In June and in July a larger extent of use was evident again, and the 95% utilization distribution expanded northeastwards from Boa Vista. Between August and November, the extent of space use contracted again, and in December there was a slight expansion towards the south.

Even though there was variation in the size of the monthly 95% utilization distribution, Boa Vista remained a consistent component of the 50% core-use area, with additional core-use areas occurring in January and February (Figure 16). The 95% utilization distribution had a minimum size of 7,907.09 km² in March and a maximum size of 56,675.25 km² in January, corresponding to 0.98% and 7.04% of the Cabo Verde's EEZ (Table 4). The size of the 50% core-use area was between 1,651.16 km² and 9,749.98 km², which equated to 0.21% and 1.21% of the EEZ. The area of the 50% core-use area, as a percentage of the corresponding 95% utilization distribution, also varied among months, ranging from 11.96% (July) to 23.25% (October).

Monthly comparisons should be interpreted cautiously because sampling effort, the number of tracked individuals and the number of years represented differed among months (as described in Section 4.2.1 above).

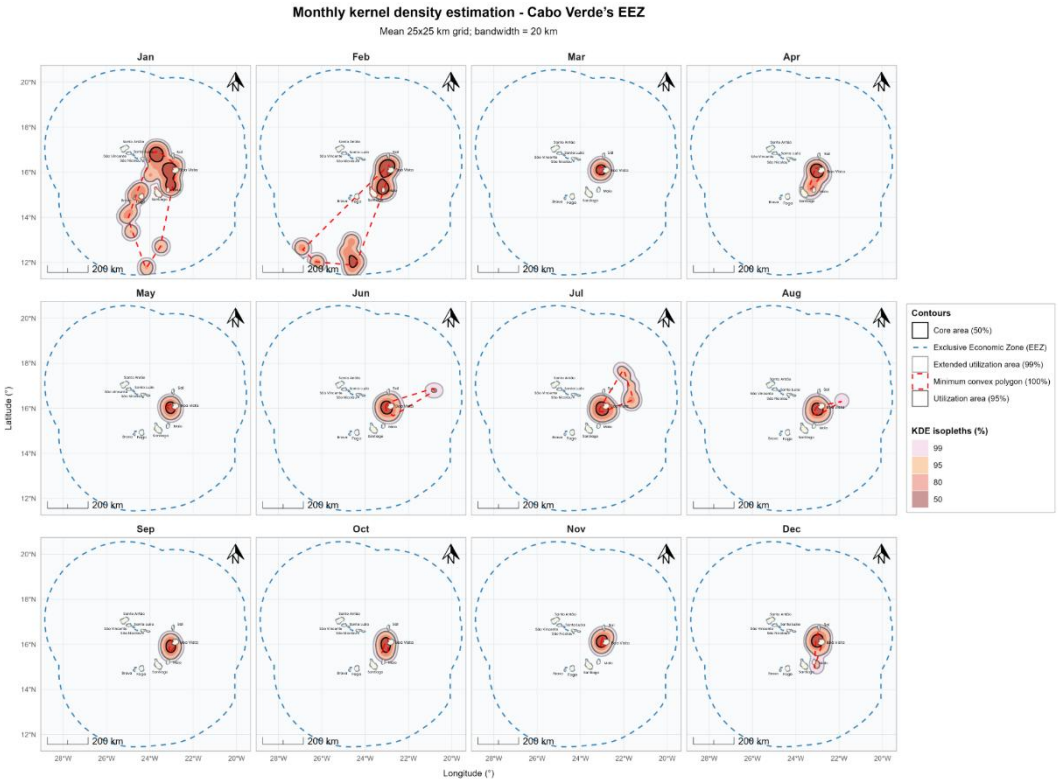


Figure 16. Monthly kernel density estimation of whale shark space use within Cabo Verde's Exclusive Economic Zone.

Table 4. Spatial metrics of monthly whale shark kernel density estimation within Cabo Verde's Exclusive Economic Zone.

Month	**Spatial estimate**	**Area (km²)**	**% of Cabo Verde's EEZ**	**No. of individuals with positions inside**
January	50% KDE – Core-use area	9749.98	1.21	3
	95% KDE – Utilization distribution	56675.25	7.04	4
February	50% KDE – Core-use area	9302.74	1.16	2
	95% KDE – Utilization distribution	43593.09	5.42	2
March	50% KDE – Core-use area	1651.16	0.21	2
	95% KDE – Utilization distribution	7907.09	0.98	2
April	50% KDE – Core-use area	2868.45	0.36	3
	95% KDE – Utilization distribution	14484.51	1.80	3
May	50% KDE – Core-use area	1907.99	0.24	4
	95% KDE – Utilization distribution	8653.07	1.08	4
June	50% KDE – Core-use area	2383.32	0.30	4
	95% KDE – Utilization distribution	13350.59	1.66	4
July	50% KDE – Core-use area	2781.95	0.35	2
	95% KDE – Utilization distribution	23255.30	2.89	3
August	50% KDE – Core-use area	2328.92	0.29	2
	95% KDE – Utilization distribution	11931.75	1.48	2
September	50% KDE – Core-use area	2122.91	0.26	4
	95% KDE – Utilization distribution	9455.69	1.17	4
October	50% KDE – Core-use area	2430.58	0.30	5
	95% KDE – Utilization distribution	10454.94	1.30	5
November	50% KDE – Core-use area	2119.79	0.26	5
	95% KDE – Utilization distribution	9773.16	1.21	5
December	50% KDE – Core-use area	2395.36	0.30	3
	95% KDE – Utilization distribution	13650.68	1.70	3

4.5 Spatial coverage and kernel density estimation overlap with MPAs and ISRAs

4.5.1 Spatial coverage within Cabo Verde's EEZ and territorial sea

Before assessing the overlap with conservation areas, the proportion of the KDE located within the marine area enclosed by the outer limit of the territorial sea was calculated. Throughout Section 4.5, the marine area enclosed by the outer limit of Cabo Verde's territorial sea is referred to as the analysis area. According to Table 5, of the estimated 95% utilization distribution within the Cabo Verde's EEZ, 81.13% was located within the analysis area. For the 50% core-use area, 100% was located within the same analysis zone. Within the analysis area, the 95% utilization distribution occupied 37.35% of the total analysis area, while the 50% core-use area occupied 4.51%. MPAs covered 2.02% of this analysis area and ISRAs covered 1.95%.

At the Cabo Verde'EEZ scale, MPAs covered 0.15% of the total marine area and ISRAs covered 0.14%. Finally, only 6% of the ISRAs are overlapped with MPAs.

Table 5. Spatial metrics used to quantify whale shark space use and overlap with Marine Protected Areas and Important Shark and Ray Areas across the two spatial scales considered.

Spatial scale	**Metric**	**Spatial coverage (%)**
Area enclosed by the outer limit of the territorial sea	95% utilization distribution located within the analysis area	81.13
Area enclosed by the outer limit of the territorial sea	50% core-use area located within the analysis area	100
Area enclosed by the outer limit of the territorial sea	Area occupied by the 95% utilization distribution	37.35
Area enclosed by the outer limit of the territorial sea	Area occupied by the 50% core-use area	4.51
Area enclosed by the outer limit of the territorial sea	Area covered by MPAs	2.02
Area enclosed by the outer limit of the territorial sea	Area covered by ISRAs	1.95
Cabo Verde's EEZ	EEZ covered by MPAs	0.15
Cabo Verde's EEZ	EEZ covered by ISRAs	0.14

4.5.2 Overlap with Marine Protected Areas

According to Figure 17 and Figure 18, MPAs within the area enclosed by the outer limit of the territorial sea covered a total of 1,207.39 km², representing 2.02% of this area. Within the 95% utilization distribution located inside the analysis area, 723.91 km² overlapped with MPAs, corresponding to 3.24% of the 95% utilization distribution. For the 50% core-use area, 53.29 km² overlapped with MPAs, representing 1.98%.

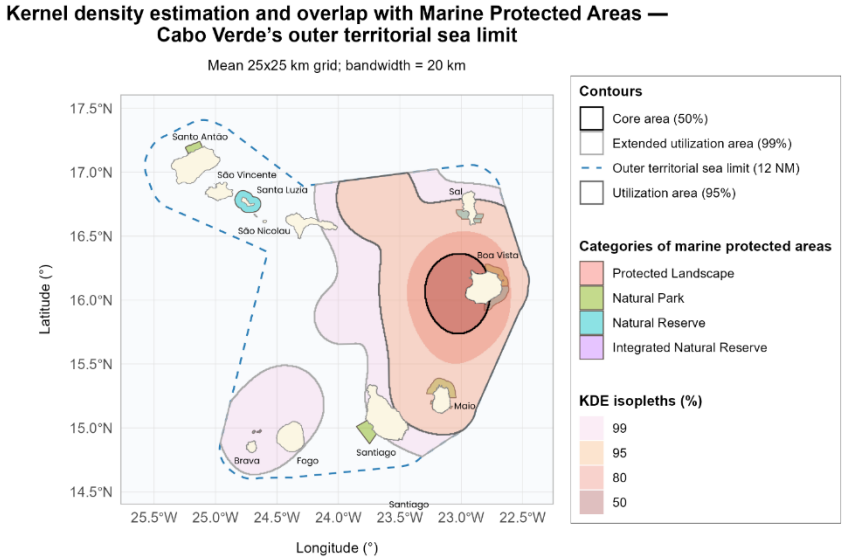


Figure 17. Kernel density estimation of whale shark space use within Cabo Verde's Exclusive Economic Zone, clipped to the outer territorial sea limit, and its overlap with Marine Protected Areas.

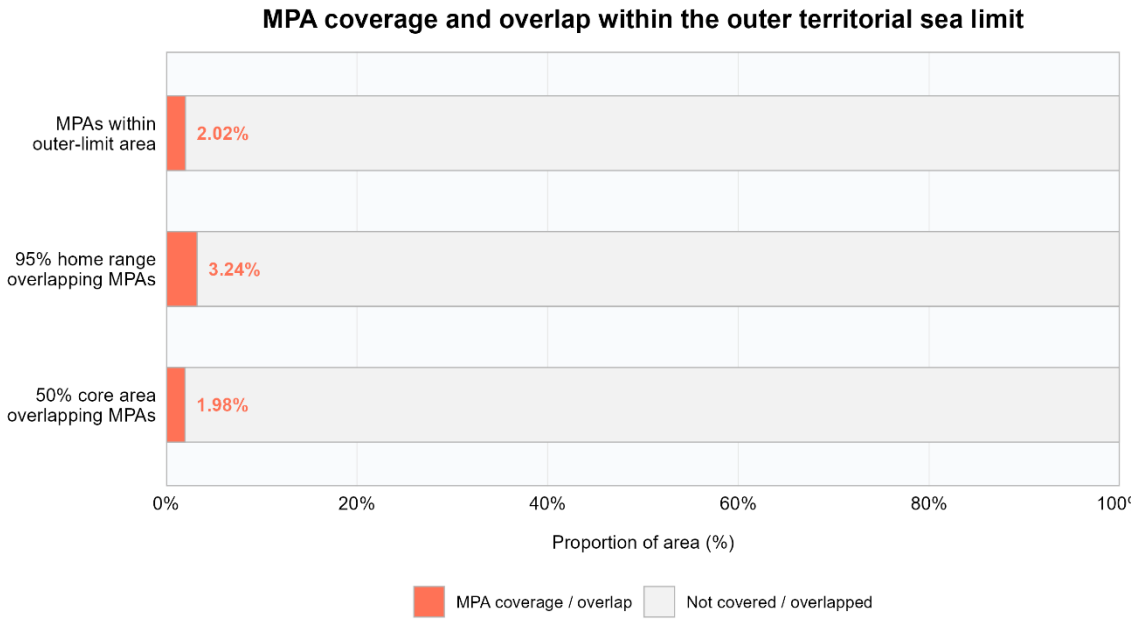


Figure 18. Spatial metrics of Marine Protected Areas coverage and overlap with the whale shark 95% utilization distribution and 50% core-use area within Cabo Verde's outer territorial sea limit.

4.5.3 Overlap with Important Shark and Ray Areas

Based on Figure 19 and Figure 20, ISRAs within the marine area enclosed by the outer limit of the territorial sea covered a total area of 1,163.03 km², representing 1.95% of this area. Within the 95% utilization distribution located inside the analysis area, 1,059.48 km² overlapped with ISRAs, corresponding to 4.75% of the 95% utilization distribution. For the 50% core-use area, 513.33 km² overlapped with ISRAs, representing 19.06% of the 50% core-use area within the same area.

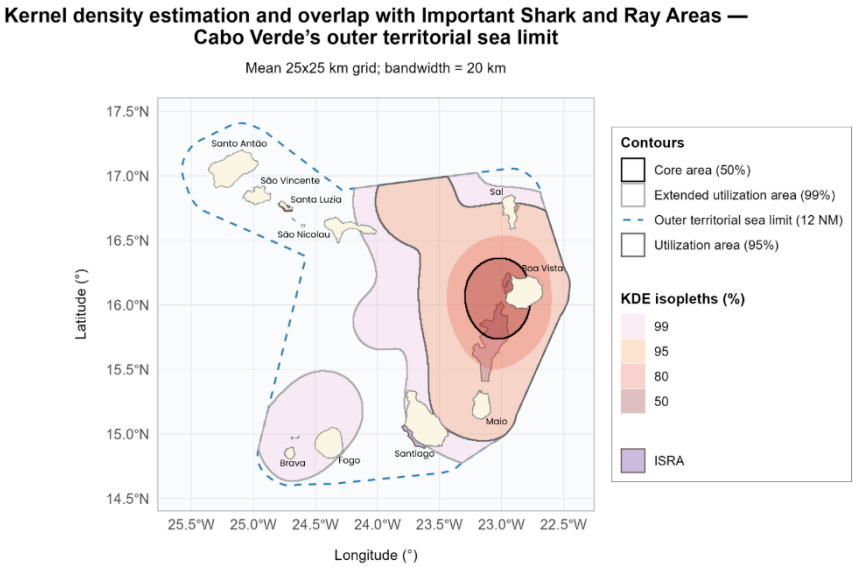


Figure 19. Kernel density estimation of whale shark space use within Cabo Verde's Exclusive Economic Zone, clipped to the outer territorial sea limit, and its overlap with Important Shark and Ray Areas.

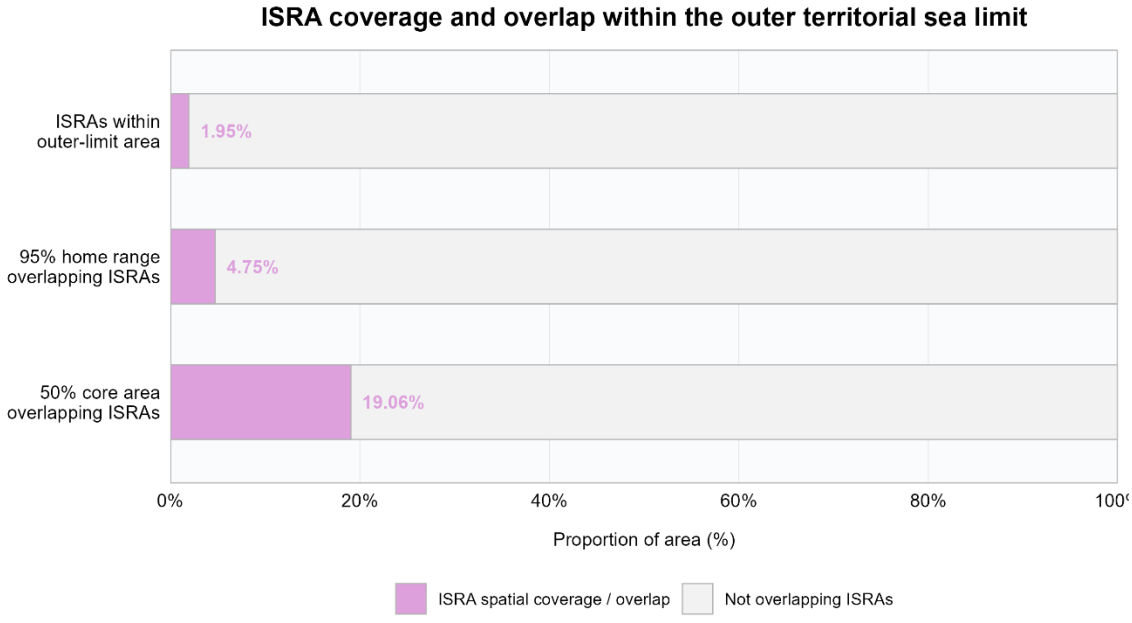


Figure 20. Kernel density estimation of whale shark space use overlapping Important Shark and Ray Areas within Cabo Verde's outer territorial sea limit.

4.5.4 Local overlap around Boa Vista

When considering only conservation areas associated with Boa Vista, we focused on eight MPAs: Ilhéu Baluarte Integral Nature Reserve, Ilhéu dos Pássaros Integral Nature Reserve, Ilhéu de Curral Velho Integral Nature Reserve, Ponta do Sol Nature Reserve, RN Boa Esperança Nature Reserve, Morro de Areia Nature Reserve, Tartaruga Nature Reserve, and Natural Park do Norte. Regarding ISRAs, three areas were considered: João Valente Shelf, Sal Rei Bay, and Sal Rei Reef.

Within the marine area enclosed by the outer limit of the territorial sea, 366.03 km² (1.64%) of the 95% utilization distribution overlapped with MPAs of Boa Vista, while 1042.95 km² (4.67%) overlapped with ISRAs (Figure 21). Between the MPAs considered, RN Tartaruga had the biggest overlap with the 95% utilization distribution, with 172.30 km², representing 0.77% of the analysis area. Among the ISRAs, João Valente Shelf showed the greatest overlap, with 942.22 km² (4.22% of the analysis area). Regarding the 50% core-use area, 53.29 km² (1.98%) overlapped with MPAs and 513.33 km² (19.06%) with ISRAs. The largest overlap with an MPA was in RN Tartaruga, covering 26.15 km² of the 50% core-use area (0.97%), while João Valente Shelf had the largest overlap among the ISRAs, covering 412.60 km² (15.32%).

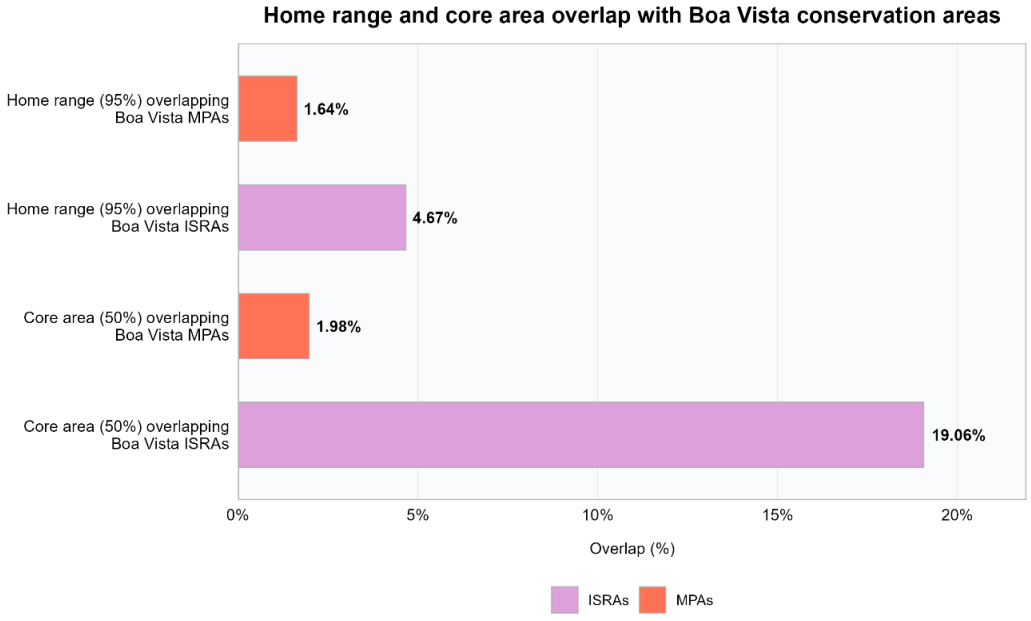


Figure 21. Spatial metrics of overlap between the whale shark 95% utilization distribution and 50% core-use area and Marine Protected Areas and Important Shark and Ray Areas associated with Boa Vista, within Cabo Verde's outer territorial sea limit.

4.6 Economic evidence from whale shark tourism

4.6.1 Literature search and study selection

The database search identified 123 records, including 56 records from Scopus and 67 from Web of Science. After duplicate removal (36 records), the remaining records were screened based on their titles, abstracts and keywords. These potentially relevant articles were reviewed in full, and 13 studies were identified as eligible for inclusion in the literature review. Backward snowballing identified four additional studies, resulting in a total of 17 studies included in the final economic review.

4.6.2 Characteristics of whale shark tourism destinations

The studies included in the economic review covered a broad geographical range of whale shark tourism destinations. According to Table 6, a total of 17 studies from eight countries (Australia, the Maldives, Madagascar, Seychelles, Mexico, Indonesia, the Philippines and Belize) were analyzed. From these eight countries, 11 specific tourism destinations were identified: Ningaloo Marine Park, South Ari Atoll MPA, Nosy Be, Mahé Island, La Paz Bay, Holbox, Cenderawasih Bay National Park, Botubarani, Donsol, Oslob and Gladden Spit Marine Reserve. Of these 11 destinations, eight were classified as island destinations and three as continental coastal settings. These destinations represented contrasting socioeconomic contexts, as indicated by differences in GDP per capita (current US$).

Among the 11 specific locations, for which an aggregation pattern could be identified, eight reported seasonal occurrence, whereas only three described year-round occurrence, namely South Ari Atoll, Cenderawasih Bay and Oslob. Estimates of the number of whale sharks associated with each site were reported inconsistently and were based on different populations, periods and estimation methods. Among studies providing number of whale sharks, the lowest reported estimate was 60–100 juvenile whale sharks in South Ari Atoll, while the highest was 500–800 individuals in Holbox. The number of whale shark tourists varied greatly among destinations. Annual numbers of tourists participating specifically in whale shark tourism ranged from 1,139 in Gladden Spit Marine Reserve, Belize in 2002 to approximately 508,000 in Oslob, Philippines in 2018. Other major destinations, such as South Ari Atoll, Holbox and La Paz Bay received tens of thousands of tourists per year. As shown in Table 6, these numbers were derived from different sources and methods, including government or management records, direct field counts or previously published

estimates.

Among the 11 distinct whale shark tourism destinations represented in the 17 studies, tourism occurred at least partly within formally protected areas in six destinations: Ningaloo Marine Park (Australia), South Ari Marine Protected Area (Maldives), Cenderawasih Bay National Park (Indonesia), Gladden Spit and Silk Cayes Marine Reserve (Belize), Holbox (Mexico) and Botubarani (Indonesia) (Anna & Saputra, 2017; Cagua et al., 2014; Davis et al., 1997; Prudnikov & Robles-Zavala, 2022; Quiros, 2005; Yasir et al., 2024). Three additional destinations were linked with spatial protection measures for specified species. The municipal waters of Donsol, Philippines, were declared a whale shark sanctuary, while part of La Paz Bay, Mexico, was formally designated as a whale shark refuge in 2018 (Hernandez Trejo et al., 2021; Pine, 2007). In the Seychelles, whale sharks have also been legally protected throughout the country since 2003, meaning that the species is protected regardless of whether individuals occur inside or outside a formal MPA (United Nations Environment Programme, 2003).

Table 6. Summary of the studies included in the economic review, covering the main characteristics of the whale shark tourism destinations analysed, including geographic and socioeconomic context, aggregation patterns and seasonality, estimated whale shark population size, annual tourist numbers, and study periods.

Authors	Country	Specific location	Geographic setting	GDP per capita (USD)	Type of aggregation	Sighting months	Reported number of whale sharks	Annual number of whale shark tourists	Reference period
(Davis et al., 1997)	Australia	Ningaloo Marine Park	Continental	US$20 479.2	Seasonal	March-June	200-400	~2 000 (CALM Log Book)[b]	1995
(Davis and Tisdell, 1999)	Australia	Ningaloo Marine Park	Continental	US$22 055.8	Seasonal (foraging)	March-May	200-400	~ 2 000 (CALM Log Book)[b]	1996
(Jones et al., 2009)	Australia	Ningaloo Marine Park	Continental	US$36 658.8	Seasonal (foraging)	March-August	200-500 (Meekan et al., 2006)[a]	6 677 (DEC records)[b]	2006
(Catlin et al., 2010)	Australia	Ningaloo Marine Park	Continental	US$36 658.8	Seasonal	March-August	N/R	6 677 (DEC records)[b]	2006
(Huveneers et al., 2017)	Australia	Ningaloo Marine Park/ Ningaloo Reef	Continental	US$62 817.2	Seasonal (Wilson et al., 2001)[a]	March-July (Wilson et al. 2001)[a]	N/R	22 124 (WA Department of Parks and Wildlife)[b]; dedicated: 8850 (40%); casual: 13 274 (60%)	2014
(Cagua et al., 2014)	Maldives	South Ari Atoll MPA	Island	US$7 461.3 (2012); US$8 236.1 (2013)	Year-round	All months	60-100 juvenils (Riley et al., 2010)[a]	72 370 (45 070 in resort) (2012); 77 930 (56 030 in resort) (2013)	2012-2013
(Ziegler et al., 2021)	Madagascar	Nosy Be	Island	US$499.8	Seasonal (foraging) (Diamant et al., 2021)[a]	September-December	>400 (Diamant et al., 2021)[a]	8 000 (Ziegler & Dearden, 2021)[a]	2018-2019
(Rowat & Engelhardt, 2007)	Seychelles	Mahé Island	Island	US$10 827.7	Seasonal	July-February	N/R	N/R	2004

NOTE: [a] Secondary citation; the original source was not consulted directly. [b] Institutional or administrative data source reported in the study; the original records were not consulted directly.

Table 6. (continuation) Summary of the studies included in the economic review, covering the main characteristics of the whale shark tourism destinations analysed, including geographic and socioeconomic context, aggregation patterns and seasonality, estimated whale shark population size, annual tourist numbers, and study periods.

Authors	Country	Specific location	Geographic setting	GDP per capita (USD)	Type of aggregation	Sighting months	Reported number of whale sharks	Annual number of whale shark tourists	Reference period
(Hernandez Trejo et al., 2021)	Mexico	La Paz Bay	Continental	US$9 649.3 (2017); US$10 084.8 (2018)	N/R	October-April	N/R	N/R	2017-2018
(Moreno-Gutiérrez et al., 2026)	Mexico	La Paz Bay	Continental	US$13 830.8 (2023); US$13 988 (2024)	Seasonal (foraging)	May-November (Ketchum, 2003)[a]	N/R	38 075 (SEMARNAT)[b]	2023-2024
(Prudnikov & Robles-Zavala, 2022)	Mexico	Holbox	Island	US$10 084.8	Seasonal (foraging) (Cárdenas-Palomo et al., 2015)[a]	May-September (Ramírez-Macías et al., 2012)[a]	500-800 (Ramírez-Macías et al., 2012)[a]	75 000 (45 000 national, 30 000 international) (Quintana Roo State Tourism Secretariat)[b]	2018
(Anna & Saputra, 2017)	Indonesia	Cenderawasih Bay National Park	Island	US$3 288.2	Year-round (Stacey et al. 2008; Mangubhai et al. 2012)[a]	All months (Stacey et al. 2008; Mangubhai et al. 2012)[a]	N/R	N/R	2015
(Djunaidi et al., 2021)	Indonesia	Botubarani	Island	US$3 521.5 (2016); US$3 861 (2018); US$4 106.9 (2019)	N/R	N/R	N/R	N/R	2016/ 2018-2019
(Pine, 2007)	Philippines	Donsol	Island	US$1 220.5	Seasonal (foraging)	March-April	119	N/R	2005
(Ziegler et al., 2019)	Philippines	Oslob	Island	US$3 168.5	Year-round	All months	N/R	508 000 (Local government records)[b]	2018
(Graham, 2003)	Belize	Gladden Spit Marine Reserve	Continental	US$4 858.9	Seasonal (foraging)	March-June	106	1 139	2002
(Quiros, 2005)	Belize	Gladden Spit Marine Reserve	Continental	US$5 153.7	Seasonal (foraging)	March-June	N/R	1 299 (Jones, 2004)[a]	2004

NOTE: [a] Secondary citation; the original source was not consulted directly. [b] Institutional or administrative data source reported in the study; the original records were not consulted directly.

4.6.3 Economic characteristics of whale shark tourism destinations

The main economic indicators reported across destinations are summarized in Table 8. In some destinations, tour prices differed according to the type of activity (observation, snorkelling or diving), type of tourist (casual or dedicated) and nationality (nacional or international). The economic value generated per tourist also varied among destinations and years. Values associated only with the whale shark activity, which in several studies corresponded directly to the reported tour price, ranged from US$10.0 for national tourists in Oslob, Philippines, to approximately US$336.4 for dedicated whale shark tourists (visitors who travelled specifically to participate in whale shark diving) at Ningaloo Reef, Australia. When broader trip-related expenditure was considered, including costs such as accommodation, food, transport and other activities, the total economic contribution per tourist ranged from US$66.8 per national tourist in Donsol, Philippines, to US$2,218 per tourist in Gladden Spit Marine Reserve, Belize. In some studies, values also differed between tourist groups, including national and international visitors and dedicated and casual whale shark tourists.

Annual economic values varied considerably among destinations. Depending on the study, these values were either reported directly by the original authors or estimated in the present review. Directly reported annual activity-related values ranged from US$13 260 in Mahé Island, Seychelles, to approximately US$10.0 M in Oslob, Philippines. Values calculated in this study, ranged from approximately US$259,800 in Gladden Spit Marine Reserve, Belize, to US$9.1 M in South Ari Atoll, Maldives.

For the total economic contributions, values directly reported by the studies ranged from US$635,324 in Donsol, Philippines, to approximately US$22.0 M at Ningaloo Reef, Australia. Values calculated in the present review ranged from US$19.0 M for national tourists to US$25.3 M for international tourists in Holbox, Mexico, while the estimated annual economic contribution for Gladden Spit Marine Reserve, Belize, was US$20.6 M.

However, it is important to note that the components included in the total economic contribution, both per tourist and annually, were not consistent across studies, as the expenses considered beyond the whale shark activity itself varied among studies. In addition, the monetary values correspond to different reference years and were not adjusted with a discout rate. Therefore, these values should be analyzed with caution, as they do not necessarily represent equivalent components of tourist expenditure.

Table 7. Main economic indicators reported for whale shark tourism destinations included in the economic review, including tour price, currency reference year, value per tourist for the activity alone or total economic contribution, and annual economic contribution associated with whale shark tourism.

Specific location	Tour price (USD)	Currency reference year	Value per tourist (USD)		Annual economic contribution (USD)	
			Activity only	Total economic contribution	Activity only	Total economic contribution
Ningaloo Marine Park	US$222	1995	US$222	US$1 754	US$444 000	US$3.5 M
Ningaloo Marine Park	US$214.1	1996	US$214.1	N/R	US$428 120	N/R
Ningaloo Marine Park	US$225.6-US$263.2	2006	US$225.6-US$263.2	US$672.4	US$1.5 M-US$1.8 M	US$4.5 M
Ningaloo Marine Park	US$225.6-US$300.8	2006	US$225.6-US$300.8	US$672.4	US$1.5 M-US$2 M	US$4.5 M
Ningaloo Marine Park/ Ningaloo Reef	US$336.4 (dedicated); US$315.5 (casual)	2014	US$336.4 (dedicated); US$315.5 (casual)	US$1 762.7 (dedicated); US$476.4 (casual)	US$3 M (dedicated); US$4.2 M (casual)	US$22 M
South Ari Atoll MPA	US$97; US$102; US$162	2012-2013	US$97; US$102; US$162	N/R	US$4.4 M (2012); US$4.6 M (2012); US$7.3 M (2012); US$5.4 M (2013); US$5.7 M (2013); US$9.1 M (2013)	US$7.6 M (2012); US$9.4 M (2013)
Nosy Be	US$60-US$70	2019	US$126 (dedicated); US$92 (casual)	US$547 (dedicated)	US$520 000	US$1.5 M
Mahé Island	US$100	2004	US$100	N/R	US$13 260	N/R
La Paz Bay	US$73.3 (national); US$52.5 (international)	2017-2018	US$73.3 (national); US$52.5 (international)	US$845.1 (national); US$1 427.4 (international)	US$2.3 M (national); US$945 000 (international)	N/R
La Paz Bay	US$74	2023-2024	US$74	US$540	US$2.8 M	US$20.6 M
Holbox	N/R	2018	N/R	US$422.2 (to national tourists); US$843.9 (to international tourists)	N/R	US$19 M (to national tourists); US$25.3 M (to international tourists)
Cenderawasih Bay National Park	N/R	2015	N/R	US$306.2 (national); US$1 411.6 (international)	N/R	US$10.5 M
Botubarani	US$42.3 (diver); US$23 (snorkeler); US$11.5 (non-diver)	2016/ 2018-2019	US$42.3 (diver); US$23 (snorkeler); US$11.5 (non-diver)	N/R	US$99 358	N/R
Donsol	N/R	2005	N/R	US$66.8 (national); US$136 (international)	US$83 727	US$635 324
Oslob	US$10 (national); US$20 (international)	2018	US$10 (national); US$20 (international)	N/R	US$10 M	N/R
Gladden Spit Marine Reserve	US$57 (snorkeling); US$127.5 (diving)	2002	US$57 (snorkeling); US$127.5 (diving)	US$2 218	N/R	US$2.5 M
Gladden Spit Marine Reserve	US$200	2004	US$200	N/R	US$259 800	N/R

5. Discussion

Satellite tracking data showed that whale sharks used a broad area of the North Atlantic, with most of their positions recorded within Cabo Verde's EEZ (771 positions). However, two individuals moved considerably further north and reached waters close to the Azores Islands. Whale shark occurrence in the North Atlantic has previously been documented, with, for example Afonso et al. (2014) reporting that whale sharks occurred in the Azores particularly between July and September and identifying the archipelago as part of the oceanic habitat used by the species in the North Atlantic. Sequeira et al. (2014) also described multiple sightings in the North Atlantic, with some recorded between 21°N and 15°S, an area that directly covers the Cabo Verde region.

Furthermore, there were individual differences in terms of total distance travelled, individual 205139 exceeded 4,000 km, individual 205144 reached approximately 2,000 km, while the remaining individuals had a cumulative movement distance of less than 1,500 km. Overall, these results show the existence of a combination of long-distance movements and more localized use of Cabo Verdean waters, along with individual differences in movement patterns. Large movements are well documented for whale sharks in other parts of their range. For example, Hueter et al. (2013) tracked a female whale shark from the Gulf of Mexico that travelled at least 7,213 km for 150 days, moving from the Caribbean towards the South Atlantic. Even longer movements have been recorded for example by Guzman et al. (2018) that tracked a female whale shark for 841 days during a journey of more than 20,000 km from Panama towards the western Pacific.

However, the movement patterns of whale sharks are very variable, and not all individuals move this way. This variation is also evident when multiple individuals from the same location were tracked. For instance, in a study in the Philippines, Araujo et al. (2018) tracked 17 juvenile whale sharks over six to 126 days. Although all individuals stayed in Philippine waters, individual movement distances varied from 86 km to 2,580 km. Moreover, other study on whale sharks tagged in Djibouti, found that there were various patterns of movement between those sharks, with some staying near the tagging site, some travelling regionally around the coast and into the Red Sea, and one travelling more than 1,000 km to the coast of Somalia (Andrzejaczek et al., 2021). Similar combinations of high mobility and prolonged use of regions have also been described in Mozambique, with Rohner et al. (2018) who found that although some satellite-tagged whale sharks left shelf waters and crossed international

boundaries, most remained within Mozambican coastal waters during their tracking periods.

The differences observed between the seven sharks in the present study therefore agree with this general pattern. However, the cumulative distances calculated here should be interpreted carefully. Tracking duration varied considerably between individuals, and the amount of available location data was also different among sharks. Individual 205139, for instance, was tracked for the longest period, which likely contributed to its higher cumulative distance. For this reason, the fact that this whale shark accumulated more than 4,000 km should not by itself be interpreted as evidence that it was intrinsically more mobile than the other individuals. Direct comparisons of movement rates between individuals would require accounting for differences in tracking duration and data availability.

In general terms, these results reinforce two important characteristics of the whale shark's movement ecology. First, the species can travel over very large distances and second, high mobility does not mean that whale sharks cannot show prolonged and concentrated use of particular regions.

The concentrated use of Cabo Verdean waters observed in this study, together with the large-scale movements made by some individuals, suggests that Cabo Verde may represent an important area within the broader movements of whale sharks in the North Atlantic. Within Cabo Verde's EEZ, the spatial use of the tracked whale sharks was not evenly distributed. The overall kernel density estimation (KDE) showed that the 95% utilization distribution represented 3.42% of the Cabo Verde's EEZ and was mainly concentrated in the eastern part of the archipelago, between Boa Vista, Sal and Maio. The 50% core-use area represented only 0.33% of the EEZ and was concentrated around Boa Vista Island. The repeated occurrence of core-use areas around Boa Vista indicates that this region was consistently used by the tracked individuals. However, the ecological reasons behind this pattern cannot be determined from the tracking data alone. Based on observed occurrences and environmental variables such as sea surface temperature and depth, Sequeira et al. (2014) developed a habitat suitability model that identified Cabo Verde as an area of high suitability for the species. The present results add spatial information to this prediction, suggesting that whale shark use within Cabo Verde may be particularly concentrated in the eastern part of the archipelago with a particular concentration around Boa Vista.

The concentration of whale shark space use within relatively restricted areas has also been reported in other regions around the world. At Ningaloo Reef, D'Antonio et al. (2024) identified a relatively restricted 50% core-use area within a substantially broader 95%

utilization distribution, with the core concentrated near Point Cloates. A similar general pattern was reported at Mafia Island, Tanzania, where Rohner et al. (2020) also identified a restricted core-use area within a broader home range. Nevertheless, it is important to emphasize that in this case, the core area did not consist of one contiguous zone but consisted of two major hotspots that were used in different periods of the year unlike in the current study and in the study be D'Antonio et al. (2024) where the core-use area was concentrated within a single area.

The relevance of Boa Vista was also confirmed using seasonal and monthly KDE. The size of the 95% utilization distribution varied throughout the seasons and the months, but although additional 50% core-use areas were identified in January and February, an area of concentrated use was consistently present around Boa Vista. This hints that the broader spatial distribution of whale sharks may vary over time within the Cabo Verde's EEZ, while the area of highest estimated use was repeatedly associated with waters around Boa Vista across the calendar months represented in the dataset. This finding should be interpreted with caution, since the number of positions and the number of individuals for the analyses differed between months and seasons. The results do not prove the existence of the continuous use of Boa Vista by the same individuals year-round but show that this area appears to be used repeatedly.

The overlap analyses showed that the spatial use of whale sharks was only partly represented within the existing Marine Protected Areas (MPAs) network. At the point level, only 21 of the 771 positions recorded within the Cabo Verde's EEZ overlapped with MPAs, corresponding to 2.7% of all positions in the EEZ. When considering the KDEs within the marine area enclosed by the outer limit of the territorial sea, although MPAs and ISRAs covered a very similar proportion of this analysis area, 2.02% and 1.95%, respectively, their overlap with whale shark space use differed considerably. In the case of MPAs, 3.24% of the 95% utilization distribution and 1.98% of the 50% core-use area overlapped with these protected areas. These two overlap measures should be interpreted separately since the point-based analysis represents the proportion of daily whale shark positions occurring within MPAs across the Cabo Verde's EEZ, whereas the KDE-based analysis represents the overlap between MPAs and the proportion of KDE within the outer limit of the territorial sea of Cabo Verde.

Low overlap between Marine Protected Areas and the space used by highly mobile marine species has already been reported. Conners et al. (2022) used tracking data from different

marine megafauna species and found that existing MPAs worldwide (with > 100 km²) provided limited spatial coverage for highly mobile species. For whale sharks specifically, using tracking data from a population tagged in Belize, the study reported an overlap of approximately 4.4% between their core area and existing MPAs. A similar limitation has been reported in the Tropical Eastern Pacific by Guzman et al. (2022) that found that whale sharks crossed 17 MPAs across 5 countries, but only 22.6% of their positions occurred within protected areas. However, the limited protection observed in these studies does not rule out the possibility that MPAs may be effective in conserving whale sharks since their effectiveness seems to largely depend on whether or not they overlap with the areas frequently and intensively used by the species. The study conducted by Reynolds et al. (2017) is a good example of this point because Ningaloo Marine Park encompasses an established aggregation site for whale sharks. While more than half of the positions took place outside the protected zones, about 41% occurred in Ningaloo Marine Park, rising to 50% during the main aggregation period. This is an indication that, although it may be difficult to conserve highly mobile species using one spatial conservation technique, MPAs that overlap with important aggregation or high-use areas can still potentially provide spatial protection during part of their movements.

In relation to the Important Shark and Ray Areas (ISRAs), the present study showed a much stronger spatial correspondence with whale shark high-use areas than the existing MPA network. The overlap analyses at the point level showed that 180 positions of the 771 positions recorded within the Cabo Verde's EEZ overlapped with ISRAs, corresponding to 23.3% of all positions in the EEZ. When considering the KDEs within the marine area enclosed by the outer limit of the territorial sea, 4.75% of the 95% utilization distribution and 19.06% of the 50% core-use area overlapped with ISRAs. This suggests that, for the individuals tracked in this study, ISRAs were more closely aligned with areas of concentrated whale shark use than the existing MPAs. Once again, point-based analysis and the KDE-based analysis should be interpreted separately.

Because MPAs and ISRAs covered similar proportions of the analysis area, the difference in the overlap was not explained simply by their total extent but likely reflected differences in their spatial location and configuration. This greater spatial overlap does not imply higher legal protection because ISRAs are not legally designated sites and do not pose any limitations to human activity within them (Rohner et al., 2025). Rather, such sites are determined using a scientific approach with a view to identify critical regions for sharks and rays

and future conservation efforts (IUCN SSC Shark Specialist Group, 2022; Rohner et al., 2025). This is especially relevant in the present study since, within the Cabo Verde's EEZ, only 6% of the total ISRA area overlapped with designated MPAs, indicating that most of the areas identified as important for sharks and rays currently fall outside formally protected areas. Similar gaps have been reported in other regions such as in the central and south American Pacific, where Mouton, et al. (2025) found that only 15.6% of ISRAs overlapped with MPAs, and only 7.3% with no-take MPAs. Likewise, in the Western Indian Ocean, only 7.1% of ISRAs overlapped with existing MPAs, with just 1.2% occurring within fully protected no-take areas (Cochran et al., 2026).

At a more local scale, among the MPAs of Boa Vista, only a small part of both the 95% utilization distribution and the 50% core-use area were covered (1.64% and 1.98%, respectively). In comparison, overlap with ISRAs was higher and differed more strongly between the 95% utilization distribution and the 50% core-use area (4.67% and 19.06%, respectively). João Valente Shelf showed the greatest overlap with the 50% core-use area among the ISRAs, while Tartaruga Natural Reserve showed the greatest overlap with the 50% core-use area among the MPAs (15.32% and 0.97% respectively).

However, the limited overlap with Tartaruga Natural Reserve should be interpreted considering the ecological importance of the habitats currently protected within this area. Tartaruga Natural Reserve is one of the key places for loggerhead turtle nesting sites in Cabo Verde and includes other relevant habitats, such as dunes and wetlands, and sites used by coastal and migratory birds (Marco et al., 2012; Silva et al., 2017). Thus, the placement of Tartaruga Natural Reserve can reflect conservation priorities that are not necessarily related to whale sharks. This may help to explain why the main whale shark core-use area was located mainly on the opposite side of this MPA, resulting in limited overlap.

In this context, the overlap between the whale shark core-use area and João Valente Shelf becomes particularly relevant. The João Valente Shelf is one of the identified ISRA (Criterion B – Range Restricted) where the Cape Verde Skate (*Raja herwigi*), a range-restricted species endemic to Cabo Verde, regularly occurs (Jabado et al., 2025). Along with the spatial patterns of the whale sharks identified in the current study, it appears that João Valente Shelf might have broader ecological significance in respect of elasmobranch species, as it supports not only an endemic ray but also part of the concentration area for whale sharks. The overlap suggests that João Valente Shelf may also be relevant to whale sharks, in addition to its recognized importance for the Cape Verde skate, although further data would be required to

establish its broader ecological importance. Taken together, these results highlight the importance of strengthening protection and management around Boa Vista, particularly in areas of high whale shark use.

Although this analysis does not attempt to propose specific boundaries for a new MPA, the results suggest that increasing spatial protection in the areas of highest whale shark use around Boa Vista could improve the representation of the core-use area within the current MPA network. It is worth noting that spatial protection does not have to cover the whole core-use area. For instance, based on a simple hypothetical scenario, protecting only half of the portion of João Valente Shelf that overlaps with the whale shark 50% core-use area would cover approximately 7.66% of the area. Together with the 1.98% of the 50% core-use area overlapping the MPAs of Boa Vista, the spatial protection can cover around 10% of the 50% core-use area. Although this will still be a minor part of the 50% core-use area, it could already provide additional protection to an important part of the habitat most intensively used by the tracked whale sharks.

Apart from spatial protection using MPAs, other measures can be used for protection within areas where whales sharks are more intensely used. At Mafia Island, Tanzania, Rohner et al. (2020) showed that whale shark core-use areas were relatively small and spatially predictable, which led the authors to propose measures such as, seasonally slow zones to mitigate vessel strikes, restrictions in the fishing gear within high-use areas and cooperation with local fishing communities. Similarly, actions could be considered around Boa Vista, especially in places where there is overlap between areas used by whale sharks and human activities. These approaches could help reduce specific pressures on the species while reinforcing the protection provided by formal spatial measures.

From the economic analysis, it became apparent that whale shark tourism had the potential to provide considerable economic benefits for areas where this activity is already established. However, the level of these benefits varied from one location to another and with the reference year. This variation was evident both in activity-related values and in the broader expenditure associated with the trip. For example, the highest total annual contribution directly reported by the studies was approximately US$22.0 million at Ningaloo Reef, followed by values calculated in the present study for Holbox, which ranged from approximately US$19.0 to US$25.3 million. The differences between the economic values in Table 7 (Results), reflect the diversity of whale shark tourism destinations included in the review, which differed in socioeconomic context, tourism volume, number and type of tourist and

tour prices. Nevertheless, these values must not be seen as comparable estimates not only because of the different components used to calculate total expenditure but also because of the differences mentioned above. For this reason, the reported values should be interpreted as destination-specific estimates rather than as directly comparable values that could be transferred to other locations such as Boa Vista.

Despite this variation, the review demonstrates that economically relevant whale shark tourism has developed under different ecological conditions. Most of the destinations for which aggregation patterns were available showed seasonal whale shark occurrence, while South Ari Atoll, Cenderawasih Bay and Oslob were characterized by year-round occurrence. This means that this form of tourism may not necessarily need the animals present all year round in order for it to be economically significant, if there is enough frequency of encounter within a certain period. Another aspect to consider is the number of whale sharks occurring at each tourism destination. It should, however, be pointed out that the seven whale sharks used in this thesis do not represent the total number of whale sharks existing in the region of Boa Vista. Other whale sharks were also tagged but for other research studies. This creates an interesting contrast with the established whale shark tourism destinations analyzed in the present study, where occurrence of whale sharks is often seasonal but involves larger numbers of individuals. In Boa Vista, whale shark positions were recorded around the area across all calendar months represented in the dataset, although the data did not demonstrate continuous year-round use by the same individuals.

Another characteristic of the destinations that have been reviewed is that the tourism of whale sharks is frequently related to spatial protection or particular management measures. In the destinations considered, nine of 11 were related to a protected area or protection/management measures. This suggests that the tourism activity of whale sharks operates within a larger framework of conservation or management programs. Nevertheless, it should be kept in mind that not all protected areas have been created only for the purposes of whale shark conservation and there are some destinations where the tourism of whale sharks existed prior to the implementation of protection measures.

A similar relationship between wildlife conservation and tourism is already evident in Boa Vista. Martins et al. (2025) found out that turtle watching tourism has developed alongside with the conservation practices and is now an economically significant element of the tourism industry in the region. The estimated annual revenue generated by turtle-watching tours increased from approximately €67,000 in 2008 to around €500,000 in 2018/2019, while

the total economic value associated with the loggerhead turtle population increased from less than €300,000 to approximately €2 million over the same period. According to the researchers, this growth was attributed to growing conservation investment and non-consumptive use through ecotourism. This provides a particularly relevant local example of how the conservation of marine megafauna can be associated with socioeconomic benefits in Boa Vista.

Humpback whale watching provides a complementary local example of how predictable marine megafauna occurrence can support wildlife tourism in Boa Vista. Humpback whales occur seasonally around the island, generally from late February to late May (Ryan et al., 2014). Despite their occurrence during a relatively restricted period of the year, their predictable seasonal presence has been sufficient to support an established whale watching activity on the island. In the case of whale sharks, positions around Boa Vista were distributed across all calendar months represented in the dataset and were concentrated in a relatively restricted area. If this pattern is confirmed through longer-term monitoring, protecting part of this heavily used area could simultaneously contribute to the conservation of the species and to the eventual implementation of regulated, non-consumptive tourism.

Thus, it is apparent that marine wildlife tourism is an established part of Boa Vista's tourism industry. Against this background, the concentrated spatial use of waters around Boa Vista by whale sharks identified in the present study creates a basis for further research of whether this species could support non-consumptive tourism. If such an activity were considered in Boa Vista, its development would need to be closely linked to conservation and management measures to ensure that increased vessel traffic and tourist interactions did not create additional pressure on this endangered species.

6. Limitations

It is worth noting that since this thesis serves as an initial exploration of the topic, there are certain limitations to be considered while analyzing its findings. First, the spatial analysis of the movements of whale sharks was carried out based on small number of individuals (seven tagged whale sharks), all of which were tagged in Boa Vista, with differences in tracking duration and temporal coverage. The fact that all individuals were tagged near Boa Vista may also have introduced a spatial sampling bias towards this area. Thus, some individuals, months and seasons were more represented than others, as monthly analyses pooled the same calendar months across different years and different individuals contributed

to different months, which makes it necessary to interpret temporal patterns and direct comparisons among months with caution. The cumulative movement distance also needs to be analyzed descriptively since individuals tracked for longer periods had more opportunity to accumulate greater distances. Besides, daily locations were not fully independent observations, since successive positions from the same individuals may be spatially and temporally correlated. Furthermore, the study did not explore the environmental factors that could be related with the observed spatial patterns and didn't assess any threats.

In addition, considering the broader scope of this thesis, which encompassed ecological, conservation and economic dimensions, and the time available for its development, it was not possible to conduct a primary socioeconomic assessment specifically for Boa Vista. This way, the analysis was conducted based on data from established whale shark tourism destinations. Moreover, the economic values reported across studies corresponded to different reference years and were not discounted to the same reference date, and the expenditure components included in the total economic contribution also differed among studies. Since the economic outcomes reported in these studies are influenced by local factors, tourism structure and the methodologies approach, they cannot be directly extrapolated to Boa Vista, but they can provide an indication of the economic potential that whale shark tourism may have if appropriate ecological, socioeconomic and management conditions are met.

7. Conclusion and future work

This thesis offers new information on the spatial ecology of whale sharks in Cabo Verde and on how it can be used for the conservation of the species. Even though whale sharks can make long distances around the North Atlantic Ocean, Boa Vista Island kept showing up as an area with concentrated and recurring use by whale sharks in Cabo Verde. The ability of the whale shark to migrate long distances while also having specific areas of concentration reinforces the significance of identifying particular areas where conservation efforts can be strategically concentrated.

Overall, the estimated whale shark use showed limited overlap with existing MPAs, and a greater proportion overlapped with ISRAs. In this context, the underrepresentation of the whale shark core-use area in the existing MPA system provides preliminary spatial evidence that may inform further assessment of spatial protection around Boa Vista. The overlap between areas of high use by whale shark and the existing ISRAs, with focus in João

Valente Shelf, further supports the ecological importance of this area. The spatial patterns identified in this thesis provide a starting point for future conservation assessments and management discussions regarding potential conservation measures in Boa Vista.

However, there are other factors to consider when it comes to the importance of preserving this species' habitat. In locations where whale sharks occur, they can also support economic activities, particularly through wildlife tourism. Although there is tourism centered on this charismatic species in other parts of the world, we cannot say with certainty that this type of tourism will take off in Boa Vista, but it is a possibility that deserves further investigation. This way, it is very important to make sure that these opportunities are developed in a responsible way, and for that, is important to keep conservation as the primary goal and economic benefits emerging as a consequence of protecting whale sharks, rather than becoming the main reason for their conservation..

Further studies should apply satellite tracking to a larger sample size and over a bigger period of time, providing greater geographical sampling and better temporal representation throughout various months of the year. Incorporation of environmental factors, prey availability and behavioral data can contribute to our understanding of the ecological causes behind the whale shark's presence in the Boa Vista area. Additional work should also validate the identified high-use areas and assess their overlap with human activities such as fisheries and vessel traffic. Finally, a primary socioeconomic assessment of Boa Vista should be conducted where tourist demand, willingness to pay, potential visitor numbers, operational costs, local benefit distribution and appropriate limits to tourism activity are examined. Together, these approaches would provide a stronger evidence base to support future conservation, management and sustainable tourism decisions regarding whale sharks around Boa Vista.

Appendix A. Search strategy used in Scopus and Web of Science

Databases and field tags:
Scopus: TITLE-ABS-KEY
Web of Science: TS

Search string:

```
("whale shark*" OR "Rhincodon typus")
   AND
   (
      touris*
      OR ecotouris*
      OR "whale shark tourism"
      OR "shark watching"
      OR "swim-with"
      OR "swimming with whale sharks"
      OR recreation*
   )
   AND
   (
      valuation
      OR "economic valuation"
      OR econom*
      OR revenue
      OR expenditure
      OR income
      OR benefit*
      OR "tourism revenue"
      OR "tourism expenditure"
      OR "direct expenditure"
      OR "economic impact"
      OR "economic contribution"
      OR "willingness to pay"
      OR WTP
      OR "consumer surplus"
      OR "travel cost"
      OR "travel cost method"
      OR "contingent valuation"
      OR socioeconomic*
   )
```

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