

GINEVRA GENNARI

**FIRST CATALOGS OF HUMPBACK
AND FIN WHALES IN THE ALGARVE
REGION**



UNIVERSIDADE DO ALGARVE

Faculdade de Ciências e Tecnologia

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AND FIN WHALES IN THE ALGARVE
REGION**

Master in Aquaculture and Fisheries
(Specialty in Fisheries)

Work made under the supervision of:
Professor Doctor Rita Castilho



UNIVERSIDADE DO ALGARVE
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Declaro ser a autora deste trabalho, que é original e inédito. Autores e trabalhos consultados estão devidamente citados no texto e constam da listagem de referências incluída.

Ginevra Gennari

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Resumo

A conservação de espécies marinhas migratórias, como as baleias de barbas, exige um conhecimento aprofundado sobre a sua distribuição, ecologia e ameaças. Estas espécies percorrem vastas áreas oceânicas, cruzando fronteiras internacionais e utilizando múltiplos habitats ao longo do ano. Apesar da sua importância ecológica e do interesse global pela sua conservação, muitas regiões do Atlântico Norte continuam sub-amostradas, o que dificulta a implementação de medidas eficazes de gestão. A costa sul de Portugal, particularmente o Algarve, é uma dessas regiões. Apesar da crescente atividade de observação de cetáceos na região, onde poucos estudos científicos se dedicaram a documentar a ocorrência regular de baleias de barbas, a sua ocorrência, os seus padrões de migração e as potenciais ameaças antropogénicas que enfrentam. Esta tese pretende colmatar essa lacuna, estabelecendo os primeiros catálogos de foto-identificação regionais de duas espécies emblemáticas de baleias de barbas: a baleia-de-bossa (*Megaptera novaeangliae*) e a baleia-comum (*Balaenoptera physalus*).

O primeiro manuscrito desta dissertação é dedicado à baleia-de-bossa e documenta dados recolhidos entre 2009 e 2024. Durante este período, foram registadas 17 ocorrências ao longo da costa do Algarve, dos quais 14 envolveram avistamentos no mar e 3 corresponderam a indivíduos encontrados mortos na costa. Os dados foram recolhidos em colaboração com empresas locais de observação de cetáceos e a Rede de Arrojamentos do Algarve (RAAlg). A identificação individual baseou-se na análise das barbatanas caudais utilizando padrões de pigmentação e características morfológicas únicas. Treze indivíduos únicos foram identificados com sucesso, e as suas imagens foram processadas e comparadas internamente e com o catálogo do Atlântico Norte (North Atlantic Humpback Whale Catalog — NAHWC). Três destes indivíduos foram avistados anteriormente em regiões distintas do Atlântico Norte: nas proximidades das Ilhas de Cabo Verde, no mar de Ligúria (Itália) e nas águas costeiras de Gairloch (Escócia). Estes resultados confirmam a conectividade migratória entre o Algarve e importantes áreas de reprodução e alimentação da população do Atlântico Norte. A distribuição temporal dos avistamentos revelou um padrão sazonal bem definido, com maior frequência na primavera (maio-junho) e no início do outono (setembro-outubro). Estes períodos coincidem com os picos de produtividade primária, levando ao incremento de toda a cadeia trófica, e em particular as baleias de barbas. Alguns indivíduos foram reavistados em locais distintos da costa algarvia com poucos dias de intervalo, indicando movimentações locais e possível uso transitório da área para alimentação. Um dos indivíduos (Mn110) foi registado três vezes em seis dias consecutivos na zona de Sagres, enquanto outro (Mn106) foi observado em Faro, Lagos e Sagres no espaço de 12 dias. Estes comportamentos reforçam a hipótese de que o Algarve poderá funcionar como uma “stopover” migratória estratégica. Os três registos de indivíduos arrojados apresentavam interações com atividades pesqueiras. Mn101, encontrado em Tavira, foi identificado como um jovem macho que anteriormente havia sido avistado nas águas da Ilha da Boavista (Cabo Verde) dois meses antes, confirmando não só a ligação entre as duas regiões como também o elevado risco que crias e juvenis enfrentam ao longo das suas rotas migratórias. Estes episódios de interação com artes de pesca sugerem que a mortalidade não natural, causada por impactos antropogénicos, pode estar sub-estimada nesta região, onde a pesca artesanal com redes de emalhar e armadilhas é amplamente praticada.

O segundo manuscrito foca-se na baleia-comum e constitui o primeiro estudo sistemático sobre esta espécie na região de Faro. Os dados foram recolhidos entre 2020 e 2024 através de excursões de observação de cetáceos, com registo de imagens fotográficas e trajetos GPS das embarcações. Foi criado um catálogo com 86 indivíduos únicos, com base nas características morfológicas da barbatana dorsal, padrões de coloração e marcas específicas. Estes dados foram posteriormente analisados através de um modelo de captura-recaptura (spatial explicit

capture-recapture — SECR), o que permitiu estimar uma população local de 1.476 indivíduos. A distribuição sazonal dos avistamentos mostrou um pico claro na primavera, particularmente entre março e maio, coincidindo com períodos de elevada produtividade primária. Durante este período, foram frequentemente observados comportamentos de alimentação e agregações mistas com outras espécies, como o golfinho-comum (*Delphinus delphis*), o roaz-corvineiro (*Tursiops truncatus*) e a baleia-anã (*Balaenoptera acutorostrata*). Este tipo de interação sugere que a área de Faro pode servir como um local de alimentação temporária, utilizado durante a sua migração. Apesar da abundância estimada ser relativamente elevada, a taxa de recaptura inter-anual foi baixa, o que indica que a maioria dos indivíduos observados provavelmente utiliza a região de forma transitória, e que a maioria da população ainda está por ser identificada. No entanto, alguns indivíduos foram reavistados dentro do mesmo ano, reforçando a possibilidade de fidelidade sazonal ao local.

Do ponto de vista metodológico, a dissertação demonstra a eficácia da utilização de plataformas de oportunidade, como as embarcações de observação de cetáceos, para recolha de dados científicos em regiões com escassez de dados científicos. Em síntese, esta dissertação fornece os primeiros dados estruturados sobre a presença, os movimentos e as ameaças que afetam baleia-de-bossa e baleias-comuns na região do Algarve. Descrevem-se pela primeira vez a ligação do Algarve com outros locais no Atlântico Norte, os padrões sazonais de uso do habitat, e as interações com artes de pesca. Estas conclusões destacam a relevância ecológica da região do Algarve para as baleias de barbas e sublinham o valor da foto-identificação e da recolha colaborativa de dados com empresas de observação de cetáceos. Os dois catálogos fornecem referências essenciais para futuras investigações e contribuem para o desenvolvimento de estratégias de conservação nas águas portuguesas.

Palavras-chave: *Balaenoptera physalus*, *Megaptera novaeangliae*, migração, foto-identificação, observação de cetáceos

Abstract

Baleen whales such as humpback (*Megaptera novaeangliae*) and fin whales (*Balaenoptera physalus*) are among the most highly migratory marine species. After experiencing severe population declines during the whaling era, both species are now showing signs of recovery. However, their complex movement patterns, wide-ranging distribution, and the absence of clearly defined population boundaries—particularly in the North Atlantic—pose challenges for monitoring and effective conservation efforts. While certain areas are recognized as key migratory corridors, the role of the southern Iberian coast, including the Algarve region in south of Portugal, remains largely unexplored. This thesis presents the first two photo-identification (photo-ID) catalogs of humpback and fin whales in the Algarve, establishing baseline data for this understudied region. The humpback whale chapter documents occurrences collected from 2009 to 2024 in collaboration with whale-watching companies and the Algarve Stranded Network (RAAAlg). Fluke photo-ID allowed for the identification of 13 unique individuals. Comparison with the North Atlantic Humpback Whale Catalog identified matches with individuals previously sighted in distant locations, including Cabo Verde, the Ligurian Sea, and Scotland. Entanglement, particularly among juveniles, emerged as a recurrent anthropogenic threat. The fin whale chapter analyzes opportunistic data collected from 2020 to 2024, namely photo-ID and GPS boat tracks, resulting in a catalog of 86 unique individuals. Spatial capture-recapture modeling estimated a local population of 1,476 individuals suggesting that a large part of the population hasn't been identified yet. Sightings peaked in spring and were often associated with feeding behavior, suggesting that the Algarve may serve as a seasonal foraging ground. However, low re-sighting rates across years suggest a transient rather than a resident use of the area. These findings highlight the ecological relevance of the Algarve for migratory baleen whales and underline the value of photo-ID and collaborative data collection with whale-watching companies. The two catalogs provide essential references for future research and inform conservation strategies in Portuguese waters.

Keywords: *Balaenoptera physalus*, *Megaptera novaeangliae*, migration, photo-identification, whale-watching

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Chapter 1 – State of the Art and Objectives

1.1.BACKGROUND

Knowledge about species occurrence at the scale of their distributional range and how they use their habitat is essential for the effective management and conservation of wildlife, especially for migratory and endangered species (e.g. Allen et al., 2016; Möller et al., 2020; Correia et al., 2021). Understanding the temporal and spatial scales of these species' movements enables identifying key habitats and assessing how human activities may affect them (e.g. Allen et al., 2016; Fraser et al., 2018; Möller et al., 2020). One of the critical challenges in cetacean conservation is addressing the issue of data deficiency (Correia et al., 2021). Consequently, almost 35% of cetacean species or their populations are declared "Data Deficient" by the IUCN, which hinders conservation efforts (e.g. Alves et al., 2018; Correia et al., 2021). Although baleen whales hold an iconic status in nature conservation, understanding their long-term spatio-temporal distribution patterns and migratory behavior remains limited for many species (Thomisch, 2016). This gap is especially pronounced in the mid-North Atlantic, where the factors influencing baleen whale migration are poorly understood, mainly due to the challenges associated with observing their movements during migration periods (Pérez-Jorge et al., 2019).

Almost 50 years ago, pioneering studies demonstrated how valuable scientific data about cetacean movements could be obtained from photos of free-swimming dolphins (Würsig and Würsig, 1977). In that work and a few others published at the same time, this method formed the foundation for what has since become a fundamental approach in marine mammalogy, leading to a scientific cascade of subsequent research and innovations in tracking cetaceans (Ballance, 2018). Photo-identification is nowadays the basis of nearly all capture-recapture modeling for cetaceans and, along with distance sampling, is one of the key methods used to model the demography of this taxon (Hammond et al., 2021; Patton et al., 2023). Over the past decade, the effectiveness of photo-identification using natural marks has dramatically improved, thanks to the availability of high-resolution digital cameras, the development of rigorous and standardized protocols for storing and analyzing images, and the use of computer-aided software to assist with individual matching (e.g. Hillman et al., 2003; Markowitz et al., 2003; Gomez-Salazar et al., 2011). As a result, photo-identification has become a reliable and widely adopted method for studying wildlife population ecology, providing valuable insights that inform conservation and management recommendations (Rock et al., 2006; Gomez-Salazar et al., 2011). Over the years, several researchers have focused on studying cetacean occurrences off the coast of Mainland Portugal (Brito, 2021). However, a comprehensive scientific methodology for analyzing the presence of coastal dolphins and whales is still lacking (Brito,

2021), as the marine environmental history of cetaceans has yet to be fully written, with key records still awaiting review (Brito and Sousa, 2011), including Mysticeti suborder.

1.2. BIOLOGY AND ECOLOGY OF BALEEN WHALES

Baleen whales (Mysticeti) are toothless predators that evolved from toothed whales (Odontoceti) to more effectively feed on groups of small-bodied prey in the littoral, epipelagic and mesopelagic ecosystems by utilising an oral filter (Demere et al., 2008; Fitzgerald, 2006, 2012; Goldbogen et al., 2016). Rather than teeth, baleen whales possess bilaterally symmetrical racks of keratinised plates that extend downward from the roof of the mouth (e.g. Szewciw et al., 2010; Young et al., 2015; Goldbogen et al., 2016). The inner edges of the baleen plates fray to reveal millimetre-scale tubules, or fringes, which interlock to form a dense fibrous mat (e.g. Williamson 1973; Goldbogen et al., 2016). This mat acts as a filter, trapping prey as water exits the mouth, allowing the prey to be swallowed (e.g. Werth and Potvin, 2016). Intermittent ram filter feeding is used by rorqual whales (Balaenopteridae) (Goldbogen et al., 2016). Lunge feeding in balaenopterids involves a two-step process: it starts with the rapid ingestion of a large volume of prey-laden water during a high-speed lunge, followed by the expulsion and filtration of the water from the stretched buccal cavity (Goldbogen, 2010; Goldbogen et al., 2007, 2016). Skimmer feeding, which is also used in balaenopterids, even if it's more common from the balaenidae family, uses a continuous bulk filtration method to capture small planktonic prey (Mayo and Marx, 1990; Werth and Potvin, 2024). They filter prey from areas where it accumulates, such as the water's surface, throughout the water column, or even near the ocean floor. As the whale opens its mouth, an incurrent flow of water, rich in prey, enters between the paired baleen racks that line the mouth (Werth and Potvin, 2024).

The humpback whale (*Megaptera novaeangliae*) (Borowski, 1781), one of the most studied baleen whales, is a member of the Balaenopteridae family and it is distinguished from other whales in the same family by extraordinarily long flippers (up to 5 m or about 1/3 of total body length), a more robust body and utilisation of very long (up to 30 min) vocalisations (National Marine Fisheries Service, 1991; Jonsgård, 1966; Clapham, 2000; Morin, 2019). Humpbacks can weigh as much as 40 tonnes (maximum recorded weight) and generally measure between 13 and 15.5 meters in length, although some individuals have been recorded at over 17 meters. Females are typically 1 to 1.5 meters longer than males on average (e.g. Chittleborough, 1965; Clapham, 2000; Morin, 2019). Humpback whales are renowned for their unique feeding behaviours. One well-known technique they use is called "bubble-netting." In this method, the whale dives deep beneath a school of fish and exhales while swimming in a circular pattern (Hain et al., 1982; Friedlaender et al., 2011). This action creates a cylinder of bubbles surrounding the fish, herding them together and making it easier for the whale to consume large

quantities of food (e.g. Hain et al., 1982; Friedlaender et al., 2011). Another feeding strategy observed in humpbacks is "lunge feeding", where the whale gathers prey closely and swallows them in a single, massive gulp (Hain et al., 1982; Morin, 2019). This technique is facilitated by the whale's ventral pleats, which can expand to increase the volume of food they can take in during feeding sessions (e.g. Clapham and Mead, 1999; Clapham, 2000; Morin, 2019). Their diet consists mainly of capelin (*Mallotus villosus*), sand eels (Sand lance) (*Ammodytes*), and krill (*Euphausiacea*) (e.g. Hain et al., 1982; Larsen and Hammond, 2004; Morin, 2019). Humpbacks are often observed feeding in small groups or individually depending on the type and quantity of prey available; however, these groups are not binding and may change frequently as members choose to leave and return at will (e.g. Whitehead, 1983; Clapham and Mead, 1999).

The fin whale (*Balaenoptera physalus*) (Linnaeus, 1758) is the second largest whale in the Balaenopteridae family, surpassed only by the blue whale (*Balaenoptera musculus*) (Mizroch et al., 1984). The cephalic region's colouration is remarkably asymmetrical, with the right dorsal side being light grey, the right ventral side being white, and the left side being dark slate dorsally and ventrally (Aguilar and García-Vernet, 2018). The baleen plates are similarly affected by this asymmetry; they are yellowish on the front third of the right maxilla and grey on the entire left side and the back two-thirds of the right side (Aguilar and García-Vernet, 2018). They are sexually dimorphic, with male fin whales that can grow up to 22 meters long, while females can reach up to 24 meters (Gambell, 1985). Their weight can range from 30 tons to 80 tons (Lockyer, 1976). Fin whales are typically found alone or in small groups and do not have as well-defined a social or school structure as toothed whales (Starrett and Tomilin, 1957; Mizroch et al., 1984). As humpbacks, fin whales feed by lunge feeding (Acevedo-Gutiérrez et al., 2002) and feed primarily on species of euphausiids, or krill, that congregate in dense shoals near the surface, notably *Euphausia superba* in the Antarctic; *E. pacifica*, *Thysanoessa inermis*, *T. longipes*, *T. spinifera* in the North Pacific; and *Meganyctiphanes norvegica* and *T. inermis* in the North Atlantic (Nemoto, 1959; Mizroch et al., 1984). Fin whales in the Northern Hemisphere exhibit more feeding flexibility (e.g. Mizroch et al., 1984; Gavrilchuk et al., 2014; Schleimer, 2021). They have been observed to exploit prey hotspots outside of their typical feeding grounds (e.g. Coakes et al., 2005; Silva et al., 2013; Schleimer, 2021), despite exhibiting high seasonal site fidelity to feeding grounds in the Gulf of Maine (Agler et al., 1993; Schleimer, 2021), the Gulf of St Lawrence (Ramp et al., 2014; Schleimer, 2021), and Ireland (Whooley et al., 2011; Schleimer, 2021).

1.3. DISTRIBUTION AND MIGRATION

Most mysticetes have a life cycle of migration, breeding and feeding; they are believed to undertake migrations involving generalised latitudinal movements rather than longitudinal movements (Lockyer, 1976). Most baleen whales are thought to migrate every year between high-latitude productive areas, where they spend the summer feeding, to tropical or subtropical oligotrophic wintering grounds used for mating and calving (Silva et al., 2013).

The humpback whale is found in all oceans worldwide, primarily in coastal waters, although it is less common in Arctic regions (e.g. Clapham, 2000; Meynecke et al., 2021). During the winter, humpbacks are typically located in temperate and tropical waters across both hemispheres, while in the summer, they tend to inhabit waters with high biological productivity, generally at higher latitudes (e.g. National Marine Fisheries Service, 199; Meynecke et al., 2021). The timing of key biological activities, such as migrations and reproduction, is closely linked to seasonal changes (e.g. National Marine Fisheries Service, 1991; Meynecke et al., 2021). As a result, these events are approximately six months out of phase between whales in the Northern and Southern Hemispheres (e.g. Winn and Reichley, 1985; National Marine Fisheries Service, 1991). Humpback whales are known for their long-distance migrations, but individuals in the Arabian Sea are the only ones who are part of a non-migratory population (Pomilla et al., 2014).

The fin whale is a widely distributed mysticete found across all major oceans, ranging from temperate to polar latitudes in both hemispheres (Edwards et al., 2015; Schleimer, 2021). However, they are generally rare or absent in equatorial regions between 20°N and 20°S (Edwards et al., 2015; Schleimer, 2021). Fin whales typically prefer deep, offshore waters, with higher densities often found near the continental shelf edge (e.g. Víkingsson et al., 2015; Muirhead et al., 2018; Schleimer, 2021). They are occasionally found in shallow coastal waters (less than 150 meters), particularly in highly productive areas (e.g. Ingram et al., 2007; Whooley et al., 2011; Schleimer, 2021). While most fin whales exhibit seasonal latitudinal movements, some records indicate their year-round presence at both high and low latitudes (e.g., Kellogg, 1929; Simon et al., 2010; Lydersen et al., 2020; Schleimer, 2021). The breeding grounds of fin whales remain unidentified, and observations of mating behaviours and newborn calves at high latitudes suggest that breeding and calving may not be restricted to lower latitudes, as is typical for humpback whales (e.g. Ingebrigsten, 1929; Baines et al., 2017).

1.3.1. Distribution and migration in the North Atlantic

All top predators in the North Atlantic must contend with the strongly seasonal nature of food resources (Pershing and Stamieszkin, 2020). During the summer equilibrium period, as is typical in systems driven by recycled production, carbon rapidly moves through the food chain or it is respired after being converted into an organic form. A second near-equilibrium community emerges during winter, characterized by low phytoplankton concentrations (e.g. Visser et al., 2011; Pershing and Stamieszkin, 2020). In spring, the shoaling of the pycnocline, combined with rising light levels, facilitates a rapid increase in phytoplankton abundance, leading to the renowned North Atlantic spring bloom (e.g. McGillicuddy et al., 1995; Pershing and Stamieszkin, 2020), which is one of the most important biological events (Visser et al., 2011). Baleen whales rely on dense aggregations of krill or fish for efficient foraging, aligning their migration with the timing of the North Atlantic spring bloom (e.g. Whitehead and Carscadden, 1985; Goldbogen et al., 2011). Krill requires several months to mature to a size suitable for baleen whale feeding (e.g. Fiedler et al., 1998; Santora et al., 2010), indicating a characteristic time lag between the phytoplankton spring bloom and the arrival of foraging baleen whales (Visser et al., 2011).

Among all the whales in the North Atlantic Ocean, the humpback whale is one of the most extensively studied (Reeves et al., 2004). The migratory behavior of humpback whales is relatively well understood, particularly regarding the endpoints of their migrations (e.g. Katona and Beard, 1990; Reeves et al., 2004). In the North Atlantic, the range of humpback whales stretches from breeding areas in the Caribbean and Cape Verde Islands to feeding grounds along the eastern United States and Canadian coastlines, as well as off Iceland, Greenland, and Norway (e.g. Kennedy et al., 2013; Hayes et al., 2019). During spring, summer, and fall, humpback whales in the North Atlantic feed in the Gulf of Maine, Gulf of St. Lawrence, waters near Nova Scotia, Newfoundland/Labrador, western Greenland, Iceland and Norway (e.g. Katona and Beard, 1990; Davis et al., 2020). These six to seven regions represent relatively discrete subpopulations supported by studies of the mitochondrial genome and individual animal movements (e.g. Clapham and Mayo, 1987; Stevick et al., 2006). The rate of de novo mutations varies significantly across taxonomic groups, with baleen whales, known for their large body sizes and low metabolic rates, thought to experience reduced intracellular DNA damage, resulting in lower mutation rates (Suárez-Menéndez et al., 2023). Previous analyses of global population structure using mtDNA indicate that humpback whales in the North Atlantic are most distinct from those in the North Pacific and less distinct from those in the Southern Hemisphere (Baker et al., 1993). Significant population structure between the eastern and

western North Atlantic feeding areas has been revealed with mtDNA (Rueg et al., 2012). During winter, humpback whales from western North Atlantic feeding areas mate and calve in West Indies (e.g. Katona and Beard, 1990; Kennedy et al., 2013), while humpback whales using eastern North Atlantic feeding areas migrate to Cape Verde islands (e.g. Reiner et al., 1996; Stevick et al., 2016) (Figure 1.1). Some individuals have been recorded in both breeding areas (Stevick et al., 2016).

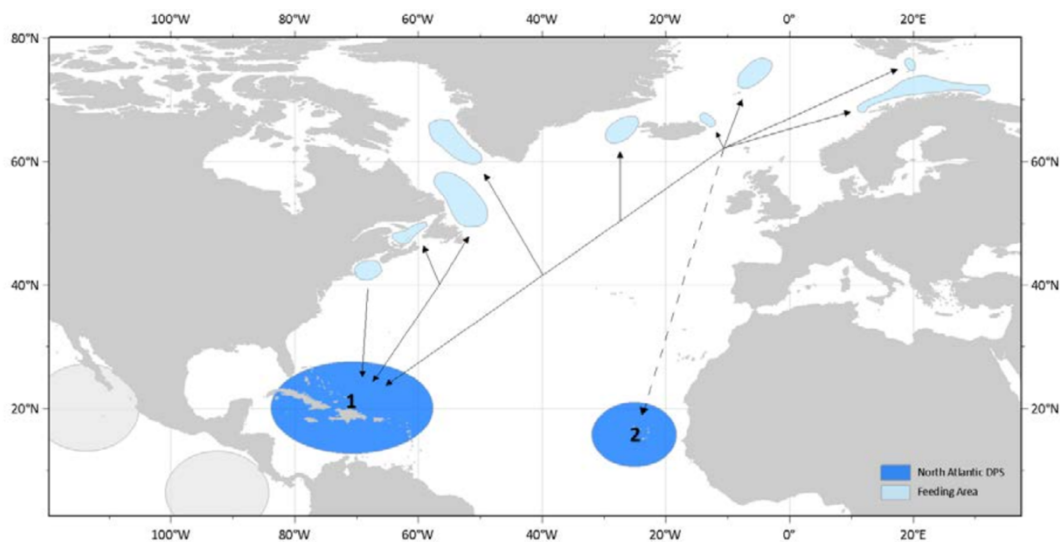


Figure 1.1: Migration pattern of humpback whales in the North Atlantic Ocean. Light blue shaded areas indicate feeding grounds while dark blue shaded areas indicate breeding and calving grounds (Bettridge et al., 2015).

The fin whale is the most abundant baleen whale species in the North Atlantic (Víkingsson et al., 2013). Between 1864 and the enforcement of the International Whaling Commission (IWC) moratorium on commercial whaling in 1985, approximately 100,000 fin whales were harvested in the North Atlantic, leading to a significant decline in the species' population (International Whaling Commission, 2009; Gauffier et al., 2020). The current population of fin whales in the North Atlantic is estimated at around 79,000 individuals, indicating a recovery from the impacts of commercial whaling in the region (Lydersen et al., 2020). The North Atlantic Marine Mammal Commission (NAMMCO) currently recognizes seven fin whale stocks in the North Atlantic, including populations in Eastern Canada, West Greenland, three central stocks that appear to mix (East Greenland, West Iceland, and East Iceland/Faroe Islands), as well as stocks in Norway and Spain (NAMMCO, 2007) (Figure 1.2). Studies have shown that fin whale songs vary between the western, central, and eastern North Atlantic, as well as between these regions and the Mediterranean Sea (e.g. Hatch and Clark, 2004; Delarue et al., 2009; Morano et al., 2012). However, samples from East Greenland and Iceland could not be definitively assigned to either of the two North Atlantic regions, implying the presence

of mixed subpopulations in these feeding grounds (e.g. Bérubé et al., 1998; Romagosa et al., 2024).

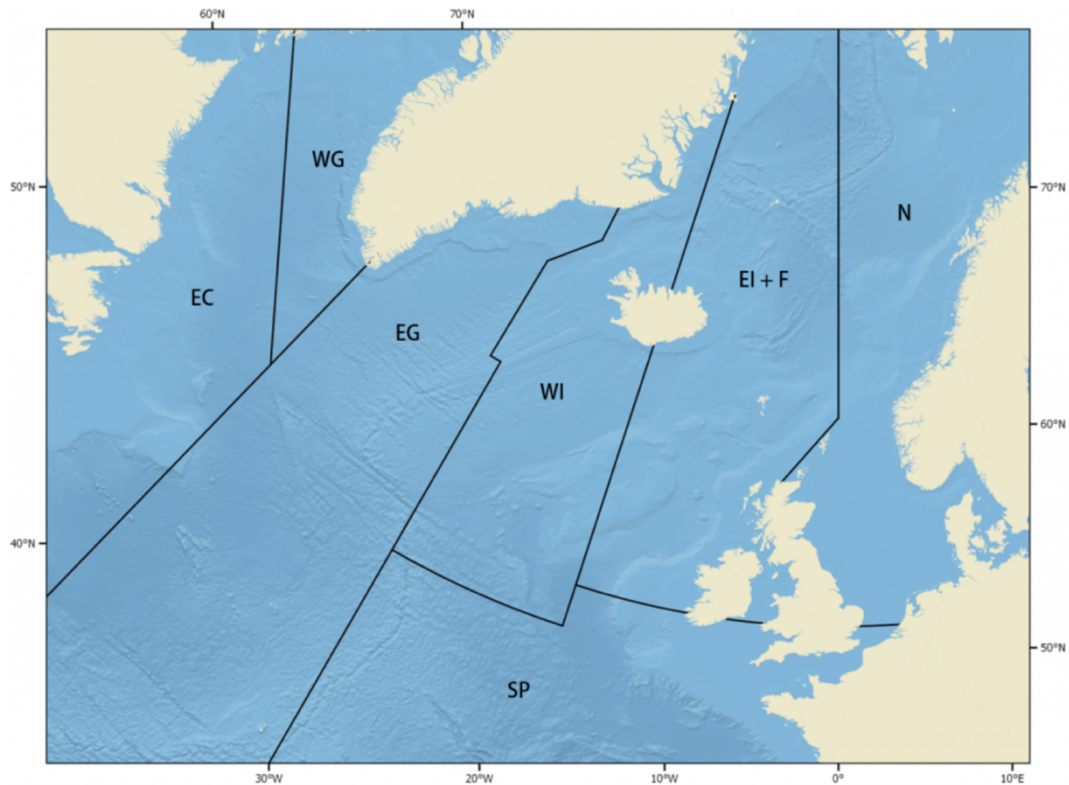


Figure 1.2: Fin whale stocks recognize by the North Atlantic Marine Mammal Commission and the International Whaling Commission. East Canada (EC); West Greenland (WG); East Greenland (EG); West Iceland (WI); East Iceland/Faroe Islands (EI+F); Norway (N) and Spain (SP) (NAMMCO, 2007).

Although fin whale summer distribution is well known, winter range is still uncertain (e.g. Norris, 1967; Simon et al., 2010). Specific breeding areas have not yet been identified, indicating that fin whale breeding may be more geographically widely distributed compared to other species (Heide-Jørgensen et al., 2008; Lyndersen et al., 2020). Newborn calves have been observed at high latitudes in the North Atlantic, suggesting that tropical or sub-tropical waters are not necessary for breeding in this species (IWC, 1992). Moreover, sightings and recordings of individuals year-round at high latitudes suggest that at least a portion of the population does not migrate (Kellogg, 1929; Clark, 1995).

1.4. ANTHROPOGENIC THREATS

The growing impact of human activities in both marine and terrestrial environments has introduced multiple and varied stressors that can influence wildlife populations through diverse mechanisms (Pirodda et al., 2023). Some stressors, such as hunting and fishing, have direct and immediate consequences on individual survival and reproduction, while others, like habitat degradation, climate change or chemical pollution, lead to long-term changes that affect key life processes by gradually altering different aspects of individual health (Kopphamel et al., 2021).

1.4.1. Interactions with fisheries activities

The rapid expansion of global fisheries over the past century has intensified interactions between fishing activities and marine megafauna, significantly heightening the risk of entanglement in fishing gear, which has been recognized as a critical conservation concern for baleen whale populations worldwide (International Whaling Commission, 2009; Cassoff et al., 2011). Baleen whale entanglements are frequently documented in the North Atlantic (Johnson et al., 2005), including the waters off Canada (Benjamins et al., 2011) and Alaska (Neilson et al., 2009). Additionally, they have been recorded in various other regions, such as Ecuador (e.g. Alava et al., 2005; Felix et al., 2006) and Hawaii (Mazduca et al., 1998). Although many baleen whales can free themselves from fishing lines or nets, as evidenced by scarring patterns observed on numerous individuals, entanglement can still result in severe long-term injuries and, in many cases, mortality (Knowlton et al., 2005). Even after escaping, remnants of the gear often remain attached to their bodies, typically entangling the mouth, flippers, or caudal peduncle, leading to prolonged physical stress, impaired movement, difficulty feeding, and an increased risk of secondary infections, further exacerbating the threat to their survival (Cassoff et al., 2011). Worsening this issue is the likelihood that entanglement-related mortality and its impact on population trends are significantly underestimated, largely due to underreporting by fishermen and the low probability of discovering and recovering affected individuals at sea (Cole et al., 2006).

In the North Atlantic, entanglement in fishing gear is the primary cause of mortality for large whales (van der Hoop et al., 2012). The most severe affected species are the critically endangered North Atlantic right whales (*Eubalaena glacialis*, NARW) and the endangered humpback whales (e.g. Cassoff et al., 2011; Cooke, 2020). Many right whale individuals have been observed carrying gear (11%; Robbins et al., 2015) and do so for months to years (van der

Hoop et al., 2016). Humpback whales are particularly prone to becoming entangled, mostly due to their morphology (Groom and Coughran, 2012). They possess long, knobby pectoral fins that account for approximately one-third of their body length (Clapham and Mead, 1999). The extended reach of these fins increases the likelihood of encountering fishing gear, with the knobby protuberances creating additional points where lines and nets can become snagged, making entanglement more likely (Groom and Coughran, 2012). Scarring observed on individually identified humpback whales reveals that entanglement has affected over three-quarters of the North Atlantic population (78%; Robbins, 2012) at least once.

1.4.2. Vessel strikes

Ship strikes involving both odontocetes and mysticetes are frequently reported across the world's oceans, with documented collisions affecting 11 large whale species, posing a growing concern for marine resource managers (e.g. Panigada et al., 2006; Conn and Silber, 2013). Except for a few regions and populations, primarily in the North Atlantic, the limited number of documented records hinders an accurate assessment of the true prevalence of collisions and the ability to analyze trends effectively (Van Waerebeek et al., 2007). Collision accidents have increased alongside the global expansion of major shipping and seaborne trade, occurring not in the coastal waters of newly industrializing countries and developing nations (Van Waerebeek et al., 2007).

Baleen whales face a higher risk of ship strikes than other marine mammals due to their large body size, their prolonged time spent at or near the surface for feeding or recovery, and their limited ability to evade approaching vessels (Nichol et al., 2017). The likelihood of fatal incidents appears higher in species inhabiting regions with increased vessel traffic and vessel speed has been recognized as a key factor influencing both the likelihood and severity of collisions (e.g. van der Hoop et al., 2012; Conn and Silber, 2013). Common consequences include fatal or non-fatal injuries such as blunt force trauma, fractured bones and propeller lacerations, which can significantly affect the survival, reproduction, and recovery of vulnerable populations (e.g. Moore et al., 2004; Pirodda et al., 2023). Fin whales account for the highest proportion (29.2%) of reported cases in the global vessel-strike database managed by the International Whaling Commission, followed by humpback whales at 21.2% and North Atlantic right whales at 16.0% (Van Waerebeek and Leaper, 2008; van der Hoop et al., 2012).

Vessel strikes can have particularly severe impacts on already small populations, such as the North Atlantic right whale, where every human induced impact adds further pressure to the already endangered population (Blondin et al., 2025). Most recorded injuries and deaths of right

whales are caused by collisions with vessels, significantly impeding population growth (Vanderlaan et al., 2008)

1.4.3. Plastic debris

Marine species, including cetaceans, are impacted by plastic debris through three main pathways: entanglement, ingestion, and exposure to toxic pollutants (Burkhardt-Holm and N’Guyen, 2019). Most entanglement cases in marine plastic debris are associated with fishery-related materials, although differentiating between entanglement in abandoned, lost, or discarded fishing gear (ALDFG) and active fishing gear remains difficult (Eisfeld-Pierantonio et al., 2022). Of particular concern are microplastics ingestion, plastic fragments smaller than 5 mm, primarily originate from the breakdown of plastics that have been released into the environment since the onset of the plastic era (Fossi et al., 2012). They pose a significant threat in aquatic environments as they frequently remain buoyant at the sea surface, tending to accumulate along current fronts (e.g. Gove et al., 2019; Zantis et al., 2022). Marine animals ingest microplastics through three primary ways: (i) active selection, where microplastics are mistaken for food, particularly by smaller organisms; (ii) trophic transfer, where microplastics move up the food web through prey consumption and (iii) accidental ingestion from the surrounding water, significant for baleen whales and other bulk-foraging filter feeders (Zantis et al., 2022).

As filter feeders, baleen whales consume and process vast amounts of seawater and due to their non-selective feeding mode, they filter organisms ranging from plankton to small fish, potentially ingesting microplastics both directly from the water column and indirectly through their prey (Besseling et al., 2015). It has been estimated that baleen whales ingest significant amounts of plastic fragments, with blue whales consuming up to ten million pieces per day (Werth et al., 2024). Recent studies have documented the presence of plastics of various sizes within the digestive tracts and tissues of baleen whales, including right, gray, fin, Bryde’s, sei, minke, and humpback whales (e.g. Alzugaray et al., 2020; Torres et al., 2023; Besseling et al., 2015). Due to their high food intake requirements, mysticetes primarily forage in prey-rich areas, in heavily polluted feeding grounds, such as the southern and eastern coasts of Asia and the Mediterranean Sea (Werth and Potvin, 2024). Potentially harmful consequences of interactions between cetaceans and marine plastic pollution include (Figure 1.3): (1) the direct and indirect ingestion of micro- and macroscopic plastic particles through the baleen filter, after which retained plastic can either (2) accumulate within the baleen, potentially clogging the filter and impairing its function temporarily or permanently or be dislodged and expelled from the

mouth. Alternatively, plastics may (3) enter the digestive tract, where they can either pass through the gut unchanged, (4) cause intestinal blockages or (5) be absorbed or integrated into muscle and other body tissues, particularly when composed of extremely small particles. Additionally, larger plastic debris such as ropes, nets, buoys, and other discarded fishing gear can (6) entangle whale body parts, including flippers and flukes, restricting movement, respiration, feeding, and other essential activities, or (7) become lodged within the baleen racks, not necessarily clogging the filter but rather damaging it by bending plates and creating gaps, ultimately compromising its filtration efficiency (Werth et al., 2024).

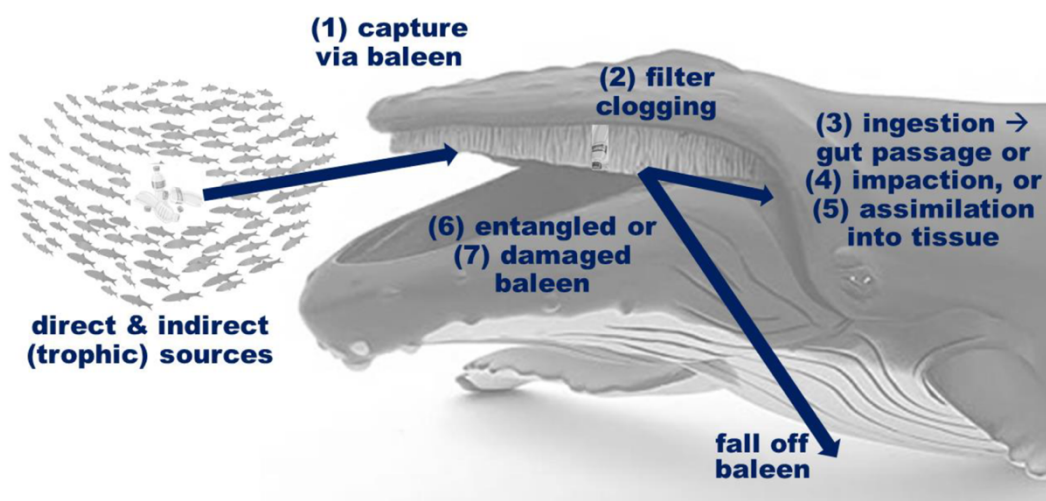


Figure 1.3: Plastic debris can enter a whale's mouth both directly, through primary or fragmented pieces, and indirectly via trophic transfer, resulting in potential harmful outcomes: (1) capture within the baleen filter, where plastic may (2) remain and obstruct filtration or be expelled from the mouth. Plastic dislodged from the filter can also (3) be swallowed, leading to either safe passage through the gut, (4) intestinal blockage, or (5) absorption and incorporation into whale tissues. Additionally, larger plastic debris can (6) entangle various body parts, impairing movement, foraging, and filtration, or (7) cause temporary or permanent damage to the baleen plates by breaking or bending them, ultimately compromising the filtration process (Werth et al., 2024).

Several hundred of chemicals are either added or absorbed by microplastic debris, including persistent organic pollutants (POPs), organochlorine contaminants (HCB, DDTs, PCBs) as well other contaminants like polyethylene, polypropylene, and phthalates (e.g. Fossi et al., 2012; Seuront et al., 2022). Due to their hydrophobic nature, these contaminants have a stronger affinity for microplastics, allowing them to act as vectors for pollutants and toxins (Nabi et al., 2022). Along with biomagnification and bioaccumulation, the ingestion of microplastics can lead to severe health effects, including congenital disabilities, endocrine disruption, immune system dysfunction, vascular damage, and neurological impairment, posing a real threat to the well-being of marine mammals (e.g. Fossi et al., 2012; Nabi et al., 2022).

1.5. METHODS USED IN STOCK IDENTIFICATION

1.5.1. *Photo-Identification*

Photo identification (photo ID) is a non-invasive method of identifying individuals through photographs. It relies on the assumption that each animal possesses distinct characteristics that can be used for recognition (e.g. Pawley et al., 2018; Araujo et al., 2019; Maglietta et al., 2022). By taking pictures and observing distinguishing marks, it is possible to track and monitor individuals or populations and investigate their migratory paths as well as any unusual behaviours they may display, such as feeding, breeding, and social interactions (e.g. Mizroch et al., 1990; Gomez-Salazar et al., 2011; Morin, 2019). However, with time, natural markings can alter, particularly in young whales, resulting in incorrect identification e.g. Carlson et al., 1990; Blackmer et al., 2000; Franklin et al., 2020).

Mark-recapture methods were originally developed and primarily used in studies where individual animals were physically captured, marked in some manner (such as painting, branding, tagging, or mutilating), released, and later physically recaptured (e.g. Jolly, 1965; Seber, 1965; Cormack, 1972; Evans and Hammond, 2003). Artificial marks are costly, transient, challenging to apply in large sample studies, and physically disruptive (e.g. Mukinya, 1976; Kelly, 2001; Morin, 2019). However, they can be a helpful tool in cases where designated species lack distinguishing characteristics or exhibit frequent changes in appearance (e.g. Hammond, 1990; Stevick et al., 2001; Morin, 2019). Since artificial markers are not always feasible, studies tend to focus on natural markings or variations in species. These markings are generally preferred because they are relatively permanent, do not require direct animal handling, and are typically large and visible on whales, making them easy to photograph (Hammond, 1990; Morin, 2019). Photo-ID photographs are typically captured from vessels during specialised photo-identification excursions and line-transect abundance surveys (e.g. Katona et al., 1979; Calambokidis et al., 2004; Morin, 2019). However, drone photography is gaining popularity for estimating abundance and can potentially become a key method for photo-identification (e.g. Goebel et al., 2015; O'Callaghan et al., 2024). It could play a significant role in future management decisions, as understanding the areas frequented by baleen whales may influence the development of new conservation strategies (Katona et al., 1979; Morin, 2019).

Fortunately, the ongoing development of sorting software has significantly increased the chances of finding a positive match while greatly reducing the time required to identify each individual (Kelly, 2001; Morin, 2019). These programs typically rely on three key criteria:

pigmentation, often using a coding system, scarring, and notch shape (Mizroch et al., 1990; Morin, 2019) (Figure 1.4 and 1.5). Once the relevant data is entered into the system, the software searches the database and presents the researcher with the whales most likely to match (Mizroch et al., 1990; Kelly, 2001; Morin, 2019).

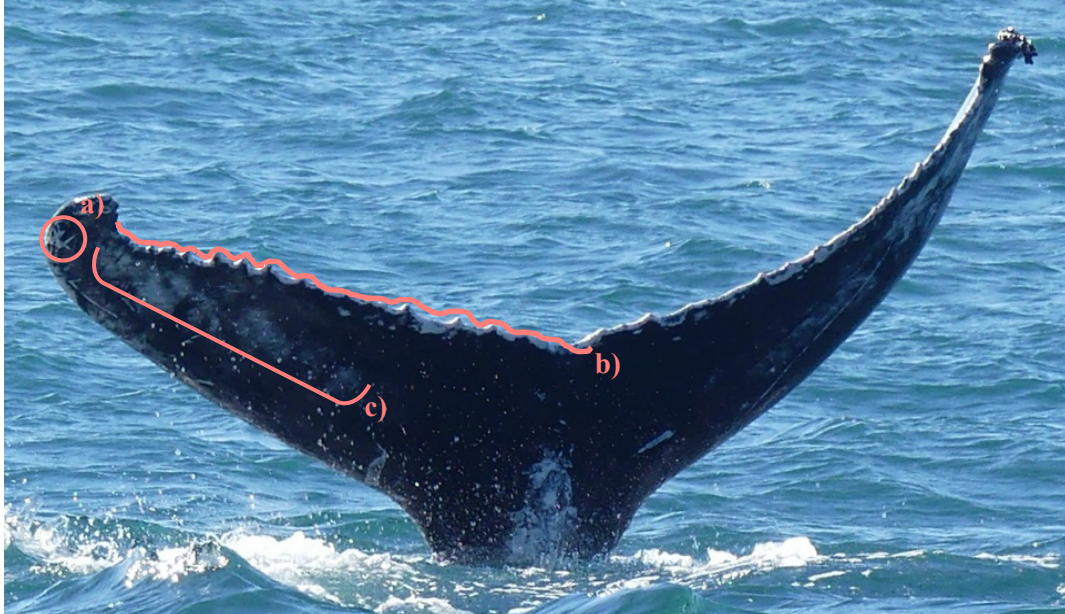


Figure 1.4: Humpback whale distinguishing characteristics for photo identification. a) Scars; b) Trailing edge; c) Pigmentation (Photo taken by Ocean Vibes).

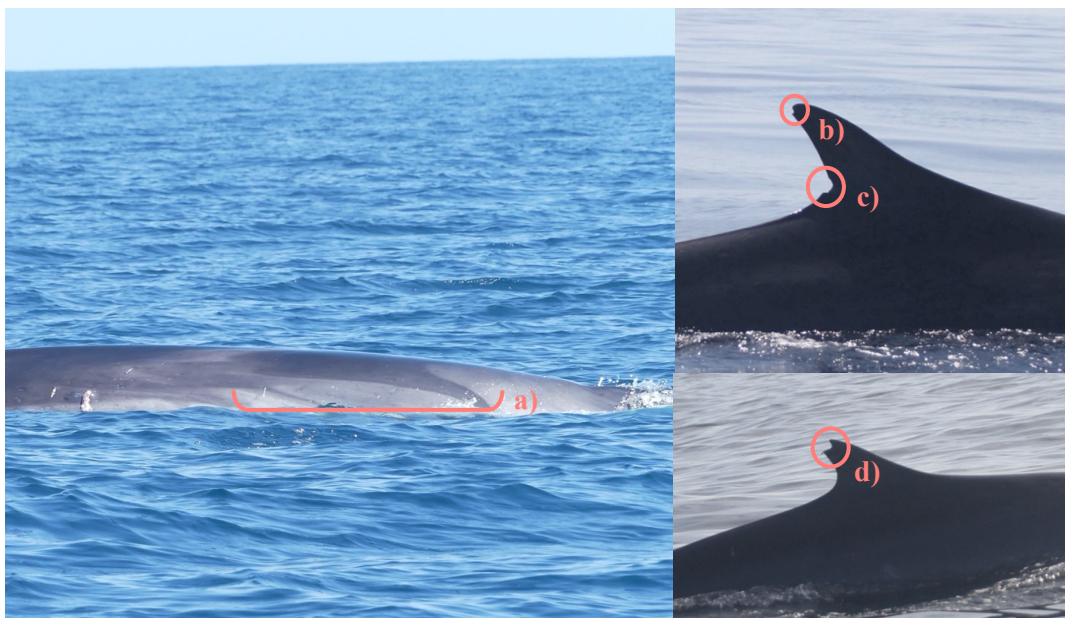


Figure 1.5: Fin whale distinguishing characteristics for photo identification. a) Chevron-blaze patterns; b) Nick; c) Notch; d) Disfigurement (Photos taken by Rui Peres dos Santos).

1.5.2. Manual and automated matching software

Over the past 15 years, photo identification has been widely utilized to study the population ecology and life history of various species, evolving from film-based photographs organized in physical catalogs to digital photography and databases (Andreotti et al., 2017). However, matching individuals across images remains expertise-driven and increasingly time-consuming as catalog size grows (Patton et al., 2023). Various image processing techniques can be applied to distinguish individuals, including manual photo matching, semi-automated methods, or fully automated machine assistance (Maroen et al., 2024).

Manual matching through pairwise image comparison is the primary approach for processing photo-ID data, largely adhering to the original methodology established by Katona and Whitehead (1981), updated with the use of digital images (Blount et al., 2022). This process involves side-by-side image matching within a database of previously identified individuals, where images are labeled by the date of capture (Maroen et al., 2024). As the size of the photographic database grows, the effort required rises, increasing the likelihood of incorrect matching due to human error or poor-quality photographs (Cheeseman et al., 2021; Blount et al., 2022). For instance, in the North Atlantic Humpback Whale Catalog maintained by Allied Whale at the College of the Atlantic, each new individual must be compared by two experienced photo-ID technicians against a catalog of 10,314 known whales, requiring an average of 51.5 minutes per whale (Cheeseman et al., 2021).

Computer-aided software and machine learning algorithms offer a promising alternative by reducing user subjectivity in the matching process, achieving high accuracy rates, and decreasing processing time (Maroen et al., 2024). All semi-automatic methods employ embedded algorithms to suggest the most likely matches, but the final decision in confirming the match ultimately rests with the user (Andreotti et al., 2017). Case-specific image recognition software packages have been successfully developed to assist researchers in the matching process for marine mammals, such as DARWIN (Stanley, 1995) and Finscan (Hillman et al., 2003). DARWIN is a computer vision system for the identification of bottlenose dolphins (*Tursiops truncatus*) employing a semi-automated process to approximate the fin outline of a new dolphin (Figure 1.6) (Stanley, 1995). Researchers manually trace the general outline of the leading and trailing edges of the dorsal fin using a cursor. This outline is then refined with an active contour before matching it against a database of previously identified dolphin fins. The program generates a ranked list of potential matches for comparison with the new fin image, providing confidence limits for the closest match to assist in the identification process (Renò et al., 2019).

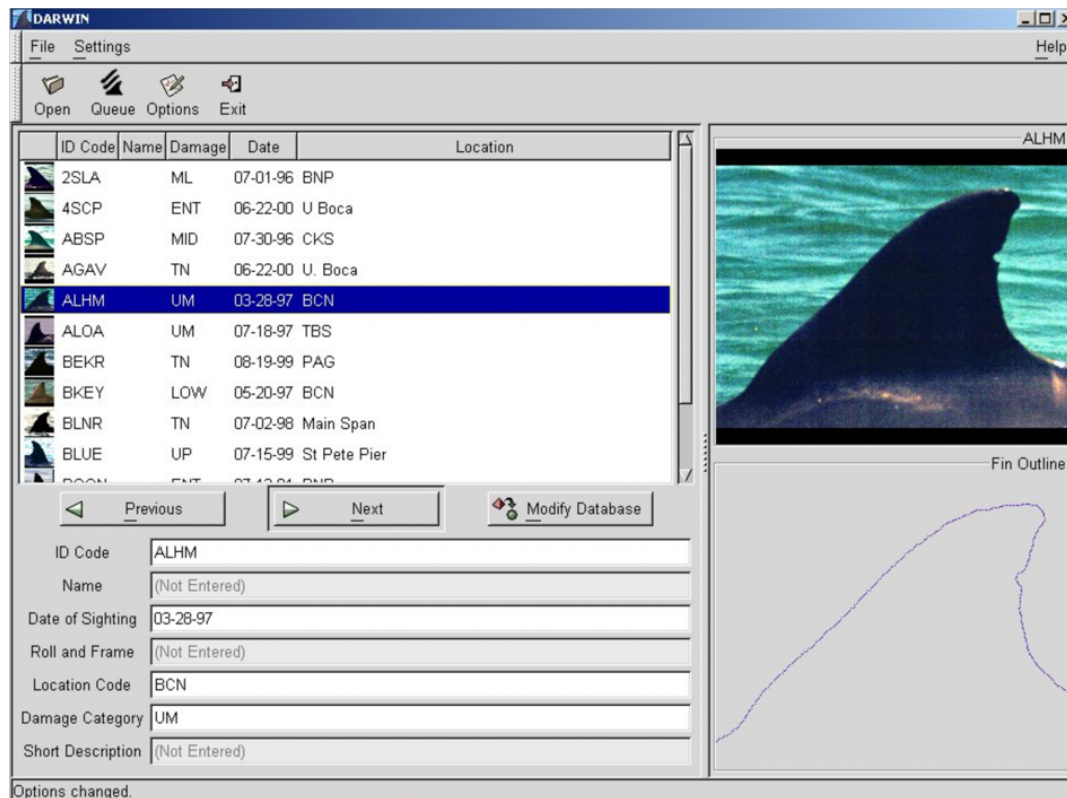


Figure 1.6: Main Window of DARWIN. The left panel displays a list of images and sighting data from the database, while the right panel shows the selected individual's image alongside its fin outline, which has been refined using an active contour (Eckerd College).

Finscan is a computer-assisted individual recognition system developed for bottlenose dolphin dorsal fin images. The model computes a description of the dorsal fin edge, compares it to a database of previously processed images, and it allows the operator to control fin description, matching, and final identification confirmation (Hillman et al., 2003).

Semi-automated image recognition has proven effective for species with clear and consistent markings, but the complex patterns and shapes of several species such as humpback whale flukes pose challenges to fully automating the matching process (Cheeseman et al., 2021). Artificial intelligence (AI) replicates human intelligence, enabling computers to perform human-like tasks and enhance efficiency across various jobs (Wang et al., 2020). AI in photo identification aims to enhance accuracy in matching individual whales, reduce time consumption and contribute to conservation efforts (Khan et al., 2022). Flukebook (<https://www.flukebook.org>) is a non-profit, open-source tool for cetacean data archiving, analysis, and photo identification, developed as part of the broader Wildbook platform (<https://wildme.org/#/wildbook>). Users upload data through a web interface, where the platform currently supports automatic matching for 15 cetacean species using seven major ID algorithms. These algorithms identify 30 species-specific features, including flukes, dorsal fins, saddle

patches, dorsal ridges, flank spots, scratches, and head callosities, returning a different best-matching image for each algorithm, emphasizing the advantage of using multiple algorithms for improved identification accuracy (Figure 1.7) (Blount et al., 2022).

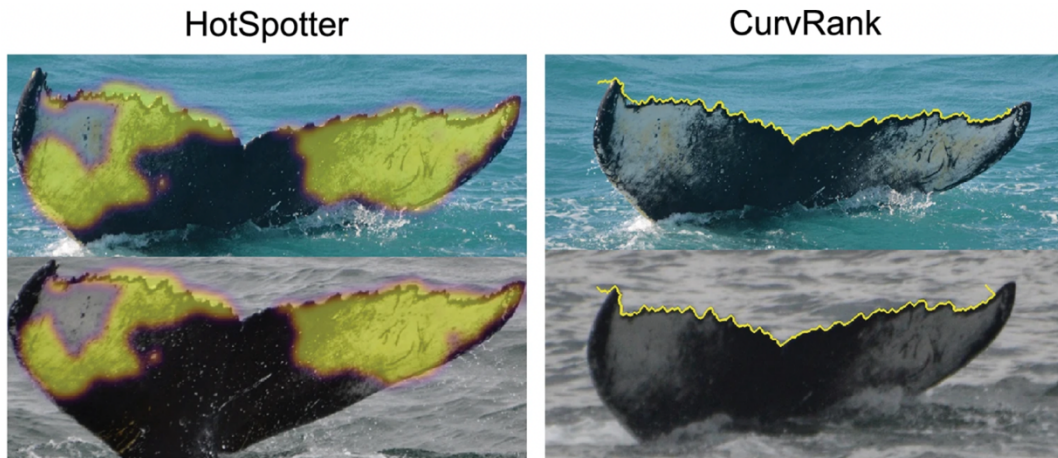


Figure 1.7: Humpback whale fluke matched using two algorithms (HotSpotter and CurvRank). The top images in both comparisons show the new unidentified fluke, while the best-matching database photos appear at the bottom. On the left, HotSpotter identifies distinctively matched “hotspots” between the images, highlighted in the comparison. On the right, CurvRank extracts and matches the trailing edges, with the highlighted segment representing the extracted contour (Blount et al., 2022).

1.5.3. Open-population models

Capture–recapture studies of open populations involve multiple sampling occasions where newly captured animals are individually marked, and the identities of previously captured animals are recorded (Nichols, 2010; Powell and Gale, 2015).

The Lincoln-Petersen method is the earliest technique used to estimate population size based on marked animals (Böhning, 2008; Powell and Gale, 2015). The method seems to have been independently discovered multiple times, for example by P.S. Laplace (1783); by C.G.J. Petersen (1889); by F.C. Lincoln (1930) and by C.H.N. Jackson (1933) (Nichols, 1992). It involves capturing an initial sample of n_1 animals, marking them, and then releasing them back into the population (Nichols, 1992). Subsequently, a second sample of n_2 animals is collected from the population and the number of previously marked animals recaptured in the second sample is denoted m_2 (Nichols, 1992). The estimate population size is calculated with the Lincoln-Petersen equation: $N^{\wedge} = \frac{n_1 \cdot n_2}{m_2}$ (Nichols, 1992; Powell and Gale, 2015). However, the need for estimators to address different sampling scenarios was later recognized, leading to the development of various classes of capture-recapture models (Nichols, 1992).

Open-population capture-recapture models are used widely in population ecology and wildlife management to estimate animal abundance and related parameters to allow estimation of time-specific survival, recruitment, population growth rate, and population size by maximum

likelihood (Efford and Schofield, 2019). In open-population models, the processes of birth, death, and migration are incorporated, allowing the population size to vary over the course of the study (Pollock and Alpizar-Jara, 2010). Two classes of open-population models have been developed: the first class exemplified by the original model of Cormack (1964), and the second class exemplified by the model of Jolly (1965), Seber (1965) and Crosbie and Manly (1985), consolidated later by Schwarz and Arnason (1996) (Nichols, 2010).

The first class is conditional on the number of animals released during each sampling occasion and it enables the estimation of subsequent survival and capture probabilities (Nichols, 2010). The second class is unconditional, and it models both the capture histories of marked animals after release and the initial captures of unmarked animals (Nichols, 2010), allowing for the estimation of quantities such as apparent survival rates, capture rates, population sizes and number of new animal (Pledger et al., 2003). In addition to these two approaches for modeling data from open populations, Pollock (1982) introduced a robust design, which incorporates sampling at two temporal scales, where multiple secondary samples are contained within each primary sample (Efford and Schofield, 2019).

The Jolly-Seber-Schwarz-Arnason (JSSA) model is the most widely used within this class of open-population models (Pollock and Alpizar-Jara, 2010), and it is considered as a fully open-population model estimating both abundance and survival (Schwarz, 2001). The JSSA model necessitates recording the number of uniquely marked and unmarked animals during each trapping occasion (Jolly, 1965; Seber, 1965; Pollock and Alpizar-Jara, 2010). It is parameterized in terms of population size N , but it doesn't account for the spatial distribution of animals, and it doesn't incorporate capture as a spatial process (Efford and Schofield, 2019).

In recent years, a major advancement has been made on the related challenge of estimating population density (Efford and Fewster, 2012), leading to the development of a set of methods known as Spatially Explicit Capture-Recapture (SECR) (e.g. Efford, 2004; Gardner et al., 2018; Efford and Schofield, 2019). The R (R Core Team, 2018) package openCR (Efford, 2019) is built upon the SECR package, extending its functionality to account for open population dynamics and implementing JSSA model in various parameterizations with spatial extensions (Efford, 2019).

1.6. OBJECTIVES

This thesis aims to establish comprehensive catalogs of baleen whale species in the Algarve, specifically of humpback and fin whales, focusing on their temporal presence and residency patterns.

- Objective 1: Assess seasonal occurrence and habitat usage of humpback whales in the Algarve and their regional connectivity within the North Atlantic basin
- Objective 2: Examine anthropogenic impacts on humpback whales, with a focus on fisheries activities
- Objective 3: Investigate fin whales sightings and site fidelity in the Faro area
- Objective 4: Estimate fin whales population size in the Algarve

These two catalogs will be the first of their kind for the Algarve, offering baseline data that can be used for future monitoring and conservation efforts. The thesis will consist of two manuscripts: the first will focus on humpback whales covering objectives 1 and 2, while the second will address fin whales covering objective 3 and 4. Both studies have been derived from previous photo-identification efforts conducted in the Algarve.

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Chapter 2 – First Manuscript

Occurrence and anthropogenic threats affecting humpback whales (*Megaptera novaeangliae*) in the Southern Iberian Atlantic waters

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ABSTRACT

Humpback whales' extensive migratory behavior and vital role in marine ecosystems make them a focal point in conservation efforts. However, migration routes in many regions remain poorly understood. The Algarve, in southern mainland Portugal, is one of these regions, experiencing upwelling events on the southwest coast, while the southeast is influenced by warm, saline Mediterranean waters. This study represents the first comprehensive effort to catalog humpback whales in the Algarve, analyzing their presence, residency patterns, and interactions with human activities. Using photo-identification techniques, data from 2009 to 2024, collected in collaboration with local whale-watching companies and the Algarve Stranding Network (RAAlg), recorded 14 live sightings and three dead stranded whales. Fluke patterns were processed with software and compared internally and with the North Atlantic Humpback Whale Catalog (NAHWC). Matches linked individuals within the Algarve and across the North Atlantic, including Boa Vista (Cabo Verde), the Ligurian Sea (Italy), and Gairloch (Scotland), highlighting extensive migration. Sightings peaked in spring and autumn, aligning with phytoplankton blooms. Entanglement in fishing gear was identified as a significant threat, especially for juveniles. This study will bridge gaps in humpback whale movements in the Eastern North Atlantic and Portugal, aiding conservation and management strategies in the Algarve.

Keywords: Algarve, catalog, fisheries interactions, migration, North Atlantic, photo-identification

2.1.INTRODUCTION

Migration is a crucial behavior for many animals, allowing them to adapt their life history requirements to their environments' temporal and spatial variability (Kettemer et al., 2022). Among marine mammals, humpback whales (*Megaptera novaeangliae*) stand out as a highly migratory species, and their survival is heavily reliant on established migratory routes (Stone et al., 1990; Kennedy et al., 2013; Peres dos Santos et al., 2022). Although this species is one of the most researched marine mammals worldwide, very little is known about its existence in various parts of the world. For nearly 50 years, photographic identification (photo-ID) techniques have facilitated in-depth studies of their long-distance migration patterns (Schevill and Backus, 1960; Katona and Whitehead, 1981; Reeves et al., 2006; Chosson et al., 2024). This type of identification is possible because individual humpback whales can be identified by the distinctive patterns on the ventral surface of their flukes (Schevill and Backus, 1960; Katona and Beard, 1990; Reeves et al., 2006), often complemented by variations in the shape, edges, scratches, and coloration of the dorsal fin (Blackmer et al., 2006). Notably, the North Atlantic Humpback Whale Catalog (NAHWC), maintained by Allied Whale at the College of the Atlantic, Bar Harbor, Maine, USA (<https://www.coa.edu/allied-whale/>), has documented over 12,000 individual humpback whales from the North Atlantic Ocean basin (Jones et al., 2025).

Typically, North Atlantic humpback whales feed at high latitudes where the cold, nutrient-rich waters in these areas promote high levels of productivity, thereby providing humpback whales with ample feeding opportunities (Smith et al., 1999; Stevick et al., 2003; Larsen and Hammond, 2004; Jones et al., 2025). Humpback whales migrate from summer and fall feeding grounds to winter breeding grounds in tropical regions characterized by warm waters (Rasmussen et al., 2007; Kettemer et al., 2022; Jones et al., 2025). In the Northeast Atlantic, humpback whales forage in the Barents Sea and surrounding waters (Leonard and Øien, 2020; Hamilton et al., 2021; Kettemer et al., 2022), as well as around Iceland (Pike et al., 2022) and East Greenland (Heide-Jørgensen and Laidre, 2015; Kettemer et al., 2022). Once they have sufficiently fed, humpback whales migrate to breeding areas in the West Indies (Stevick et al., 2003; Stevick et al., 2006b) or the Cabo Verde Islands (Wenzel et al., 2009; 2020), where the population of humpback whale breeding and calving is listed as endangered under the US Endangered Species Act (ESA) (Chosson et al., 2024). These migratory patterns underscore the importance of nutrient-rich environments in the North Atlantic, including coastal and mid-ocean areas that could serve as stopover sites (Visser et al., 2011; Grove et al., 2023).

One of these coastal areas is the Algarve, influenced locally by upwelling events, mostly occurring in the southwestern area (Marçalo et al., 2024), while the southeastern area is affected by the warmer and more saline waters of the Mediterranean Sea (Bettencourt et al., 2004). These natural processes, which bring nutrient-rich waters to the surface, significantly enhance the local marine ecosystem, creating a productive environment where various prey species, such as krill and small fish, thrive (Bakun et al., 2015). Consequently, the region's enhanced biodiversity not only sustains local marine species but also significantly contributes to the growth of the tourism industry. The Algarve is a prominent European tourist destination renowned for its whale-watching industry and marine biodiversity (e.g. Claro, 2009; Sequeira et al., 2009; Morais et al., 2021). The industry is notably seasonal, with peak activity from late spring to early fall, although some companies continue whale-watching operations throughout the year (Morais et al., 2021). Despite the numerous companies involved, formal scientific research on the area remains limited (Morais et al., 2021). As a well-known tourist destination, the Algarve encompasses various economic sectors, including fisheries (Bueno-Pardo et al., 2021; Bellanova et al., 2022) and agriculture, especially for citrus crops (Chester and Chester, 2010), almond production (Oliveira, 2024) and figs (De Santos Loureiro and Fernandes, 2021). The Algarve shelf is often traversed by maritime routes linking the northern Atlantic Ocean with the Mediterranean Sea (Bellanova et al., 2022). These human activities contribute to significant anthropogenic impacts that potentially can affect marine mammals.

Given the lack of studies and the crucial role of the Algarve in providing nutrient-rich waters, it is hypothesized that this region could serve as a critical foraging habitat along humpback whale migratory routes, as observed in other cetacean species. For example, common short-beaked, *Delphinus delphis*, and bottlenose dolphins, *Tursiops truncatus*, have important foraging areas in the Algarve region (Forli et al., 2024; Marçalo et al., 2024, 2025). This region could serve as an ideal stopover, allowing humpback whales to replenish their strength after extensive periods of travel. Furthermore, the recent discovery of three young humpback whales stranded along the Algarve coast (Ana Marçalo, personal communication) also suggests that younger individuals may be exploring areas beyond their usual migratory route, potentially encountering new, human-made threats. This study aims to assess the presence of humpback whales in the Algarve region by determining their seasonal patterns and specific areas of occurrence. To achieve this, individuals identified in the Algarve will be compared with those in the NAHWC. We also intend to investigate the impact of the Algarve's human activity on humpback whales, providing a comprehensive understanding of their potential threats.

2.2. MATERIAL AND METHODS

2.2.1. Study Area

The study area corresponds to the coastal area of the Algarve region in southern Portugal, extending from Tavira to Sagres. The data were collected from platforms of opportunity, namely Ocean Vibes operating in Faro (Figure 2.1, red municipality), WildWatch operating in Lagoa (Figure 2.1, orange municipality), SeaLife operating in Lagos (Figure 2.1, green municipality), Mar Ilimitado and AlgarveDolphinLovers operating in Vila do Bispo (Figure 2.1, blue municipality), more precisely in Sagres and Burgau respectively.

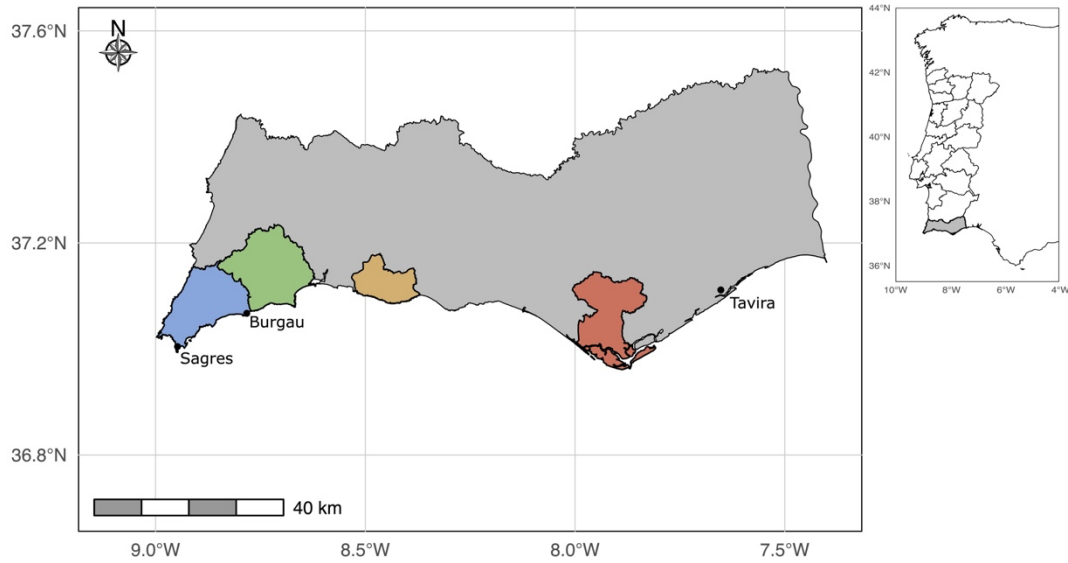


Figure 2.1: Map of the study area along the Algarve coast in southern Portugal, with the Algarve region shaded in gray. Key municipalities where data were collected from local whale-watching companies are color-coded: Faro in red, Lagoa in orange, Lagos in green, and Vila do Bispo in blue. The top-right inset shows the location of the Algarve in Portugal.

2.2.2. Data Collection

The collection of images and data for individual humpback photo-ID occurred from 2009 to 2024 with the aid of local whale-watching companies. These sea trips lasted 1.5 to 2.5 hours, with 1 to 4 daily trips depending on the season and weather conditions. Sightings were documented from the boat, and trained observers and biologists gathered data. For stranded humpback whales, fluke pictures were taken by RAAlg, who operated continuously throughout the Algarve region from 2010 to 2017 and from October 2020 to the present.

2.2.3. Photograph Identification

The features used to identify individual humpback whales were ventral flukes and dorsal fins for the Algarve regional catalog. Additionally, the GPS position of each sighting was

collected. The photos taken in the field were analyzed with a web-based, multi-species software for the processing, matching, and storing of digital photo-identification images called MICS-PIX (Paquet et al., 2009). Each fluke photograph was categorized based on its percentage of black pigmentation by assigning a number from one to five, where type one is less than 20% black and type five is between 85% and 100% black (Friday et al., 1997, 2000). More information about that individual was then added, including location, exact GPS coordinates when available, sex, whether the individual was a calf or not, and any other relevant comments. Lastly, each photo was assigned a letter according to its quality, starting with 'Cat *', meaning the best possible quality, and going down to the letter C or D for poor-quality photos. Three independent researchers confirmed the distinguishing features of each individual. After this matching process, individuals were assigned a code number in the regional catalog. Afterward, only individuals with fluke ID pictures were compared with the NAHWC, and these images were compared to the complete catalog according to the standards in Katona and Whitehead (1981) and Jones et al. (2025) (Table 2.1).

2.3. RESULTS

Between 2009 and 2024, 9,890 trips were conducted by the whale-watching operators included in this study. While data from 2009 to 2019 were available from a single operator, the dataset from 2020 to 2024 includes contributions from multiple whale-watching companies. Seasonal distribution of field effort shifted noticeably between the two periods from 2009 to 2019 and 2020 to 2024 (Table 2.2). During 2009–2019, winter trips made up only 1.18% of the total effort (58 out of 4.926 trips), while in 2020–2024, this rose to 3.69% (183 out of 4.964 trips). Spring remained relatively stable, representing 18.11% of trips in 2009–2019 (892 out of 4.926 trips) and 20.10% in 2020–2024 (998 out of 4.964 trips). Summer consistently dominated field effort, although it decreased slightly, comprising 62.36% of all trips in 2009–2019 (3.071 out of 4.926 trips) and 55.05% in 2020–2024 (2.732 out of 4.964 trips). Autumn effort also increased, rising from 18.37% during 2009–2019 (905 out of 4.926 trips) to 21.17% in 2020–2024 (1.051 out of 4.964 trips). Excluding years 2020 and 2021, when severe restrictions on regular whale-watching operations were implemented due to the COVID-19 pandemic, winter effort rose from 3.69% to 4.22% (162 out of 3.838 trips), spring from 20.10% to 24.73% (949 out of 3.838 trips), summer decreased from 55.05% to 52.16% (2.002 out of 3.838 trips) and autumn from 21.17% to 18.89% (725 out of 3.838 trips). With whale-watching efforts, and since the establishing of a regional stranding network (RAAlg, established in 2010), seventeen occurrences have been reported in this region, initially estimated to involve potentially up to eighteen individual humpback whales before the photo-identification process. Of these, three were found dead and stranded; photo-identification was possible for two of them, while for the third, identification was not feasible due to both fluke lobes being cut/removed, excluding it from the Algarve regional catalog and thus from code assignment (Table 2.1). Given the lack of some GPS positions, the sightings were assigned to the closest city in the Algarve.

Table 2.1: Humpback whale individual sightings and respective re-sighting within the Algarve and with the North Atlantic Humpback Whales Catalog.

Code number	Date	Area	Number of individuals	Fluke ID	Re-sighting to
None	2014-05-10	Cabanas de Tavira (stranded)	1	No	Not re-sighted
Mn101	2021-06-10	Tavira (stranded)	1	Yes	2021-04-10, Boa Vista-Cabo Verde
Mn102	2023-06-04	Lagos			2023-04-16, Liguria-Italy; 2023-06-04, Sagres-Algarve

	2023-06-04	Sagres	1	Yes	2023-04-16, Liguria- Italy; 2023-06-04, Lagos-Algarve
Mn103	2023-09-22	Faro	1	Yes	2023-07-31, Gairloch-Scotland
Mn104	2024-05-18	Faro	1	Yes	Not re-sighted
Mn105	2024-05-27	Portimao	1	Yes	Not re-sighted
Mn106	2024-09-10	Faro	1	Yes	2024-09-20, Lagos-Algarve; 2024-09-22, Sagres-Algarve
	2024-09-20	Lagos			2024-09-10, Faro-Algarve; 2024-09-22, Sagres-Algarve
	2024-09-22	Sagres			2024-09-10, Faro-Algarve; 2024-09-20, Lagos-Algarve
Mn107	2022-11-24	Lagos (stranded)	1	Yes	Not re-sighted
Mn108	2024-10-27	Faro	2	Yes	Not re-sighted, one of the individuals was not identified
Mn109	2009-07-12	Sagres	1	No	Not re-sighted
Mn110	2015-09-01; 2015-09-02; 2015-09-06	Sagres	1	Yes	Not re-sighted
Mn111	2012-07-05	Ria Formosa Natural Park (Faro)	1	No	Not re-sighted
Mn112	2017-07-10	Sagres	1	Yes	Not re-sighted
Mn113	2019-10-31	Sagres	1	Yes	Not re-sighted

Table 2.2: Total number of trips between 2009 to 2019, 2020 to 2024, 2022 to 2024 across each season.

	Total number of trips			
Period	Winter	Spring	Summer	Autumn
2009–2019	58	892	3.071	905
2020–2024	183	998	2.732	1.051
2022–2024	162	949	2.002	725

After the photo-quality determination for identification process, it was possible to identify thirteen individuals (Mn101-Mn113) of the seventeen occurrences, including two stranded animals and one with two humpback whales sighted together. Additionally, the non-identified individual found dead in 2014 was confirmed to be a distinct animal, bringing the total number of individual humpback whales recorded in the region to fourteen. An initial internal comparison of each individual confirmed a match (Mn106) between three sightings twelve days

apart in different areas of the Algarve (Figure 2.2, yellow points). This link between Faro, Lagos, and Sagres (Figure 2.3h, i, l) and between Lagos and Sagres (Figure 2.2, dark pink arrow; Figure 2.3d, e) underscore the importance of Algarve coastal areas. Additionally, one individual (Mn110) was recorded three times in succession within six days in the Sagres area (Figure 2.2, brown point). A subsequent comparison with the NAHWC revealed three further matches (Mn101, violet points; Mn102, pink points; Mn103, light blue points) between individuals in the Algarve and various locations across the North Atlantic basin, including one match identified in the Mediterranean Sea (Figure 2.2).

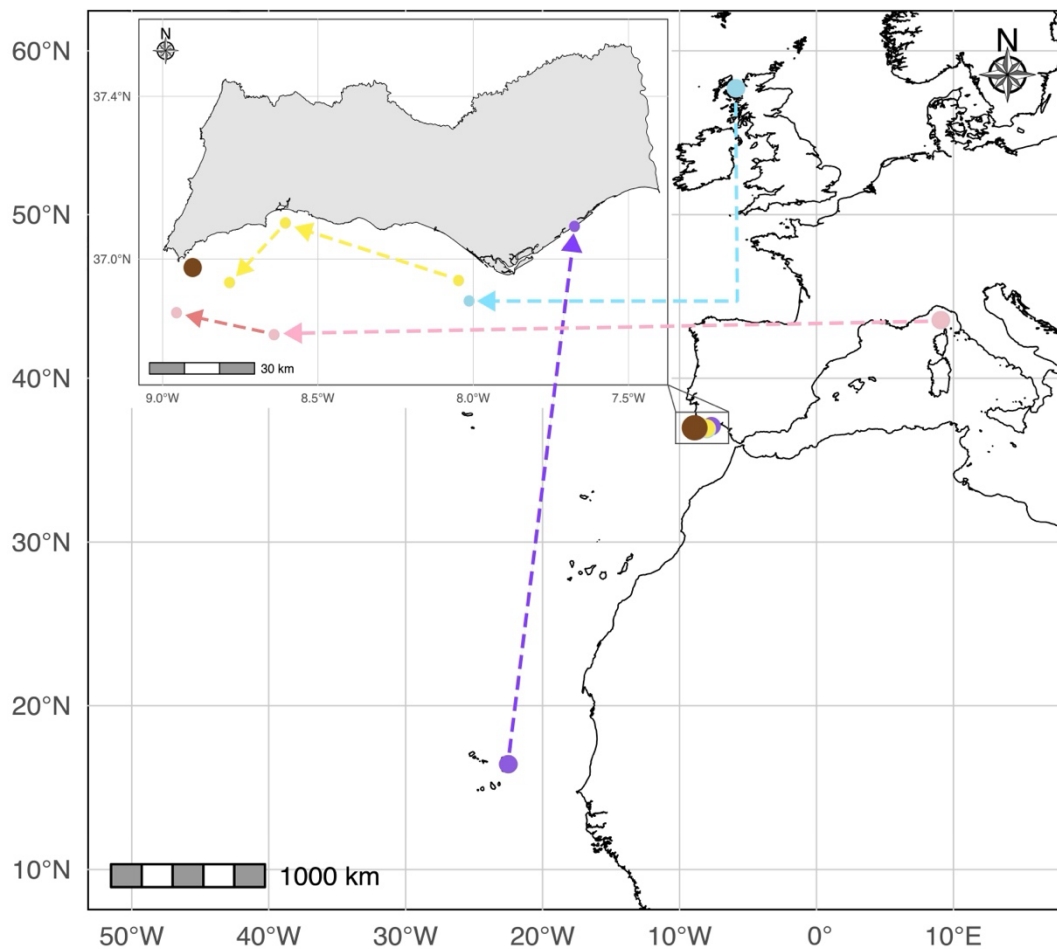


Figure 2.2: Occurrence of humpback whales re-sighted elsewhere in the North Atlantic and the Algarve region. Mn101 between Boa Vista (Cabo Verde) and Tavira (violet); Mn102 between Ligurian Sea (Italy) and Algarve (light pink) and Lagos and Sagres (dark pink arrow); Mn103 between Gairloch (Scotland) and Faro (light blue); Mn106 between Faro, Lagos and Sagres (yellow); Mn110 recorded three times in succession within six days in the Sagres area marked with a brown circle. Lines represent graphically the shortest migratory distance, not migratory pathways.

Connections have been traced from the Ligurian Sea (Italy) to Sagres and Lagos (Figure 2.3c, d, e), indicating migratory pathways that link these regions. Another significant match

involves Gairloch (west Scotland) and Faro (Figure 2.3f, g), showcasing the mesoscale migratory movements of humpback whales.

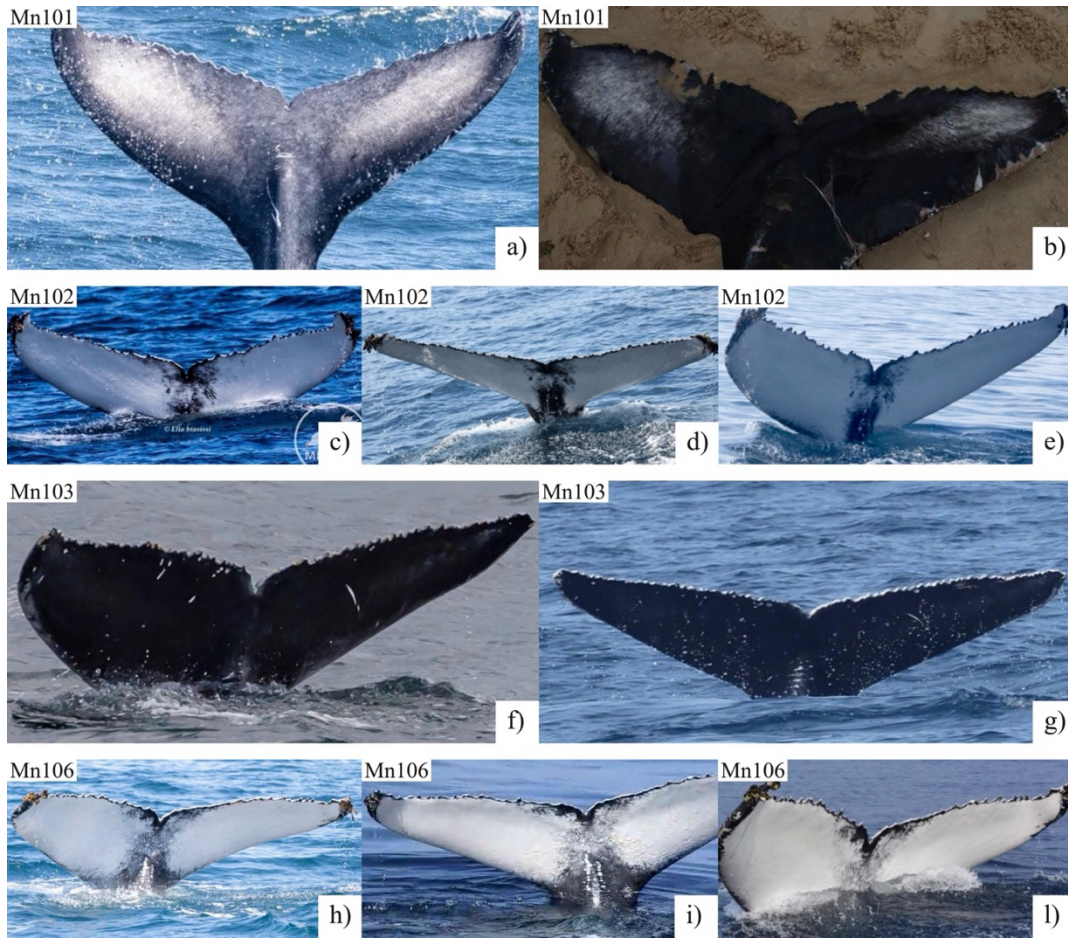


Figure 2.3: Fluke photo-identification comparison of matched humpback whale individuals sighted in the Algarve and elsewhere in the North Atlantic. The images show confirmed matches of different individuals within different locations: Mn101 in (a) Boa Vista; (b) Tavira; Mn102 in (c) Liguria Sea; (d) Lagos; (e) Sagres; Mn103 in (f) Gairloch; (g) Faro; Mn106 in (h) Faro; (i) Lagos; (l) Sagres.

Of the two stranded individuals identified, one (Mn101) was matched with the NAHWC. This match identified between Boa Vista (Cabo Verde) and Tavira, Portugal (Figure 2.3a, b) involved a male individual stranded in Tavira measuring 6.87 meters, suggesting that it was a calf (Clapham et al., 1999; Boye et al., 2020), which was confirmed with the photo-ID information from Cabo Verde, where the same individual had been observed in early April that year in a known breeding ground from the northeast Atlantic population (Wenzel et al., 2020). This individual has been reported to RAAI, entangled in a pots fishery a few days before his stranding. The other two stranded individuals showed clear interactions with human activities (Mn107 and a non-identified individual) and were female calves/juveniles measuring 8.6 and 8.7 meters (Clapham et al., 1999), respectively. Mn107 exhibited a line mark (Figure 2.4a). At the same time, the non-identified animal showed clear cuts on its flippers

(Figure 2.4b) and the fluke (Figure 2.4c), indicating that these individuals had clear interactions with fishing gear.

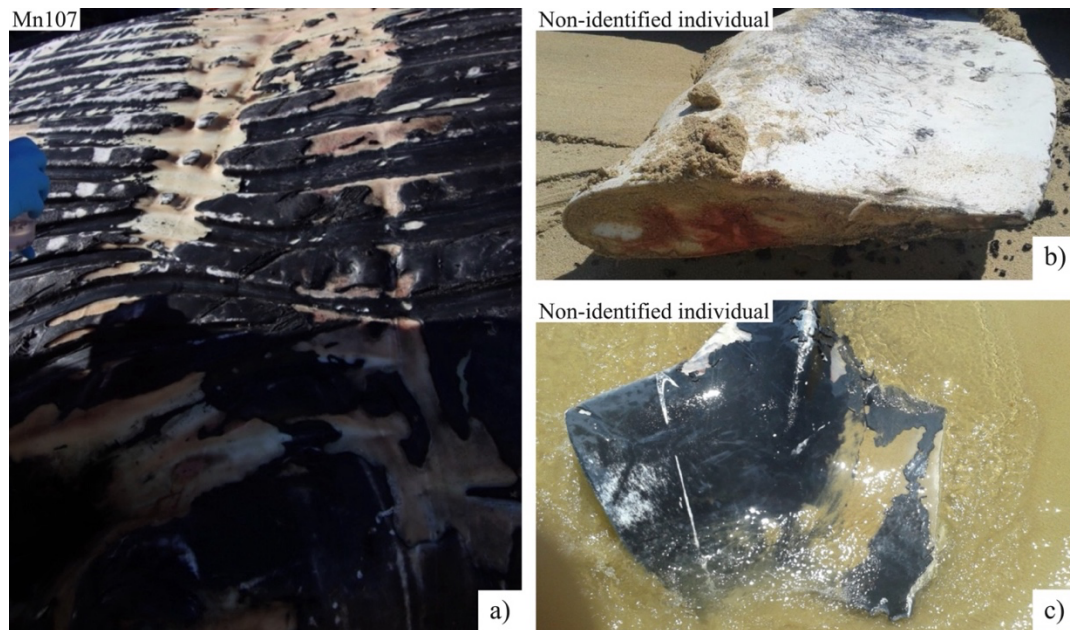


Figure 2.4: Evidence of human-related impacts on stranded humpback whale individuals: (a) Mn107 exhibiting a distinct line mark indicative of entanglement in fishing gear; (b) and (c) A non-identified stranded individual clearly displaying cuts on its flipper and fluke suggesting that the animal was trapped in a net and fishermen had to cut the entangled body parts to release it.

2.4. DISCUSSION

This study provides the first assessment of fisheries' impact on humpback whales in the Algarve region. The seasonal presence of humpback whales along the Algarve coast offers new insights into the migratory behavior of this species in the Northeast Atlantic. By documenting regular occurrences during specific periods of the year and identifying individual whales through photo-identification, this study sheds light on the ecological significance of southern Portuguese waters as part of a larger migratory corridor. While the data support the idea of the Algarve acting as a transitory zone, potentially used for opportunistic feeding, several patterns and anomalies warrant closer examination. These include variations in sighting frequency, the possible influence of human activity on reporting rates, and the incidence of fisheries-related strandings. The following discussion explores these patterns in greater detail, offering interpretations in the context of regional oceanography, migratory timing, and anthropogenic pressures.

Our results reveal that humpback whales occur annually in the Algarve region, mostly during spring to early summer (May to July) and late summer to early autumn (September to November). The number of individuals was consistent, except for October and November, which recorded the lowest numbers. The fact that humpback whales are sighted primarily in spring (May and June) aligns with their northward migration from Cabo Verde or Northwest Africa, where the last recorded sightings occur in the final week of May (Wenzel et al., 2020), while their presence in early autumn aligns closely with the timing of phytoplankton blooms in the Algarve region (Santos et al., 2020). During these seasons, nutrient-rich waters often lead to increased phytoplankton production in the Algarve region, which serves as a critical food source for various marine organisms, including the small fish and krill that humpback whales typically feed on (Coelho et al., 2007; Botterell, 2023). The uniformity in the number of sightings during these times of the year suggests that humpback whales are taking advantage of the abundant food resources available during these periods in this area. This hypothesis is further reinforced by the observation of an individual (Mn110) recorded three times in non-consecutive days within six days in September 2015 in the Sagres area, as well as another individual (Mn106) sighted in three different areas of the Algarve within a 12-day span during September 2024.

The decrease in observations in October and November, the months with the fewest observations, may indicate that during these months, humpback whales start their migration to

winter breeding grounds in tropical regions (Smith and Pike, 2009; Kennedy et al., 2013; Kowarski et al., 2021). From 2021 to 2024, the interval with the most sightings, the number of individual humpback whales has increased during the years, suggesting either a growth in individuals that visit this area, which may have become part of a new migratory route, or an increased human engagement in whale-watching activities outside the typical Algarve season from June to September (Morais et al., 2021). Supporting this, a comparison of efforts between 2009–2019 and 2020–2024 showed an increase in whale-watching activity during winter, spring, and autumn. 2021 and 2022 had the lowest sightings. This trend may be attributed to several factors, including changes in human activity due to the COVID-19 pandemic. During the pandemic, the tourist sector suffered a significant drop (Castanho et al., 2021), and there were significant restrictions on boating and recreational activities, which likely resulted in fewer opportunities for whale-watching and fewer sightings being reported. As restrictions eased and people returned to the water more frequently, boat outings increased, probably leading to more whale sightings. Using photo-identification techniques, this research successfully established links between individual humpback whales migrating through the NE Atlantic, shedding light on migration behavior. Baleen whales, including humpback whales, traverse vast latitudinal and longitudinal ranges within the NE Atlantic, migrating freely across this expansive area (Alves et al., 2018; Purcari, 2023). This extensive movement results in significant temporal and spatial variation in species composition across different sub-regions of the NE Atlantic (Correia et al., 2020; Purcari, 2023).

Our findings also suggest that when entering newly explored habitats, these extensive movements increase the exposition of this species to local anthropogenic impacts, including fishing activities, with potentially severe consequences for the population. The coastal waters off Western Iberia are critical fishing grounds and foraging areas for marine megafauna, causing overlaps between fisheries' target species and the diet of some air-breathing marine megafauna species (Alexandre et al., 2022; Marçalo et al. 2024, 2025). A substantial component of Portuguese fishing is small-scale fisheries because 85% of the fleet is formed of small-scale vessels using static gears (Pita and Gaspar, 2020). Although small-scale fisheries in mainland Portugal, such as purse seining, bottom-set nets (gill and trammel), set longlines, pots, and traps (Pita and Gaspar, 2020) dominate the fishing scenario, demersal trawling also remains a critical activity due to its economic contribution, particularly through high-value crustacean fisheries (Bueno-Pardo et al., 2021). Because of the cumulative effects of human activity on their environment, migratory marine animals are becoming more and more susceptible to extinction and population drops (Halpern et al., 2015; Pérez-Jorge et al., 2020). In mainland Portugal,

especially in southern waters, interactions between fisheries and cetaceans mainly concern bottlenose dolphins, short-beaked common dolphins and striped dolphins (*Stenella coeruleoalba*) (Marçalo et al., 2015, 2021, 2024, 2025; Alexandre et al., 2022).

This study revealed that approximately 18% of sightings were found dead and stranded due to interactions with fishing gear. However, this percentage is based on a small sample size and may represent an overestimation that does not fully reflect the true impact at the population level. Despite this limitation, it nonetheless raises concern when compared with studies that estimate that humpback whale populations in Iceland, the Gulf of Maine, and Alaska become entangled in fishing gear at rates of 2%, 14-17%, and 8% per year, respectively (Basran and Rasmussen, 2021). A study in Iceland assesses that approximately 25% of humpback whales show scarring, indicating they have been entangled in fishing gear at least once (Basran and Rasmussen, 2021). At the same time, a study in northern Southeast Alaska determined that the number of humpback whales entangled has increased, with scarring most frequently observed on the caudal peduncle (Neilson et al., 2009).

A study that aimed to investigate fisheries interaction with humpback whales in the western North Atlantic revealed that entanglements are a significant cause of injury and death for humpback whales, involving buoy line and/or groundline and with common attachment sites being the tail (53%) and the mouth (43%) (Johnson et al., 2006). The same study reported that three humpback whales were known to have died after entanglement. Similarly, pot and trap fishing gear is the leading cause of non-natural mortality in baleen whales stranded in Scotland, where 50% of humpback whales were caught in groundlines between pots (Leaper et al., 2022). The stranded individuals in this study were young and possibly less experienced or more vulnerable in avoiding anthropogenic impacts.

The vulnerability of stranded individuals observed in this study is consistent with research from the Gulf of Maine, where stranded whales were also found to be sexually immature (Wiley and Asmutis, 1995) and with the age-class of stranded whales catalogued in the York Bight Apex (NYBA) (Brown et al., 2022). Humpback whale populations have shown signs of worldwide recovery (Ristau et al., 2019), possibly leading to a broader distribution and expansion into previously unexplored areas. Consequently, human activities in these regions may need to adapt fishing methods or timing to mitigate their impact on this species.

This study offers the most detailed analysis of humpback whale presence and migration in the Atlantic Southern Iberia, including the first regional photo-ID catalogue. Humpback whales were observed annually in the Algarve, mainly from May to July and again from September to November. Spring sightings reflect northward migration from Cabo Verde or Northwest Africa,

while autumn presence may indicate southward migration or also be linked to local phytoplankton blooms. Between 2021 and 2024, sightings increased, possibly due to more humpback whales visiting the region or greater whale-watching efforts outside the usual season. The repeated use of this region by humpback whales indicates the potential importance of the Algarve as a migratory stopover habitat, serving as a temporary feeding rather than a long-term habitat. However, entering new areas may increase exposure to anthropogenic threats, particularly fishing practices, especially for young exploratory individuals, possibly leading to future mortalities. While reported incidents in Portuguese waters remain sparse, the lack of dedicated research underscores the urgency for further studies. By addressing these knowledge gaps, future research can provide a stronger foundation for conserving and managing this and other cetacean species in the Algarve region.

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Chapter 3 – Second Manuscript

Opportunistic data for assessing abundance and site fidelity of fin whales (*Balaenoptera physalus*) in the Faro area, Portugal

ABSTRACT

Fin whales (*Balaenoptera physalus*) distribution and migration remain poorly understood in parts of the North Atlantic. One of these regions is the Algarve in southern Portugal, shaped by seasonal upwelling and Atlantic-Mediterranean water exchange. This area represents a potentially critical yet poorly understood habitat for this species. This study presents the first comprehensive assessment of fin whale abundance and site fidelity in the Faro area. Data were collected from 2020 to 2024 through photo-identification and GPS boat tracks, in collaboration with a local whale-watching company. A regional catalog of 86 individuals was established, and an open spatially explicit capture-recapture model estimated a population of 1.476 individuals. Sightings peaked in spring, likely linked to phytoplankton blooms and foraging opportunities. While re-sighting rates were low, some individuals returned across years, indicating possible seasonal site fidelity. Our results demonstrate the value of data collected from platforms of opportunity in an under-surveyed region and provide a foundation for ongoing monitoring efforts. Results also highlight the Faro area's ecological relevance as a seasonal feeding ground for fin whales and offer insights to support future conservation in the eastern North Atlantic.

Keywords: Algarve, capture-recapture, photo-identification, whale-watching

3.1. INTRODUCTION

Abundance, defined as the number of individuals within a population, is a fundamental parameter for ecosystem assessment and wildlife conservation strategies, serving as essential metric for evaluating population status, monitoring trends, and identifying drivers of population growth or decline (e.g. Peel et al., 2014; Pike et al., 2005; Sharpe and Berggren, 2024; Tardy et al., 2023). However, detecting trends in marine wildlife populations has long been recognized as a challenge, particularly for broad-scale surveys of oceanic species, like cetaceans. Their biological and behavioral characteristics, such as spending most of their time submerged and ranging across vast distances, make data collection logistically tricky, and even harder to estimate abundance among these species (e.g., Pace et al., 2017; Sharpe and Berggren, 2024).

Among cetaceans, the fin whale (*Balaenoptera physalus*) has experienced some of the most dramatic fluctuations in abundance over the past 200 years (Schleimer et al., 2019). During the commercial whaling era (approximately 1890–1980), more than 900,000 fin whales were harvested globally, leading to a population decline of over 70% (Edwards et al., 2015). Fin whale abundance in the post-whaling era appears to have increased off the west coast of the USA, along the coast of western Greenland, in the Northeast and Central Atlantic and the northern Gulf of Alaska (Edwards et al., 2015), however, in other regions, the extent of their recovery remains uncertain due to limited data (Edwards et al., 2015). In 2018, the global abundance of this species was estimated at approximately 100,000 individuals, and it remains classified as ‘Vulnerable’ on the IUCN Red List of Threatened Species (Tardy et al., 2023). The fin whale is a widely distributed and long-lived species, inhabiting warm to cold oceans globally; it has traditionally been considered migratory, undertaking long-distance movements between summer feeding and winter breeding grounds. However, numerous exceptions to this pattern have been documented (Falcone et al., 2022). Year-round resident populations with limited or variable migratory patterns have been recorded in the semi-enclosed, warm waters of the Gulf of California (e.g., Bérubé et al., 2002; López et al., 2019) and the Mediterranean Sea (e.g., Castellote et al., 2011; Geijer et al., 2016; Notarbartolo-di-sciara et al., 2003). While fin whales are known to range across the entire North Atlantic basin, they also exhibit strong site fidelity to specific feeding grounds, suggesting regional variations in population dynamics and highlighting the importance of long-term, small-scale studies (Schleimer et al., 2019).

Understanding these dynamics is essential for estimating population trajectories, which have been approached through analyses integrating abundance estimates with harvest statistics and other relevant data (Biuw et al., 2024). There are two major classes of methods for

measuring abundance: line-transect surveys and capture-recapture methods. Ship line-transect methods (Burnham and Anderson, 1976) have been widely used to estimate whale abundance, including for Antarctic minke whales, fin whales in the North Atlantic, and baleen whales in the North Pacific (e.g., Calambokidis and Barlow, 2004; Barlow et al., 2011). These methods require measuring the perpendicular distances of animals from the survey track, with representative coverage typically achieved through systematic transect lines that uniformly span the study area (Norris et al., 2017).

Capture-recapture (or mark-recapture) techniques rely on the ability to uniquely identify, and track individuals based on photographs of their natural markings, in which re-sightings of marked individuals are used to calculate abundance (e.g., Dawson et al., 2008; Peel et al., 2014). The choice of method depends on whether the population being studied is closed, remaining unchanged during the investigation, or open, subject to changes through birth, death, and migration (Schwarz and Seber, 1999). Within this field of research, Spatially Explicit Capture-Recapture (SECR) models are increasingly being utilized for abundance estimation, offering a key advantage over non-spatial methods by mitigating the edge effect (i.e., temporary immigration/emigration) (Sharpe and Berggren, 2024). For cetaceans, most capture-recapture methods rely on individual identification, which is typically achieved through one of three approaches: satellite telemetry (e.g., Andrews et al., 2019; Sepúlveda et al., 2018), genotyping (Palsbøll et al., 1997), and photo-identification (Photo-ID) (Hammond, 1990). These methodologies typically rely on data collected from ship-based or aerial surveys, which are highly resource-intensive, and they require extensive data collection over many years, which can be costly (e.g., Bertulli et al., 2017; Sharpe and Berggren, 2024). To mitigate this, whale-watching (WW) has emerged as a valuable source of opportunistic data (Peres dos Santos et al., 2025), where observations are gathered during regular tours with paying customers. In this context, the photo-identification technique (Würsig and Würsig, 1977) is commonly used, allowing individuals to be identified based on natural markings, with the collected photos processed to obtain individual resighting over time.

In Portugal, between 1998 and 2008, WW experienced significant growth, accounting for approximately 23% of total revenues in Europe, the highest share on the continent (Forli et al., 2024). Of the 90 licensed WW companies in mainland Portuguese waters, 52 operate along the southern coast, known as the Algarve region (Forli et al., 2024). Despite intensive WW in the Algarve region, dedicated survey efforts to cetacean species have been limited, and information regarding their occurrence, spatial distribution, habitat preferences, and abundance remains scarce (e.g., Cartagena-Matos et al., 2021; Correia et al., 2015).

We hypothesized that fin whales show seasonal site fidelity in the Algarve, with higher occurrence during spring months, and WW vessels can provide valuable insights into their distribution, movement patterns, and abundance. The aim of this study is to provide baseline knowledge on the status of fin whales occurring in the Faro area (central region of the Algarve coastal waters) using opportunistic data collection from WW, namely photo-identification and boat tracks. First, a fin whale catalog is created, and the population size is estimated during consecutive years. Second, the degree of site fidelity and movement patterns is assessed during successive years and different seasons. Finally, this study evaluates the effectiveness of opportunistic data collection from WW vessels as a cost-efficient alternative for long-term monitoring of fin whale populations within the Faro area.

3.2. MATERIAL AND METHODS

3.2.1. Study Area

The Faro area is situated along the southwestern coast of the Iberian Peninsula, in the Algarve region, approximately between 36-37° N and 8-7° W (Figure 3.1A). Offshore waves affecting the Algarve shore are driven by SW and SE components, and they originate from the Atlantic or the area between Gibraltar and the coast (Vicente et al., 2008). The southern boundary of the Iberian upwelling is separated from the Northwest African upwelling by the Gulf of Cádiz and the entrance to the Mediterranean Sea (Relvas and Barton, 2002). During summer, the establishment of a thermally induced low-pressure center over the Iberian Peninsula generates westerly winds off the southern Portuguese coast, driving local upwelling in this area (Ferreira et al., 2022).

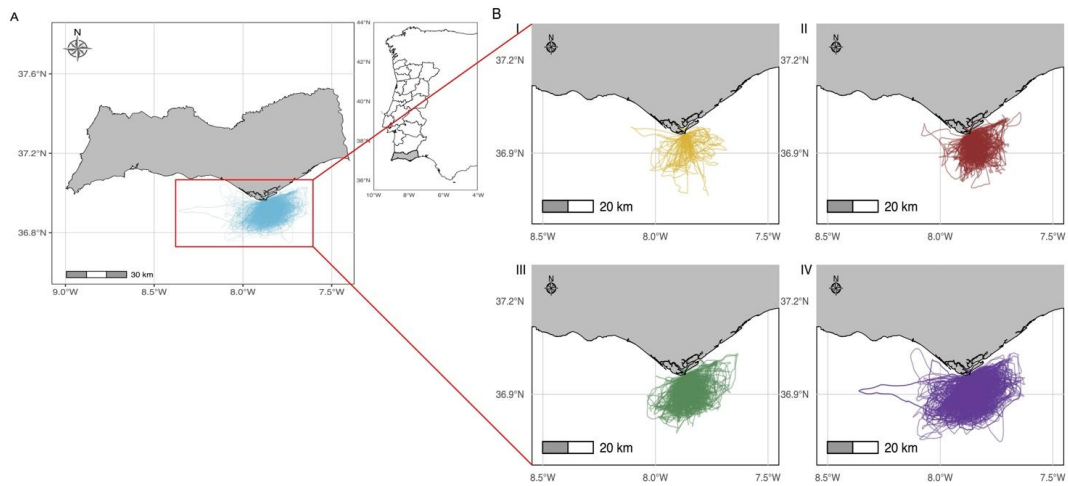


Figure 3.1: (A) Map of the Algarve region, shaded in gray, with the red box highlighting the study area off the coast of Faro. In blue, the boat tracks recorded during whale-watching trips from 2021 to 2024. The top-right inset illustrates the location of the Algarve within the entirety of the Portuguese mainland. (B) Each panel represents the boat tracks recorded in a different year: (I) 2021 in yellow, (II) 2022 in red, (III) 2023 in green, and (IV) 2024 in violet.

3.2.2. Data collection

Data collection occurred year-round during whale-watching trips operated by Ocean Vibes WW company, including daily WW excursions with customers and dedicated scientific surveys. Fin whale photo-IDs images were collected from 2020 to 2024, while boat tracks were automatically recorded every 15 seconds for the whole duration of the trips, just for the years 2021 (from August on) to 2024 (Figure 3.1B). Survey efforts were weather-dependent, and operations were suspended when marine weather conditions were not suitable. Fin whale sightings were documented from the boat, with trained observers gathering data. When a fin whale was sighted, photo-IDs were collected for individual identification using a Canon 7D and

an objective 70-300 mm Tamron. During dedicated scientific surveys, aerial images of the body, chevron, and peduncle were also taken whenever possible. Sightings data were annotated to document the date, boat trip number, sighting number, time, the presence of other species, and the clue that enabled the animal detection (e.g., birds, blow).

3.2.3. Photograph Identification

Photo identification of fin whales (Hammond et al., 1990) primarily relies on identifying distinctive features such as notches, nicks, and disfigurements of the dorsal fins, along with the chevron-blaze patterns on their right side and the left body portion visible during surfacing sequences (Agler et al., 1990; Ramp et al., 2021). All the fin whale photo-IDs images taken between 2020 and 2024 were renamed with a standardized identifying label that included the WW company abbreviation, the date, the region, and the picture number, as in the following example: OVB.2024-05-18.ALG.7183. Each picture was cropped down to a size of 2:1, making sure not to remove important parts of the animal. The photos were then imported and analyzed using MICS-PIX, a web-based, multi-species software for processing, matching, and storing digital photo-identification images (Paquet et al., 2009). Before uploading to MICS-PIX, fin whale dorsal fin photographs were categorized into nine groups based on their shape and marks (1-Hocked; 2-Pointy Tip; 3-Classic; 4-Broad tip; 5-Triangular; 6-With notch; 7-With prominent notch; 8-Deformation/Amputation; 9-Unknown) (Paquet et al., 2009). More information about each individual was added, including location, exact GPS coordinates when available, whether the individual was a calf, and other relevant comments. Lastly, each photo was assigned a quality rating, starting with ‘Cat*’, meaning the best possible quality, and going down to the letter C or D for poor-quality photos. After the importation of MICS-PIX, three independent researchers verified and confirmed the distinguishing features of each individual. In the case of no matches for a picture, a code number was given to that individual in the catalogue; if a match was found, both pictures were assigned to the same code.

3.2.4. Open Population Capture-Recapture analysis

The R package *openCR* (open population capture-recapture) (Efford, 2024) was employed to estimate population density, fitting an open-population spatial model based on the Jolly-Seber Schwarz-Arnason (JSSA) framework (Jolly, 1965; Seber, 1965; Schwarz and Arnason, 1996), accounting for temporary immigration, emigration, births, and deaths of individuals. The parameters estimated were super-population density (superD), the detection function intercept

(λ_0), and detection function scale (σ). Super-population density refers to how many animals are found within a certain area, with each animal assumed to have an activity center and its central location. Since animals are more likely to be detected close to this center and less likely to be seen farther away, estimating density requires considering the spatial nature of the sampling process (Efford, 2025b). The detection function intercept indicates the probability of detecting an individual when its activity center is located directly at a detector. Lastly, the detection function scale describes how detection probability decreases with increasing distance from the activity center. Because fin whale sightings were made during boat-based surveys spread out across space, we created a virtual grid with 1 km cell resolution over the study area. Grid cells were treated as traps, with encounter histories constructed based on the presence or absence of individuals within each cell during specific sampling occasions. Cells were classified as ‘active’ if visited by a boat during a survey, and ‘inactive’ if not. Each detection event was geo-referenced by assigning it to the centroid of the corresponding grid cell. Similarly, the presence or absence of individuals was linked to the coordinates of the grid cell’s center point, resulting in a geo-referenced encounter history.

Due to data limitations, the years 2020 and 2021 were excluded from the capture-recapture model. In 2020, boat tracks were not available, while in 2021, they were only partially recorded. Additionally, individuals without geographic coordinates were also excluded from the analysis.

3.2.5. *Software and Packages*

Statistical analyses were conducted using the R statistical software (R Core Team, 2023). In addition to the *openCR* (Efford, 2024) and *secr* (Efford, 2025a) packages, other relevant packages were employed, including the *tidyverse* suite (Wickham et al., 2019), *ggplot2* (Wickham, 2016) for advanced plotting, *ggspatial* (Dunnington, 2023) for spatial data visualization, and the R compendium *azores.fkw* (Peres dos Santos et al., 2025) for the capture-recapture model.

3.3. RESULTS

3.3.1. Descriptive analysis

A total of 881 trips were conducted from 2021 to 2024, as no effort data were available for 2020; nonetheless, 170 fin whale sightings were recorded over the entire study period from 2020 to 2024. Fin whales were recorded in every month of the year (Figure 3.2). January and October had the lowest number of observations, with only one sighting per month, followed by July with three sightings. Sightings increased noticeably in February and March, with 17 and 16 observations respectively, and continued to rise through spring, reaching 40 in April and peaking in May with 51 sightings, the highest monthly total.

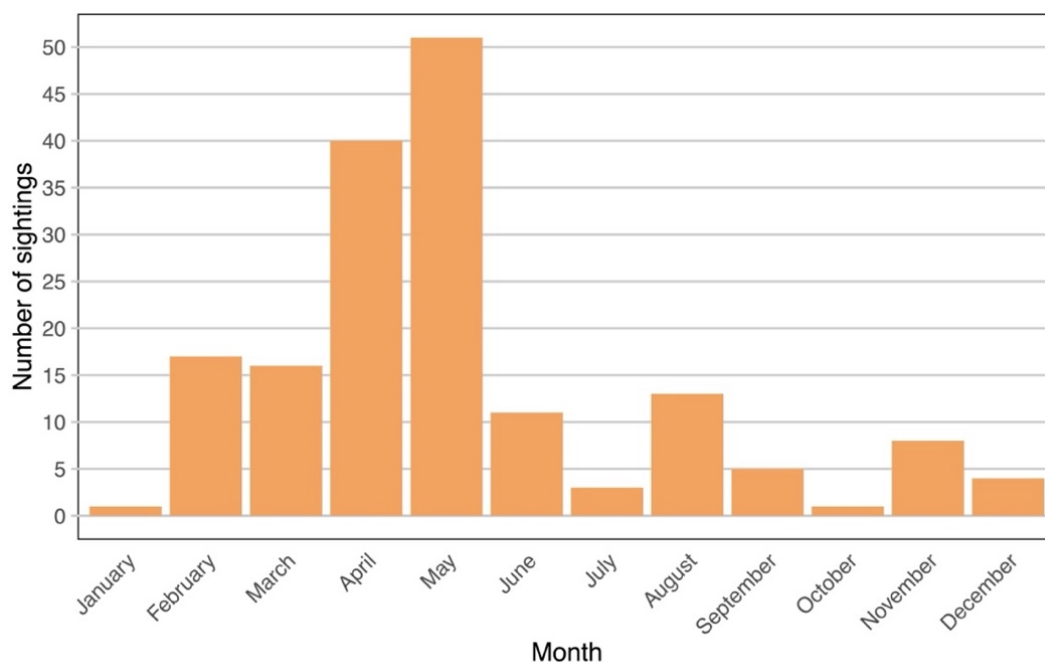


Figure 3.2: Monthly distribution of fin whale sightings recorded between 2020 and 2024. The highest number of observations occurred in May.

Among all observed behaviors, feeding/foraging was the most frequently recorded, with 75 observations out of 170, showing a sharp peak in May and followed by a noticeable decline through summer and autumn (Figure 3.3). A smaller secondary peak appeared in August. Travelling was the second most common behavior, with 30 observations out of 170, peaking earlier, in April, and showing a similar secondary peak in August, mirroring the foraging pattern. Other behaviors, such as logging/resting and milling, maintained relatively low and steady frequencies throughout the year.

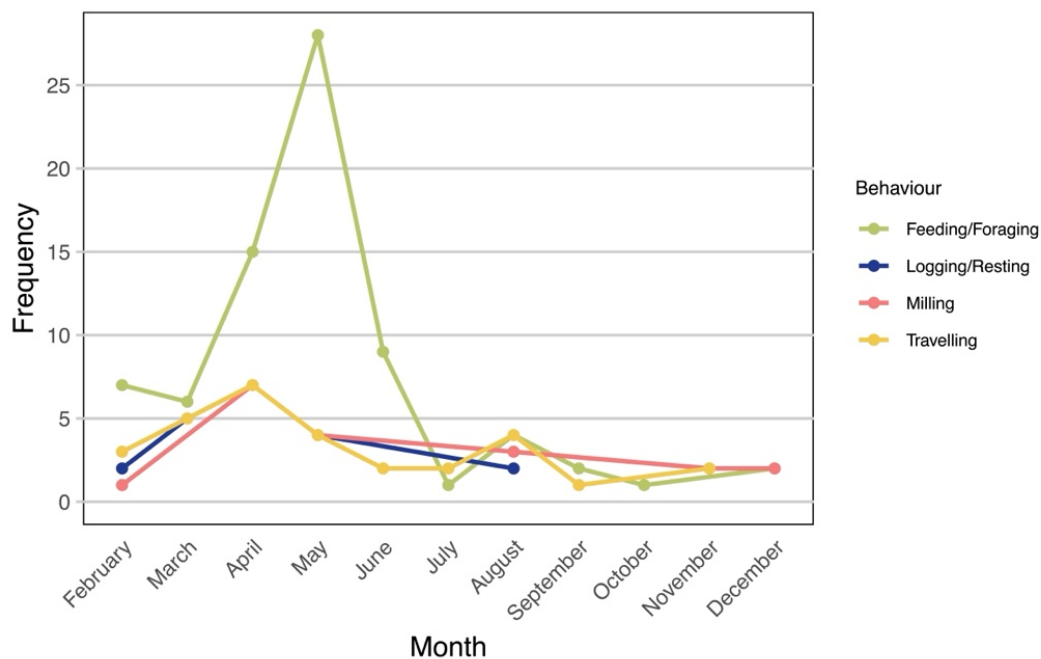


Figure 3.3: Monthly frequency of observed behaviors (feeding/foraging, logging/resting, milling, travelling) throughout the year.

Fin whales were observed in 24% of all sightings in mixed-species groups. The most associated species was the short-beaked common dolphin (*Delphinus delphis*), present in 68% of the mixed-species encounters (Figure 3.4). Common bottlenose dolphins (*Tursiops truncatus*) and common minke whales (*Balaenoptera acutorostrata*) were observed in 15% and 10% of the mixed-species groups, respectively. Striped dolphins (*Stenella coeruleoalba*) appeared in 4% of the cases, while sei whales (*Balaenoptera borealis*) were recorded in 2%. April stood out as a key month for species associations, with the highest number of mixed-species encounters. Notably, common dolphins were the only species observed in association with fin whales nearly every month, excluding only October and December.

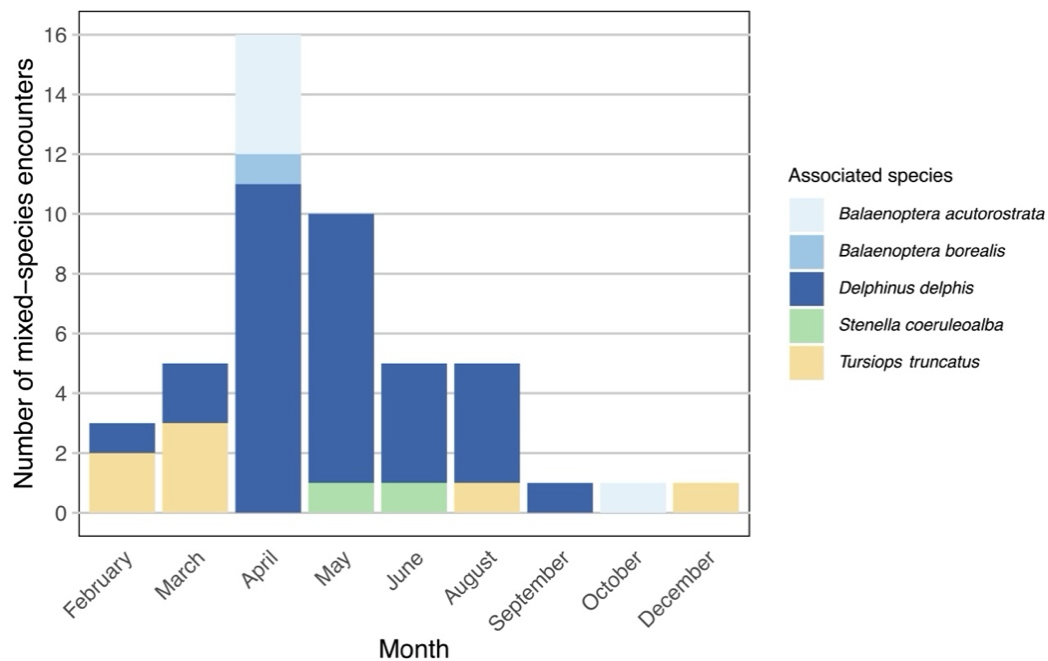


Figure 3.4: Monthly occurrence of mixed-species encounters observed with fin whales. The short-beaked common dolphin was the only species observed nearly every month, while April showed the highest number of mixed-species encounters.

3.3.2. Photograph collection

The first regional catalogue of fin whales in the Algarve was created, with 86 unique individuals identified (Bp301-Bp386), and used to build the photo-identification catalogue. The most prevalent dorsal fin shape was Type 3 – Classic (38%), followed by Type 4 – Broad tip (17%) and Type 5 – Triangular (15%). Approximately 10% of the identified individuals showed nicks and notches in the trailing edge of their dorsal fin, while approximately 20% were recorded with attachments. Identified fin whale individuals were sighted throughout the entire study period, from 2020 to 2024, with a progressive increase in the number of new individuals identified over time (Figure 3.5). Through an analysis of inter-annual recaptures, two individuals were re-sighted twice, once in 2022 and again in 2023 (Figure 3.5).

The intra-annual percentage of recapture was 7% for 2023, with one individual resighted in the same year, and 9% for 2024, with four individuals resighted in the same year. All intra-annually re-sighted individuals were observed on consecutive days during spring, except for those re-sighted in 2023 and one in 2024, each observed five days apart.

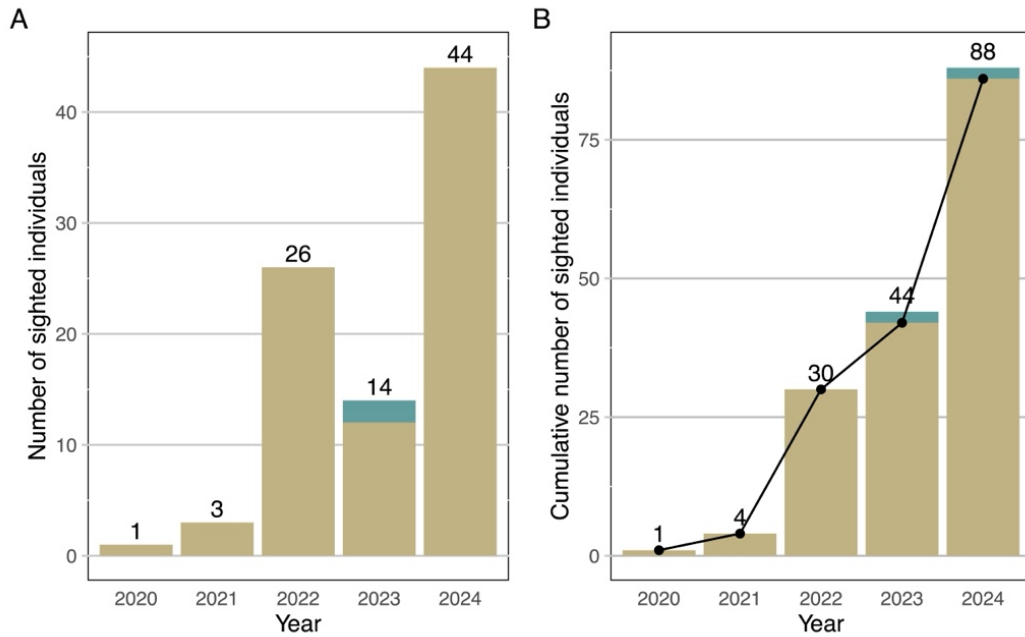


Figure 3.5: (A) The number of fin whale individuals identified each year is shown, with new individuals identified highlighted in beige and inter-annual re-sighted individuals in turquoise. (B) A discovery curve is used to depict the cumulative number of identified individuals over time.

The most frequently sighted individual was Bp301, observed once in 2022 and twice in 2023, and identified by a distinctive mark on the anterior portion of its left head side (Figure 3.6).

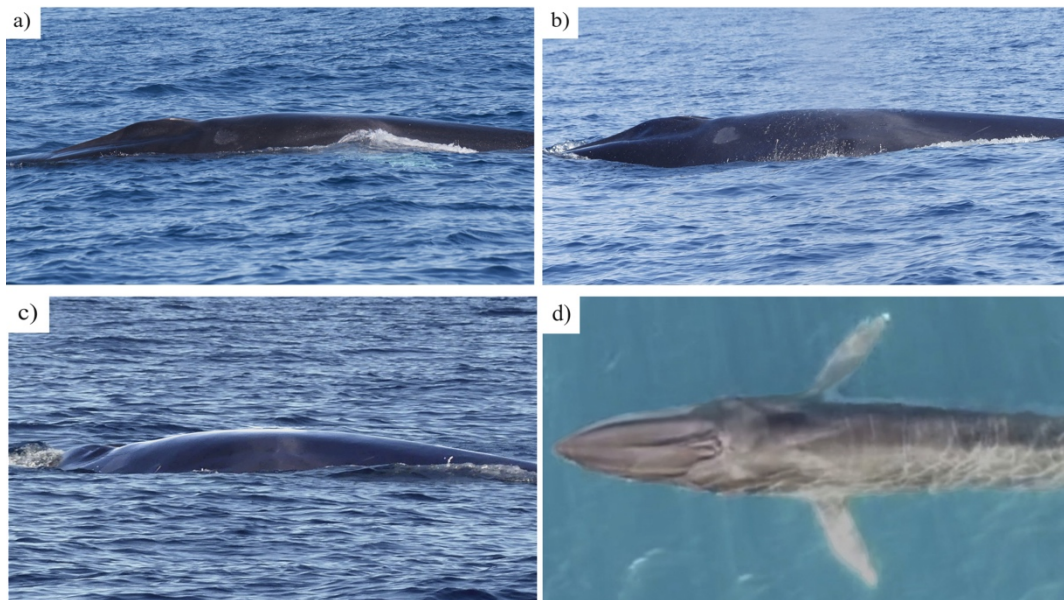


Figure 3.6: Photographs of the left side front and aerial view front of the most frequently sighted fin whale individual, Bp301, documented on a) 2022-04-15; b) 2023-03-23; c) 2023-03-27; d) 2023-03-27. The individual was identified by a distinctive white mark on its left side's front portion (Photos taken by Ocean Vibes; drone picture taken by Jan Hofman under the permit number AOC/08/2022).

3.3.3. *OpenCR Model*

For the Open Population Capture-Recapture model, only unique individuals identified from 2022 to 2024 with valid geographic positions were used, resulting in a total of 78 individuals. The parameters – the super-population density (superD), the maximum expected number of detections (λ_0), and home-range size (σ) – were extracted from the best-fitted open population capture-recapture model, selected using Akaike Information Criterion (AIC). The Algarve fin whale population size estimation (AFWPSE) was derived from the estimated density (Table 3.1).

Table 3.1: Summary of parameters from the open population capture–recapture model, including population density (superD), encounter rate (λ_0), activity range (σ), and Algarve fin whale population size estimation, along with their respective standard errors (SE), lower confidence limits (lcl), and upper confidence limits (ucl).

Variable	Estimate	SE	lcl	ucl
SuperD	$3,35 \times 10^{-3}$	$2,28 \times 10^{-3}$	8.86×10^{-4}	1.27×10^{-2}
λ_0	$2,10 \times 10^{-6}$	$1,29 \times 10^{-6}$	$6,33 \times 10^{-7}$	6.99×10^{-6}
σ	1.5216,27	5.475,44	7.516,41	3.0803.91
AFWPSE	1.476	1002	390	5588

3.4. DISCUSSION

Fin whale occurrences in the Faro area reveal important aspects of the species' seasonal distribution and habitat use in the Northeast Atlantic. Photo-identification across multiple years of monitoring supports the role of this region as a regularly used area during spring, possibly linked to foraging opportunities. While these results point to the Faro area as a transit zone or a seasonal feeding ground, certain elements remain unclear and merit further attention. Among them are the low rate of individual re-sightings and the scarcity of inter-annual recaptures.

Our results reveal that fin whales were recorded throughout the entire study period, from 2020 to 2024, displaying a clear seasonal pattern in their occurrence. Sightings occurred in all months, with the highest numbers reported in April and May. The increased occurrence during these months, along with the re-sighting of five individuals within the same year in these periods – one in 2023 and four in 2024 – just a few days apart, suggests that fin whales were likely taking advantage of abundant food resources available in the area during spring. This hypothesis is further supported by the initial behavior recorded during the sightings. In April and May, the most frequent behavior observed was feeding/foraging, indicating active exploitation of prey-rich zones. Such behavior suggests that the area may serve as a seasonal feeding hotspot for fin whales.

In contrast, during the rest of the year, behavioral records were more varied, with fewer instances of feeding noted. This seasonal presence appears to coincide with the progression of the North Atlantic Spring bloom, which begins around December–January at approximately 35°N and expands across the basin through spring months (e.g. Meyer et al., 2024; Visser et al., 2011), covering latitudes from 30°N - 50°N and longitudes from 60°W - 0°W (Martinez et al., 2011). Of all fin whale sightings, 22% occurred in mixed-species groups, with the short-beaked common dolphin being the most frequently associated species. During spring blooms, these conditions may encourage species to co-occur in shared feeding grounds, potentially enhancing foraging efficiency through associative behaviors (Syme et al., 2021). This finding is consistent with a study conducted in the New York Bight, where short-beaked common dolphins were observed in association with fin whales during three out of four mixed-species foraging events (Lomac-MacNair et al., 2022). A study in southern California bight. However, fin whales and common dolphins are present in mixed-species groups during travelling behavior (Bacon et al., 2017). Another study in different Italian seas (Pelagos Sanctuary, central and southern Tyrrhenian Sea, Sicily Channel, and western Ionian Sea) recorded mixed groups of common dolphins and fin whales mainly during feeding and/or travelling activities (Pace et

al., 2015). Further research is needed to investigate the factors driving these interactions and the potential benefits they may confer in the Algarve region.

Photo-identification studies of fin whales in the North Atlantic have primarily focused on the northwestern Atlantic and the Mediterranean Sea. The largest existing catalogue is maintained by Allied Whale at the College of the Atlantic (USA), comprising 841 fin whale individuals photographed since 1968, mainly off the northeastern coast of the United States (Robbins et al., 2008). In the Mediterranean Sea, a catalogue of 507 fin whale individuals has been maintained since 1990 by several research groups (Zanardelli et al., 2022). This study successfully identified 86 unique fin whale individuals, creating the first Algarve regional catalogue. While the use of dorsal fin characteristics allows for recognition of individuals from both sides, this method may be limited when individuals lack distinctive features such as nicks, notches, or attachments (Elliser et al., 2022), as identification based entirely on dorsal fin shape can be more challenging due to changes over time (Degollada et al., 2023). In this study, around 70% of the identified individuals lacked distinctive markings, which may have limited the accuracy of individual identification and potentially led to an underestimation of identified individuals and re-sightings.

On the other hand, when using pigmentation patterns as criteria for photo-ID, such as the chevron-blaze pattern or the left front portion of the body, individuals can't be matched from opposite sides, limiting the ability to confirm identity across different angles. In this light, manual matching software and semi- or fully automated identification tools should be considered valid approaches. While the accuracy of these computerized identification software is still under evaluation and largely depends on the algorithms used (e.g., Besson et al., 2022; Patton et al., 2024), their greatest significant advantage lies in the potential to drastically reduce the amount of time and effort needed to identify individuals from photographs, making them particularly valuable for large datasets and long-term monitoring programs (e.g., Cheeseman et al., 2021; Thompson et al., 2021).

Two of the 86 identified fin whale individuals were recorded in multiple years, both first observed in 2022 and re-sighted in 2023. This results in an overall re-sighting rate of approximately 2.5%, which is lower than those reported in other studies. In the northwestern Mediterranean Sea, re-sighting rates were estimated at 16.3% (Tardy et al., 2023) and 14% (Zanardelli et al., 2022), while in the Gulf of Maine, 43% of identified fin whale individuals have been observed across multiple years (Robbins et al., 2008). The notably lower rate found in this study could be attributed to several factors. Most importantly, the studies cited above are all based on long-term monitoring programs. Those conducted in the Mediterranean Sea span

approximately 10 to 20 years, while the Gulf of Maine study extends over four decades, providing the opportunity for more detailed insights into population structure and dynamics (Lindenmayer et al., 2012). Secondly, survey effort may also play a key role. Variability in the number of trips conducted, seasonal coverage, and weather conditions can all influence sighting probabilities and the chances of re-identifying individuals. Thirdly, the fin whale population in the Mediterranean Sea is considered resident. However, part of the population, the so-called north-eastern North Atlantic population, appears to migrate between the North Atlantic Ocean and the Balearic Region through the Strait of Gibraltar (Tardy et al., 2023). A study in the Mediterranean Sea, have observed limited interannual variation in fin whale distribution, along with the recurring use of specific hotspots (Panigada et al., 2024); these factors are especially significant in geographically constrained environments like the Mediterranean Sea, where the relatively enclosed nature of the basin may contribute to higher re-sighting rates.

In our study, the continued increase in the cumulative number of identified individuals suggests that a substantial portion of the population had yet to be observed. However, inter-annual recaptures suggest that some individuals return to the area. Nonetheless, these recaptures involved only a very small portion of the overall population, considering that 86 individual fin whales were identified, and the abundance estimate for the area reaches 1.476 individuals. If site fidelity existed, it would imply more recaptures. Our population size estimate is comparable to the one reported for the North-western Mediterranean Sea between 2008 and 2019, with 1.295 individuals estimated from genotype sampling and 1.549 individuals estimated through photo-identification data (Tardy et al., 2023). However, our result represents less than half of the population calculated in the western Mediterranean Sea in the summer of 1991, which was estimated at 3.583 individuals (Forcada et al., 1996). The estimate of fin whale abundance provided in this study considers only the individuals reported in the area off Faro; therefore, it may not accurately represent the abundance estimation for fin whales in the whole Algarve region.

This study highlights the value of collecting data aboard WW vessels, particularly in areas where such operations exist but scientific monitoring is limited. However, data gathered from platforms of opportunity have inherent limitations, which can vary depending on the type of platform and the observer's experience (Stack and Currie, 2022). Firstly, to comply with WW regulations in the Algarve, each sighting was limited to a maximum of 30 minutes (Decree - Law No. 9/2006, of January 6th), which constrained the ability to take high-quality photos for identification. Additionally, it is important to note that the absence of boat track data for the years 2020 and 2021 poses a significant research gap, limiting the accuracy of fin whale

population size estimation. Nevertheless, as observed in other regions, partnerships with WW operators have proven valuable for collecting non-invasive data on cetaceans, offering important insights for conservation efforts (Peres dos Santos et al., 2025).

In conclusion, this study provides the first insight into fin whale presence and population structure in the Faro area, highlighting its role as a potentially important seasonal feeding ground in the Northeast Atlantic. Despite inherent limitations linked to data collection from platforms of opportunity, such as restricted sighting durations and incomplete spatial coverage, the results demonstrate the value of WW collaborations in generating non-invasive data. Establishing the first regional photo-identification catalogue, evidence of seasonal recurrence, and occasional inter-annual re-sightings suggests that this area may hold ecological relevance for part of the North Atlantic fin whale population. Continued research in this region will be essential to improve the accuracy of abundance estimates, assess site fidelity, and clarify the Faro area's role within broader migratory and foraging dynamics of fin whales in the North Atlantic.

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Appendix – I: R scripts for humpback whales (Chapter 2)

1.1. Municipalities

```
#ALGARVE MAP WITH MUNICIPALITIES
# === Load required packages ===
library(sf)
library(dplyr)
library(ggplot2)
library(ggspatial)

# === Load the Portugal shapefile ===
Portugal <- st_read("/Volumes/TESI/Portugal.shp")

## Reading layer `Portugal' from data source `/Volumes/TESI/Portugal.shp' using driver `ESRI Shapefile'
## Simple feature collection with 20 features and 9 fields
## Geometry type: MULTIPOLYGON
## Dimension:      XY
## Bounding box:  xmin: -31.26819 ymin: 30.03018 xmax: -6.189142 ymax: 42.15432
## Geodetic CRS: WGS 84

# === Extract the Algarve region ===
Algarve <- Portugal |>
  filter(NAME_1 == "Faro")

# === Load municipalities shapefile ===
Concelhos <- st_read("/Volumes/TESI/GIS FIN/concelhos-shapefile/concelhos.shp")

## Reading layer `concelhos' from data source
## `/Volumes/TESI/GIS FIN/concelhos-shapefile/concelhos.shp' using driver `ESRI Shapefile'
## Simple feature collection with 308 features and 14 fields
## Geometry type: MULTIPOLYGON
## Dimension:      XY
## Bounding box:  xmin: -31.26819 ymin: 30.03018 xmax: -6.189142 ymax: 42.15432
## Geodetic CRS: WGS 84

# === Filter the municipalities of interest: Faro, Lagoa, Lagos, Vila do Bispo ===
concelhos_selezionati <- Concelhos |>
  filter(NAME_2 %in% c("Faro", "Lagoa", "Lagos", "Vila do Bispo"))

# === Assign a custom color to each municipality ===
concelhos_selezionati$colore <- case_when(
  concelhos_selezionati$NAME_2 == "Faro" ~ "#FF2400",
  concelhos_selezionati$NAME_2 == "Lagoa" ~ "#FFA500",
  concelhos_selezionati$NAME_2 == "Lagos" ~ "#32CD32",
  concelhos_selezionati$NAME_2 == "Vila do Bispo" ~ "#1E90FF"
)

# === Create the map with the highlighted municipalities ===
ggplot() +
  geom_sf(data = Algarve, fill = "gray", color = "black", linewidth = 0.2) +
  geom_sf(data = concelhos_selezionati, aes(fill = colore), color = "black", linewidth = 0.3, alpha = 0.5) +
  scale_fill_identity() +
  scale_x_continuous(
    limits = c(-9.1, -7.4),
```

```

    breaks = seq(-9, -7.5, by = 0.5)
  ) +
  scale_y_continuous(
    limits = c(36.7, 37.6),
    breaks = seq(36.8, 37.6, by = 0.4)
  ) +
  annotation_scale(location = "bl", bar_cols = c("grey60", "white"),
    pad_x = unit(0.1, "in"), pad_y = unit(0.1, "in")) +
  annotation_north_arrow(location = "tl", which_north = "true",
    height = unit(0.3, "in"), width = unit(0.3, "in"),
    style = north_arrow_nautical(fill = c("grey40", "white")))
) +
theme_minimal() +
theme(
  panel.background = element_rect(fill = 'white', color = "black"),
  axis.title = element_blank(),
  panel.grid = element_line(color = 'gray80', linewidth = 0.2),
  axis.text = element_text(size = 8)
)

```


1.2. Coordinates

```
#ALGARVE MAP WITH HUMPBACK WHALE COORDINATES
# === Load required packages ===
library(sf)
## Warning: package 'sf' was built under R version 4.3.3
## Linking to GEOS 3.13.0, GDAL 3.8.5, PROJ 9.5.1; sf_use_s2() is TRUE
library(dplyr)
## Attaching package: 'dplyr'
## The following objects are masked from 'package:stats':
##   filter, lag
## The following objects are masked from 'package:base':
##   intersect, setdiff, setequal, union
library(ggplot2)
library(ggspatial)

# === Load the Portugal shapefile ===
Portugal <- st_read("/Volumes/TESI/Portugal.shp")

## Reading layer `Portugal' from data source `/Volumes/TESI/Portugal.shp' using driver `ESRI Shapefile'
## Simple feature collection with 20 features and 9 fields
## Geometry type: MULTIPOLYGON
## Dimension:      XY
## Bounding box: xmin: -31.26819 ymin: 30.03018 xmax: -6.189142 ymax: 42.15432
## Geodetic CRS:   WGS 84

# === Extract the Algarve region ===
Algarve <- Portugal |>
  filter(NAME_1 == "Faro")

# === Load humpback whale coordinates ===
humpback <- st_read("/Volumes/TESI/GIS HUMPBACK/Coord humpback.shp") |>
  mutate(
    colore = case_when(
      Code == "Mn101" ~ "#9B5DE5",
      Code == "Mn102" ~ "#FFC0CB",
      Code == "Mn103" ~ "#76D7EA",
      Code == "Mn106" ~ "#FFEB3B",
      Code == "Mn110" ~ "#8B4513",
      TRUE ~ "gray"
    ),
    dimensione = case_when(
      Code == "Mn110" ~ 5,
      TRUE ~ 2.7
    )
  )

## Reading layer `Coord humpback' from data source
##   `/Volumes/TESI/GIS HUMPBACK/Coord humpback.shp' using driver `ESRI Shapefile'
## Simple feature collection with 11 features and 4 fields
## Geometry type: POINT
## Dimension:      XY
## Bounding box: xmin: -22.50542 ymin: 16.43162 xmax: 9.081 ymax: 57.71428
## Geodetic CRS:   WGS 84

# === Create the final map: Algarve + whale points ===
ggplot() +
  geom_sf(data = Algarve, fill = "gray90", color = "black", linewidth = 0.2) + #
```

```

geom_sf(data = humpback, aes(color = colore, size = dimensione)) + #
scale_color_identity() +
scale_size_identity() +
scale_x_continuous(
  limits = c(-9, -7.45),
  breaks = seq(-9, -7.5, by = 0.5)
) +
scale_y_continuous(
  limits = c(36.73, 37.55),
  breaks = seq(37, 37.6, by = 0.4)
) +
annotation_scale(
  location = "bl",
  bar_cols = c("grey60", "white"),
  pad_x = unit(0.1, "in"),
  pad_y = unit(0.1, "in")
) +
annotation_north_arrow(
  location = "tl", which_north = "true",
  height = unit(0.3, "in"), width = unit(0.3, "in"),
  style = north_arrow_nautical(fill = c("grey40", "white"))
) +
theme_minimal() +
theme(
  panel.background = element_rect(fill = 'white', color = "black"),
  axis.title = element_blank(),
  panel.grid = element_line(color = 'gray80', linewidth = 0.2),
  axis.text = element_text(size = 8)
)

```

#WORLD MAP WITH HUMPBACK WHALE COORDINATES

```
# === Load required packages ===
library(sf)
library(dplyr)
library(ggplot2)
library(ggspatial)

# === Load the coastline shapefile ===
coastline <- st_read("/Volumes/TESI/coastline/Coastline.shp")
## Reading layer `Coastline' from data source `/Volumes/TESI/coastline/Coastline.s
hp' using driver `ESRI Shapefile'
## Simple feature collection with 4133 features and 3 fields
## Geometry type: LINESTRING
## Dimension: XY
## Bounding box: xmin: -180 ymin: -85.22194 xmax: 180 ymax: 83.6341
## Geodetic CRS: WGS 84

# === Load whale coordinates ===
humpback <- st_read("/Volumes/TESI/GIS HUMPBACK/Coord humpback.shp") |>
  mutate(
    colore = case_when(
      Code == "Mn101" ~ "#9B5DE5",
      Code == "Mn102" ~ "#FFC0CB",
      Code == "Mn103" ~ "#76D7EA",
      Code == "Mn106" ~ "#FFEB3B",
      Code == "Mn110" ~ "#8B4513",
      TRUE ~ "gray"
    ),
    dimensione = case_when(
      Code == "Mn110" ~ 3,
      TRUE ~ 2
    )
  )

## Reading layer `Coord humpback' from data source
## `/Volumes/TESI/GIS HUMPBACK/Coord humpback.shp' using driver `ESRI Shapefile'
## Simple feature collection with 11 features and 4 fields
## Geometry type: POINT
## Dimension: XY
## Bounding box: xmin: -22.50542 ymin: 16.43162 xmax: 9.081 ymax: 57.71428
## Geodetic CRS: WGS 84

# === Create the final map: coastline + whale points ===
ggplot() +
  geom_sf(data = coastline, fill = "gray85", color = "black", linewidth = 0.2) +
  # Coste
  geom_sf(data = humpback, aes(color = colore, size = dimensione)) +
  scale_color_identity() +
  scale_size_identity() +
  scale_x_continuous(
    limits = c(-25, 15),
    breaks = seq(-25, 15, by = 10)
  ) +
  scale_y_continuous(
    limits = c(10, 60),
    breaks = seq(10, 60, by = 10)
  ) +
  annotation_scale(location = "bl", bar_cols = c("grey60", "white"),
    pad_x = unit(0.1, "in"), pad_y = unit(0.1, "in")) +
  annotation_north_arrow(location = "tr", which_north = "true",
```

```

                                height = unit(0.3, "in"), width = unit(0.3, "in"),
                                style = north_arrow_nautical(fill = c("grey40", "white"))
) +
theme_minimal() +
theme(
  panel.background = element_rect(fill = 'white', color = "black"),
  axis.title = element_blank(),
  panel.grid = element_line(color = 'gray80', linewidth = 0.2),
  axis.text = element_text(size = 8)
)

```

Appendix – II: R scripts for fin whales (Chapter 3)

2.1. Boat tracks

```
#ALGARVE MAP WITH BOAT TRACKS
# === Load required packages ===
library(dplyr)
## Attaching package: 'dplyr'
## The following objects are masked from 'package:stats':
##   filter, lag
## The following objects are masked from 'package:base':
##   intersect, setdiff, setequal, union
library(ggplot2)
library(sf)
## Warning: package 'sf' was built under R version 4.3.3
## Linking to GEOS 3.13.0, GDAL 3.8.5, PROJ 9.5.1; sf_use_s2() is TRUE
library(ggspatial)
library(readxl)

# === Load Portugal shape file ===
Portugal <- st_read("/Volumes/TESI/Portugal.shp")

## Reading layer `Portugal' from data source `/Volumes/TESI/Portugal.shp' using driver `ESRI Shapefile'
## Simple feature collection with 20 features and 9 fields
## Geometry type: MULTIPOLYGON
## Dimension:      XY
## Bounding box: xmin: -31.26819 ymin: 30.03018 xmax: -6.189142 ymax: 42.15432
## Geodetic CRS:   WGS 84

# === Extract the Algarve region ===
Algarve <- Portugal |>
  filter(NAME_1 == "Faro")

# Load boat tracks data
boat_trips_by_min <- read_xlsx("/Volumes/TESI/boat_trips_by_min.xlsx")

# === Create the map ===

boat_tracks_map <- ggplot(data = boat_trips_by_min) +
  geom_path(aes(x = longitude, y = latitude, group = trip),
            alpha = 0.5,
            colour = "#2ab8da",
            linewidth = 0.3) +
  geom_sf(data = Algarve, fill = "gray", color = "black", linewidth = 0.2) +
  scale_x_continuous(
    limits = c(-9.1, -7.4),
    breaks = seq(-9, -7.5, by = 0.5)
  ) +
  scale_y_continuous(
    limits = c(36.7, 37.6),
    breaks = seq(36.6, 37.6, by = 0.2)
  ) +
  annotation_scale(location = "bl", bar_cols = c("grey60", "white"),
                  pad_x = unit(0.1, "in"), pad_y = unit(0.1, "in")) +
  annotation_north_arrow(location = "tl", which_north = "true",
                        height = unit(0.3, "in"), width = unit(0.3, "in"),
                        style = north_arrow_nautical(fill = c("grey40", "white")))
```

```
) +
  theme_minimal() +
  theme(
    panel.background = element_rect(fill = 'white', color = "black"),
    axis.title = element_blank(),
    panel.grid = element_line(color = 'gray80', linewidth = 0.2),
    axis.text = element_text(size = 8)
  )
```

#ALGARVE MAP WITH BOAT TRACKS FOR DIFFERENT YEARS

```
library(dplyr)
library(ggplot2)
library(sf)
library(ggspatial)
library(lubridate)
## Warning: package 'lubridate' was built under R version 4.3.
## Attaching package: 'lubridate'
## The following objects are masked from 'package:base':
##   date, intersect, setdiff, union
library(patchwork)
## Warning: package 'patchwork' was built under R version 4.3.3

# === Function to create yearly boat track maps ===
plot_boat_tracks_by_year <- function(data, year_selected, color_hex, label_tag) {
  data_year <- data %>%
    filter(year == year_selected)
  ggplot(data = data_year) +
    geom_path(aes(x = longitude, y = latitude, group = trip),
              alpha = 0.5,
              colour = color_hex,
              linewidth = 0.3) +
    geom_sf(data = Algarve, fill = "gray", color = "black", linewidth = 0.2) +
    scale_x_continuous(
      limits = c(-8.5, -7.5),
      breaks = seq(-9, -7.5, by = 0.5)
    ) +
    scale_y_continuous(
      limits = c(36.7, 37.288),
      breaks = seq(36.6, 37.3, by = 0.3)
    ) +
    annotation_scale(
      location = "bl",
      bar_cols = c("grey60", "white"),
      pad_x = unit(0.1, "in"),
      pad_y = unit(0.1, "in")
    ) +
    annotation_north_arrow(
      location = "tl",
      which_north = "true",
      height = unit(0.160, "in"),
      width = unit(0.1, "in"),
      style = north_arrow_nautical(
        fill = c("grey40", "white"),
        text_size = 5
      )
    ) +
    labs(tag = label_tag) +
    theme_minimal() +
```

```

    theme(
      panel.background = element_rect(fill = 'white', color = "black"),
      axis.title = element_blank(),
      panel.grid = element_line(color = 'gray80', linewidth = 0.2),
      axis.text = element_text(size = 6),
      plot.tag = element_text(size = 8, hjust = 0, vjust = 1),
      plot.tag.position = c(0.07, 1),
      plot.margin = margin(t = 0, r = 0, b = 0, l = 1)
    )
  }
# === Define colors for each year ===
color_2021 <- "#E6B422"
color_2022 <- "#A52A2A"
color_2023 <- "#2E8B57"
color_2024 <- "#6E3A99"

# === Generate 4 maps with tag I-IV ===
track_2021 <- plot_boat_tracks_by_year(boat_trips_by_min, 2021, color_2021, "I")
track_2022 <- plot_boat_tracks_by_year(boat_trips_by_min, 2022, color_2022, "II")
track_2023 <- plot_boat_tracks_by_year(boat_trips_by_min, 2023, color_2023, "III")
track_2024 <- plot_boat_tracks_by_year(boat_trips_by_min, 2024, color_2024, "IV")

# === Combine the 4 maps into a 2x2 layout ===
combined_plot_core <- (track_2021 + track_2022) / (track_2023 + track_2024) +
  plot_layout(heights = c(1, 1))

```

#MAP FOR PORTUGAL AND SPAIN

```

# === Load required packages ===
library(ggplot2)
library(sf)
library(dplyr)

# === Load Portugal shapefile ===
Portugal <- st_read("/Volumes/TESI/Portugal.shp")
## Reading layer `Portugal' from data source `/Volumes/TESI/Portugal.shp' using driver `ESRI Shapefile'
## Simple feature collection with 20 features and 9 fields
## Geometry type: MULTIPOLYGON
## Dimension: XY
## Bounding box: xmin: -31.26819 ymin: 30.03018 xmax: -6.189142 ymax: 42.15432
## Geodetic CRS: WGS 84

# === Load Europe shapefile ===
Europe <- st_read("/Volumes/TESI/GIS FIN/Europe/Europe_merged.shp")

## Reading layer `Europe_merged' from data source
## `/Volumes/TESI/GIS FIN/Europe/Europe_merged.shp' using driver `ESRI Shapefile'
## Simple feature collection with 38 features and 2 fields
## Geometry type: MULTIPOLYGON
## Dimension: XY
## Bounding box: xmin: -31.26819 ymin: 27.63736 xmax: 44.83499 ymax: 71.18125
## Geodetic CRS: WGS 84

# === Extract Portugal mainland ===
portugal_mainland <- Portugal |>
  filter(TYPE_1 == "Distrito") |>

```

```

  filter(!NAME_1 %in% c("Azores", "Madeira"))
# === Extract the Algarve ===
Algarve <- Portugal |> filter(NAME_1 == "Faro")
# === Extract Portugal and Spain from Europe shapefile ===
europe_filtered <- Europe |> filter(GID_0 %in% c("PRT", "ESP"))

# === Ensure same CRS ===
target_crs <- st_crs(Portugal)
europe_filtered <- st_transform(europe_filtered, crs = target_crs)
portugal_mainland <- st_transform(portugal_mainland, crs = target_crs)
Algarve <- st_transform(Algarve, crs = target_crs)

# === Plot finale ===
combined_map <- ggplot() +
  # 1. Coastline of Portugal and Spain
  geom_sf(data = europe_filtered, fill = NA, color = "black", linewidth = 0.3) +
  # 2. Portugal mainland
  geom_sf(data = portugal_mainland, fill = "white", color = "black", linewidth =
0.3) +
  # 3. Highlight the Algarve
  geom_sf(data = Algarve, fill = "gray", color = "black", linewidth = 0.5) +
  # 4. Set coordinates
  scale_x_continuous(limits = c(-10, -4), breaks = seq(-10, -4, by = 2)) +
  scale_y_continuous(limits = c(35.5, 44), breaks = seq(36, 44, by = 2)) +
  coord_sf(xlim = c(-10, -4), ylim = c(35.5, 44), expand = FALSE) +
  # Set style
  theme_minimal() +
  theme(
    axis.title = element_blank(),
    panel.background = element_rect(fill = "white", color = "black"),
    panel.grid.major = element_blank(),
    legend.position = "none",
    plot.title = element_blank(),
    plot.margin = margin(t = 15, r = 10, b = 10, l = 10)
  )

```


2.2. Occurrence

#GRAPH OF MONTHLY SIGHTINGS FREQUENCY

```
# === Load required packages ===
library(readxl)
library(dplyr)
## Attaching package: 'dplyr'
## The following objects are masked from 'package:stats':
##   filter, lag
## The following objects are masked from 'package:base':
##   intersect, setdiff, setequal, union
library(ggplot2)
library(lubridate)
## Warning: package 'lubridate' was built under R version 4.3.3
## Attaching package: 'lubridate'
## The following objects are masked from 'package:base':
##   date, intersect, setdiff, union
library(ggtext)

# === Load data ===
df <- read_excel("/Volumes/TESI/sightings_ginevra_final.xlsx")

# === Monthly summary ===
df_summary <- df %>%
  mutate(date = as.Date(date),
         Month = month(date, label = TRUE, abbr = FALSE)) %>%
  group_by(Month) %>%
  summarise(Sightings = n()) %>%
  mutate(Month = factor(Month, levels = month.name))

# === Plot bar chart ===
ggplot(df_summary, aes(x = Month, y = Sightings)) +
  geom_col(fill = "sandybrown", show.legend = FALSE) +
  scale_y_continuous(limits = c(0, 51), breaks = seq(0, 51, by = 5)) +
  labs(x = "Month",
       y = "Number of sightings") +
  theme_minimal(base_size = 12) +
  theme(
    panel.background = element_rect(fill = "white", color = "black"),
    axis.ticks = element_line(colour = "grey80"),
    axis.ticks.x = element_blank(),
    panel.grid.major.x = element_blank(),
    panel.grid.major.y = element_line(colour = "gray80"),
    panel.grid.minor.y = element_blank(),
    panel.grid.minor.x = element_blank(),
    axis.line.x.top = element_line(color = "gray80"), # << linea superiore grigia
    axis.text.x = element_text(angle = 45, hjust = 1),
    plot.title = element_blank()
  )
)
```

2.3. Behavior

#GRAPH OF MONTHLY OBSERVED BEHAVIORS

```
# === Load required packages ===
library(readxl)
library(dplyr)
## Attaching package: 'dplyr'
## The following objects are masked from 'package:stats':
##   filter, lag
## The following objects are masked from 'package:base':
##   intersect, setdiff, setequal, union
library(ggplot2)
library(lubridate)
## Warning: package 'lubridate' was built under R version 4.3.3
## Attaching package: 'lubridate'
## The following objects are masked from 'package:base':
##   date, intersect, setdiff, union

# === Load data ===
df <- read_xlsx("/Volumes/TESI/sightings_ginevra_final.xlsx")

# === Prepare data ===
df_line <- df %>%
  filter(!is.na(`Activ.Inicial`), !is.na(date)) %>%
  mutate(
    month = month(date, label = TRUE, abbr = FALSE)
  ) %>%
  count(month, `Activ.Inicial`)

# === Define custom colors ===
palette_behaviour <- c(
  "Feeding/Foraging" = "#B8C56A",
  "Milling" = "#F57C7C",
  "Logging/Resting" = "#1F3A93",
  "Travelling" = "#F2C94C"
)

# === Line plot of behaviors by month ===
ggplot(df_line, aes(x = month, y = n, group = `Activ.Inicial`, color = `Activ.Inicial`)) +
  geom_line(linewidth = 1) +
  geom_point(size = 2) +
  scale_color_manual(values = palette_behaviour) + scale_y_continuous(
    limits = c(0, 28),
    breaks = seq(0, 28, by = 5)
  ) +
  labs(
    x = "Month",
    y = "Frequency",
    color = "Behaviour"
  ) +
  theme_minimal(base_size = 13) +
  theme(
    panel.background = element_rect(fill = "white", color = "black"),
    axis.ticks = element_line(colour = "grey80"),
    axis.ticks.x = element_blank(),
    panel.grid.major.x = element_blank(),
    panel.grid.major.y = element_line(colour = "gray80"),
    panel.grid.minor.y = element_blank(),
```

```
panel.grid.minor.x = element_blank(),  
axis.line.x.top = element_line(color = "black"),  
axis.text.x = element_text(angle = 45, hjust = 1),  
plot.title = element_blank(),  
legend.text = element_text(size = 8),  
legend.title = element_text(size = 9)  
)
```

2.4. Mixed-species

```
#GRAPH OF MIXED-SPECIES OBSERVATIONS
# === Load required packages ===
library(readxl)
library(ggplot2)
library(forcats)
library(dplyr)
## Attaching package: 'dplyr'
## The following objects are masked from 'package:stats':
##   filter, lag
## The following objects are masked from 'package:base':
##   intersect, setdiff, setequal, union
library(tidyr)
library(stringr)
library(lubridate)
## Warning: package 'lubridate' was built under R version 4.3.3
## Attaching package: 'lubridate'
## The following objects are masked from 'package:base':
##   date, intersect, setdiff, union
library(ggtext)
library(RColorBrewer)

# === Load data ===
bp <- read_xlsx("/Volumes/TESI/sightings_ginevra_final.xlsx")

# === Filter rows with valid "other_species" and date ===
mixed <- bp %>%
  filter(!is.na(other_species), !is.na(date)) %>%
  mutate(month = month(date, label = TRUE, abbr = FALSE))

# === Separate and count co-occurring species ===
species_month_counts <- mixed %>%
  separate_rows(other_species, sep = ",\\s*") %>%
  mutate(other_species = str_trim(other_species)) %>%
  count(month, other_species, sort = TRUE) %>%
  group_by(other_species) %>%
  mutate(percent_within_species = round(n / sum(n) * 100, 2)) %>%
  ungroup()

# === Italicize species names for the legend ===
species_month_counts <- species_month_counts %>%
  mutate(other_species_italic = case_when(
    other_species == "Delphinus delphis" ~ "*Delphinus delphis*",
    other_species == "Tursiops truncatus" ~ "*Tursiops truncatus*",
    other_species == "Balaenoptera acutorostrata" ~ "*Balaenoptera acutorostrata*"
  ),
  other_species == "Balaenoptera borealis" ~ "*Balaenoptera borealis*",
  other_species == "Stenella coeruleoalba" ~ "*Stenella coeruleoalba*",
  TRUE ~ paste0("*", other_species, "*")
  ))

# === Order month ===
species_month_counts$month <- factor(species_month_counts$month, levels = month.name, ordered = TRUE)

# === Custom colors for species ===
colori_principali <- c(
  "*Delphinus delphis*" = "#3E64A7",
```

```

"*Tursiops truncatus*" = "#F4DE9C",
"*Balaenoptera acutorostrata*" = "#E4F1F7",
"*Balaenoptera borealis*" = "#9EC4E4",
"*Stenella coeruleoalba*" = "#ADDFAF" # Colore azzurrino dedicato
)

# === Plot the graph ===
ggplot(species_month_counts, aes(x = month, y = n, fill = other_species_italic)) +
  geom_col(position = "stack") +
  scale_y_continuous(limits = c(0, 16), breaks = seq(0, 16, by = 2)) +
  scale_x_discrete(name = "Month") +
  labs(
    y = "Number of mixed-species encounters",
    fill = "Associated species"
  ) +
  scale_fill_manual(values = colori_finali) +
  theme_minimal(base_size = 12) +
  theme(
    legend.position = "right",
    legend.text = element_markdown(size = 8), # markdown attivo per corsivo
    legend.title = element_text(size = 9),
    legend.key = element_rect(fill = NA, color = NA),
    panel.background = element_rect(fill = "white", color = "black"),
    axis.ticks = element_line(colour = "grey80"),
    axis.ticks.x = element_blank(),
    panel.grid.major.x = element_blank(),
    panel.grid.major.y = element_line(colour = "gray80"),
    panel.grid.minor.x = element_blank(),
    panel.grid.minor.y = element_blank(),
    axis.text.x = element_text(angle = 45, hjust = 1),
    plot.title = element_blank()
  )
)

```

2.5. Discovery curve

```
#GRAPH OF DISCOVERY CURVE
# === Load required packages ===
library(tidyverse)
## Warning: package 'purrr' was built under R version 4.3.3
## Warning: package 'lubridate' was built under R version 4.3.3
## — Attaching core tidyverse packages ————— tidyverse 2.0.0 —
##
## ✓ dplyr      1.1.4      ✓ readr      2.1.5
## ✓ forcats   1.0.0      ✓ stringr    1.5.1
## ✓ ggplot2    3.5.1      ✓ tibble     3.2.1
## ✓ lubridate 1.9.4      ✓ tidyr      1.3.1
## ✓ purrr     1.0.4
## — Conflicts ————— tidyverse_conflicts() —
##
## ✗ dplyr::filter() masks stats::filter()
## ✗ dplyr::lag()     masks stats::lag()
## ⓘ Use the conflicted package (<http://conflicted.r-lib.org/>) to force all conflicts to become errors
library(patchwork)
## Warning: package 'patchwork' was built under R version 4.3.3
library(metR)
## Warning: package 'metR' was built under R version 4.3.3
## Attaching package: 'metR'
## The following object is masked from 'package:purrr':
##   cross
library(sf)
## Warning: package 'sf' was built under R version 4.3.3
## Linking to GEOS 3.13.0, GDAL 3.8.5, PROJ 9.5.1; sf_use_s2() is TRUE
library(secr)
## Warning: package 'secr' was built under R version 4.3.3
## This is secr 5.2.1. For overview type ?secr
## Attaching package: 'secr'
## The following object is masked from 'package:lubridate':
##   ms
## The following object is masked from 'package:purrr':
##   reduce
library(openCR)
## Warning: package 'openCR' was built under R version 4.3.3
## This is openCR 2.2.7. For overview type ?openCR and see openCR-vignette.pdf
library(ggspatial)
library(azores.fkw)
## Attaching package: 'azores.fkw'
## The following objects are masked from 'package:lubridate':
##   mday, month, week, yday, year
library(readxl)

# === Load dataset ===
bp_path <- "/Volumes/TESEI/bp.individuals.xlsx"
bp.individuals <- read_xlsx(bp_path)
# === Filter individuals with non-NA values ===
bp.individuals1 <- bp.individuals |>
  dplyr::filter(!is.na(individual))

# === Build discovery data ===
discovery <- dplyr::left_join(
```

```

    individuals_per_year(bp.individuals1) |> dplyr::rename(total = n),
    count_of_new_individuals_per_year(individuals = bp.individuals1) |> dplyr::renam
e(new = n),
    by = "year"
) |>
    mutate(old = total - new)

# === Cumulative data ===
discovery_cum <- discovery |>
    mutate(
        total = cumsum(total),
        new = cumsum(new),
        old = cumsum(old)
    )

# === Long format for plotting ===
data_long <- discovery |>
    pivot_longer(cols = c(new, old), names_to = "Individuals", values_to = "count")
|>
    mutate(
        Individuals = if_else(Individuals == "old", "Recaptured", "Captured"),
        Individuals = factor(Individuals, levels = c("Recaptured", "Captured")),
        year = as.factor(year)
    )

data_long_cum <- discovery_cum |>
    pivot_longer(cols = c(new, old), names_to = "Individuals", values_to = "count")
|>
    mutate(
        Individuals = if_else(Individuals == "old", "Recaptured", "Captured"),
        Individuals = factor(Individuals, levels = c("Recaptured", "Captured")),
        year = as.factor(year)
    )

# === Plot 1: Stacked bar for yearly data ===
discovery_plot1 <- ggplot(data_long) +
    geom_bar(stat = "identity", aes(x = year, y = count, fill = Individuals)) +
    scale_fill_manual(values = c("Recaptured" = "#5F9EA0", "Captured" = "#C2B280"))
+
    labs(x = "Year", y = "Number of sighted individuals") +
    geom_text(aes(x = year, y = total + 0.5, label = total), data = discovery, vjust
= 0, size = 4) +
    theme(
        legend.position = "none",
        panel.background = element_rect(fill = "white", color = "black"),
        axis.ticks = element_line(colour = "grey80"),
        axis.ticks.x = element_blank(),
        panel.grid.major.x = element_blank(),
        panel.grid.major.y = element_line(colour = "gray80")
    ) +
    scale_y_continuous(limits = c(0, 45)) +
    scale_x_discrete(name = "Year")

# === Plot 2: Cumulative plot ===
discovery_plot2 <- ggplot(data_long_cum) +
    geom_bar(stat = "identity", aes(x = year, y = count, fill = Individuals)) +
    scale_fill_manual(values = c("Recaptured" = "#5F9EA0", "Captured" = "#C2B280"))
+
    labs(x = "Year", y = "Cumulative number of sighted individuals") +

```

```

  geom_text(aes(x = year, y = total + 1.5, label = total), data = discovery_cum, v
just = 0, size = 4) +
  geom_line(data = filter(data_long_cum, Individuals == "Captured"), aes(x = year,
y = count, group = 1)) +
  geom_point(data = filter(data_long_cum, Individuals == "Captured"), aes(x = year
, y = count, group = 1)) +
  theme(
    legend.position = "none",
    panel.background = element_rect(fill = "white", color = "black"),
    axis.ticks = element_line(colour = "grey80"),
    axis.ticks.x = element_blank(),
    panel.grid.major.x = element_blank(),
    panel.grid.major.y = element_line(colour = "gray")
  ) +
  scale_y_continuous(limits = c(0, 90)) +
  scale_x_discrete(name = "Year")

# === Combine plots ===
discovery_figure <- discovery_plot1 + discovery_plot2 + plot_annotation(tag_levels
= 'A')

```


2.6. Capture-recapture model

#JSSAsecr ESTIMATION

```
library(tidyverse)
## Warning: package 'purrr' was built under R version 4.4.1
## Warning: package 'lubridate' was built under R version 4.4.1
## — Attaching core tidyverse packages — tidyverse 2.0.0 —
##
## ✓ dplyr      1.1.4      ✓ readr      2.1.5
## ✓ forcats   1.0.0      ✓ stringr    1.5.1
## ✓ ggplot2    3.5.1      ✓ tibble     3.2.1
## ✓ lubridate  1.9.4      ✓ tidyr      1.3.1
## ✓ purrr     1.0.4
## — Conflicts — tidyverse_conflicts() —
##
## ✗ dplyr::filter() masks stats::filter()
## ✗ dplyr::lag()     masks stats::lag()
## ⓘ Use the conflicted package (<http://conflicted.r-lib.org/>) to force all conflicts to become errors
library(patchwork)
## Warning: package 'patchwork' was built under R version 4.4.1
library(metR)
## Warning: package 'metR' was built under R version 4.4.1
## Attaching package: 'metR'
## The following object is masked from 'package:purrr':
##   cross
library(sf)
## Warning: package 'sf' was built under R version 4.4.1
## Linking to GEOS 3.11.0, GDAL 3.5.3, PROJ 9.1.0; sf_use_s2() is TRUE
library(secr)
## Warning: package 'secr' was built under R version 4.4.1
## This is secr 5.0.0. For overview type ?secr
## Attaching package: 'secr'
## The following object is masked from 'package:lubridate':
##   ms
## The following object is masked from 'package:purrr':
##   reduce
library(openCR)
## This is openCR 2.2.6 pre-release. For overview type ?openCR and see openCR-vignette.pdf
library(ggspatial)
library(azores.fkw)
## Attaching package: 'azores.fkw'
## The following objects are masked from 'package:lubridate':
##   mday, month, week, yday, year

# === Load data ===
path <- "/Users/ruisantos/Desktop/Tese Ginevra/data-raw"
bp_path <- here::here(path, "bp.individuals2.xlsx")
boat_path <- here::here(path, "boat_trips_by_min.xlsx")
write_path <- here::here(path, "openCR.analysis")
source(file.path(path, "my-functions_RM.R"))
bp.individuals <- readxl::read_xlsx(bp_path)

bp.individuals$latitude[7] <- 36.86891667
bp.individuals$longitude[7] <- -7.826444444
bp.individuals <- bp.individuals |>
```

```

dplyr::mutate(
  latitude = as.numeric(latitude),
  longitude = as.numeric(longitude)
) #|> dplyr::filter(abs(as.numeric(latitude)) > 90 | abs(as.numeric(longitude))
> 180)

bp.individuals.sf <- bp.individuals |>
  st_as_sf(coords = c("longitude", "latitude"), crs = 32629)

boat_trips_by_min <- readxl::read_xlsx(boat_path)
#path <- here::here("inst/opencr_analysis/")

set.seed(1)
utm_resolution <- 1000
buffer <- 10000
ncores <- 10
trace <- TRUE

boat_trips_by_min2 <-
  boat_trips_by_min |>
  add_sessions(
    psession_fn = \(x) azores.fkw::year(dat = x, dtm_var = "trip"),
    ssession_fn = \(x) azores.fkw::week(dat = x, dtm_var = "trip")
  )
boat_trips_by_min3 <- boat_trips_by_min |>
  dplyr::select(c("longitude", "latitude")) |>
  dplyr::rename(lat=latitude) |>
  dplyr::rename(lon=longitude)

boat_trips_by_min4 <- boat_trips_by_min3 |>
  longlat_to_utm(crs_from = 4326, crs_to = 32629)

boat_trips_by_min5 <- dplyr::bind_cols(boat_trips_by_min4, boat_trips_by_min3)

boat_trips_by_min6 <- dplyr::bind_cols(boat_trips_by_min2, boat_trips_by_min5)

# === Find position of "week" ===
week_pos <- which(names(boat_trips_by_min6) == "week")

# === Construct new column order ===
new_order <- c(
  names(boat_trips_by_min6)[1:(week_pos - 1)],
  names(boat_trips_by_min5),
  "week",
  names(boat_trips_by_min6)[(week_pos + 1):ncol(boat_trips_by_min6)]
)
# === Reorder ===
boat_trips_by_min7 <- boat_trips_by_min6 %>% select(all_of(new_order))
boat_trips_by_min8 <- boat_trips_by_min7 |>
  dplyr::select(-c("longitude", "latitude")) |>
  dplyr::rename(latitude=lat) |>
  dplyr::rename(longitude=lon)

# === Create grid ===
grid <- create_grid_N29(
  x_range = range(boat_trips_by_min$longitude),
  y_range = range(boat_trips_by_min$latitude),
  utm_resolution = utm_resolution

```

```

)

bp.individuals <- bp.individuals |>
  dplyr::filter(format(date, "%Y") != "2020") |>
  dplyr::filter(format(date, "%Y") != "2021")

length(unique(bp.individuals$individual))

## [1] 78

bp.individuals$sighting_id <- as.integer(bp.individuals$sighting_id)
bp.individuals$date <- as.Date(bp.individuals$date)

individuals2 <-
  bp.individuals |>
  add_sessions(
    psession_fn = \(x) azores.fkw::year(dat = x, dtm_var = "initial_time"),
    ssession_fn = \(x) azores.fkw::week(dat = x, dtm_var = "initial_time")
  )

capture_data <- dplyr::bind_cols(individuals2, find_grid_cells(individuals2, grid
= grid)[ "index" ])
capture <- create_capture(capture_data = capture_data) |>
  dplyr::filter(!is.na(Detector))

# === Boat effort ===
boat_effort_per_week <- boat_effort_per_week_N29(boat_trips = boat_trips_by_min8,
grid = grid)
effort <- boat_effort_per_week

# === Create capture history object ===
caphist <- secr::read.caphist(
  captfile = write_capture(capture, file = file.path(write_path, "capture.txt")),
  trapfile = write_effort(effort, file = file.path(write_path, "effort.txt")),
  binary.usage = FALSE,
  detector = "multi"
)
## Warning: dropping repeat detections within occasions at exclusive detectors
## (traps)
## Warning: dropping repeat detections within occasions at exclusive detectors
## (traps)
## No errors found :-)

# === Create mask ===
Portugal <- sf::st_read(file.path(path, "Portugal/Portugal.shp"))
## Reading layer `Portugal' from data source
##   `/Users/ruisantos/Desktop/Tese Ginevra/data-raw/Portugal/Portugal.shp'
##   using driver `ESRI Shapefile'
## Simple feature collection with 20 features and 9 fields
## Geometry type: MULTIPOLYGON
## Dimension:      XY
## Bounding box:   xmin: -31.26819 ymin: 30.03018 xmax: -6.189142 ymax: 42.15432
## Geodetic CRS:   WGS 84

Algarve <- Portugal |>
  dplyr::filter(NAME_1 == "Faro")
exclude_regions <- sf::st_transform(Algarve, crs = 32629)

habitat_mask <- create_mask_N29(
  x_range = range(boat_trips_by_min8$longitude),

```

```

y_range = range(boat_trips_by_min8$latitude),
utm_resolution = utm_resolution,
buffer = buffer,
exclude_regions = exclude_regions
)

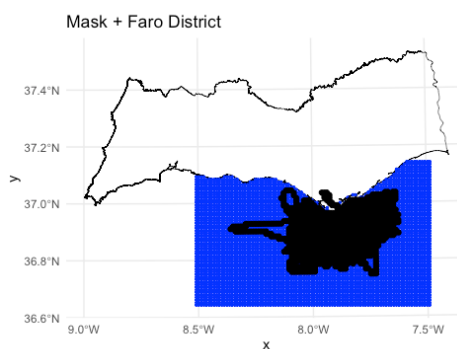
## Warning: some traps are inside non-habitat polygon(s)

capture_data_sf <- capture_data |>
  st_as_sf(coords = c("longitude", "latitude"), crs = 4326) |>
  sf::st_transform(crs = 32629)

effort_sf <- effort |>
  dplyr::select(c("index", "easting", "northing")) |>
  st_as_sf(coords = c("easting", "northing"), crs = 32629)

ggplot() +
  geom_sf(data = exclude_regions, fill = NA, color = "black") +
  geom_point(data = habitat_mask, aes(x = x, y = y), color = "blue", size = 0.5) +
  theme_minimal() +
  labs(title = "Mask + Faro District") +
  geom_sf(data = capture_data_sf) +
  geom_sf(data = effort_sf)

```



```

# === Range in meters along easting (`x`) ===
x_length <- diff(range(habitat_mask$x)) + utm_resolution

# === Range in meters along northing (`y`) ===
y_length <- diff(range(habitat_mask$y)) + utm_resolution

# === Full area (including area of islands) in hectares ===
full_area_ha <- x_length * y_length / 10000

# === Study area (excludes area of islands) in hectares ===
study_area_ha <- (nrow(habitat_mask) * utm_resolution^2) / 10000
JSSAsecrib <- openCR::openCR.fit(
  caphist,
  type = 'JSSAsecrib',
  mask = habitat_mask,
  ncores = ncores,
  trace = trace
)

## Preparing design matrices
## Warning in autoini(ch1, msk1): 'autoini' failed to find g0; setting initial g0
## = 0.1
## Maximizing likelihood...

```

##	Eval	Loglik	lambda0	phi	b	superD	sigma
##	1	-1479.116	-2.2504	0.8473	0.3333	-8.8347	8.6194
##	2	-1479.116	-2.2504	0.8473	0.3333	-8.8347	8.6194
##	3	-1479.116	-2.2504	0.8473	0.3333	-8.8347	8.6194
##	4	-1479.116	-2.2504	0.8473	0.3333	-8.8347	8.6194
##	5	-1479.116	-2.2504	0.8473	0.3333	-8.8347	8.6194
##	6	-1479.116	-2.2504	0.8473	0.3333	-8.8347	8.6194
##	7	-1479.116	-2.2504	0.8473	0.3333	-8.8347	8.6194
## Warning in log(pdot): NaNs produced							
## Warning in dpois(ncf, N * meanpdot, log = TRUE): NaNs produced							
##	8	NA	-121.5114	-10.4678	-1.1416	-2.5124	81.6964
##	9	-879.094	-14.1765	-0.2842	0.1858	-8.2024	15.9271
##	10	-879.093	-14.1765	-0.2842	0.1858	-8.2024	15.9271
##	11	-879.094	-14.1765	-0.2842	0.1858	-8.2024	15.9271
##	12	-879.094	-14.1765	-0.2842	0.1858	-8.2024	15.9271
##	13	-879.093	-14.1765	-0.2842	0.1858	-8.2024	15.9271
##	14	-879.094	-14.1765	-0.2842	0.1858	-8.2024	15.9271
##	15	-2068.306	-11.3429	0.2745	-0.0479	-4.9699	16.1674
##	16	-840.020	-13.8510	-0.2200	0.1590	-7.8311	15.9547
##	17	-840.019	-13.8510	-0.2200	0.1590	-7.8311	15.9547
##	18	-840.020	-13.8510	-0.2200	0.1590	-7.8311	15.9547
##	19	-840.020	-13.8510	-0.2200	0.1590	-7.8311	15.9547
##	20	-840.020	-13.8510	-0.2200	0.1590	-7.8311	15.9547
##	21	-840.020	-13.8510	-0.2200	0.1590	-7.8311	15.9547
##	22	-7289.705	-11.0583	0.5671	0.0500	-3.6564	16.3360
##	23	-806.073	-13.5717	-0.1413	0.1481	-7.4137	15.9928
##	24	-806.072	-13.5717	-0.1413	0.1481	-7.4137	15.9928
##	25	-806.073	-13.5717	-0.1413	0.1481	-7.4137	15.9928
##	26	-806.073	-13.5717	-0.1413	0.1481	-7.4137	15.9928
##	27	-806.072	-13.5717	-0.1413	0.1481	-7.4136	15.9928
##	28	-806.073	-13.5717	-0.1413	0.1481	-7.4137	15.9928
##	29	-964.790	-12.6145	0.3080	0.2074	-5.4266	16.2046
##	30	-782.986	-13.3583	-0.0411	0.1613	-6.9705	16.0400
##	31	-782.986	-13.3582	-0.0411	0.1613	-6.9705	16.0400
##	32	-782.986	-13.3583	-0.0411	0.1613	-6.9705	16.0400
##	33	-782.986	-13.3583	-0.0411	0.1613	-6.9705	16.0400
##	34	-782.986	-13.3583	-0.0411	0.1613	-6.9705	16.0400
##	35	-782.986	-13.3583	-0.0411	0.1613	-6.9705	16.0401
##	36	-780.876	-13.1518	0.2158	0.2758	-6.2961	16.1211
##	37	-780.876	-13.1517	0.2158	0.2758	-6.2961	16.1211
##	38	-780.876	-13.1518	0.2158	0.2758	-6.2961	16.1211
##	39	-780.876	-13.1518	0.2158	0.2758	-6.2961	16.1211
##	40	-780.876	-13.1518	0.2158	0.2758	-6.2961	16.1211
##	41	-780.876	-13.1518	0.2158	0.2758	-6.2961	16.1212
##	42	-775.871	-13.2826	0.2199	0.3103	-6.6425	16.0810
##	43	-775.871	-13.2825	0.2199	0.3103	-6.6425	16.0810
##	44	-775.871	-13.2826	0.2199	0.3103	-6.6425	16.0810
##	45	-775.871	-13.2826	0.2199	0.3103	-6.6425	16.0810
##	46	-775.871	-13.2826	0.2199	0.3103	-6.6425	16.0810
##	47	-775.871	-13.2826	0.2199	0.3103	-6.6425	16.0810
##	48	-775.468	-13.2987	0.3333	0.3175	-6.5696	16.0934
##	49	-775.468	-13.2986	0.3333	0.3175	-6.5696	16.0934
##	50	-775.468	-13.2987	0.3333	0.3175	-6.5696	16.0934
##	51	-775.468	-13.2987	0.3333	0.3175	-6.5696	16.0934
##	52	-775.468	-13.2987	0.3333	0.3175	-6.5695	16.0934
##	53	-775.468	-13.2987	0.3333	0.3175	-6.5696	16.0934
##	54	-775.161	-13.3634	0.5654	0.3075	-6.4875	16.1120
##	55	-775.161	-13.3633	0.5654	0.3075	-6.4875	16.1120

##	56	-775.161	-13.3634	0.5654	0.3075	-6.4875	16.1120
##	57	-775.161	-13.3634	0.5654	0.3075	-6.4875	16.1120
##	58	-775.161	-13.3634	0.5654	0.3075	-6.4875	16.1120
##	59	-775.161	-13.3634	0.5654	0.3075	-6.4875	16.1120
##	60	-774.697	-13.5153	1.0418	0.2694	-6.3717	16.1442
##	61	-774.698	-13.5153	1.0418	0.2694	-6.3717	16.1442
##	62	-774.697	-13.5153	1.0418	0.2694	-6.3717	16.1442
##	63	-774.697	-13.5153	1.0418	0.2694	-6.3717	16.1442
##	64	-774.697	-13.5153	1.0418	0.2694	-6.3717	16.1442
##	65	-774.697	-13.5153	1.0418	0.2694	-6.3717	16.1442
##	66	-773.878	-13.8824	2.1784	0.1602	-6.1586	16.2124
##	67	-773.878	-13.8824	2.1784	0.1602	-6.1586	16.2124
##	68	-773.878	-13.8824	2.1784	0.1602	-6.1586	16.2124
##	69	-773.878	-13.8824	2.1784	0.1602	-6.1586	16.2124
##	70	-773.878	-13.8824	2.1784	0.1602	-6.1586	16.2124
##	71	-773.878	-13.8824	2.1784	0.1602	-6.1586	16.2124
##	72	-773.727	-14.1131	3.0148	0.0532	-6.0449	16.2533
##	73	-773.727	-14.1131	3.0148	0.0532	-6.0449	16.2533
##	74	-773.727	-14.1131	3.0148	0.0532	-6.0449	16.2533
##	75	-773.727	-14.1131	3.0148	0.0532	-6.0449	16.2533
##	76	-773.727	-14.1131	3.0148	0.0532	-6.0449	16.2533
##	77	-773.727	-14.1131	3.0148	0.0532	-6.0449	16.2533
##	78	-773.683	-14.0474	2.9088	0.0457	-6.0895	16.2409
##	79	-773.683	-14.0473	2.9088	0.0457	-6.0895	16.2409
##	80	-773.683	-14.0474	2.9088	0.0457	-6.0895	16.2409
##	81	-773.683	-14.0474	2.9088	0.0457	-6.0895	16.2409
##	82	-773.683	-14.0474	2.9088	0.0457	-6.0895	16.2409
##	83	-773.683	-14.0474	2.9088	0.0457	-6.0895	16.2409
##	84	-773.623	-13.9640	2.9685	0.0062	-6.1644	16.2236
##	85	-773.623	-13.9640	2.9685	0.0062	-6.1644	16.2236
##	86	-773.623	-13.9640	2.9685	0.0062	-6.1644	16.2236
##	87	-773.623	-13.9640	2.9685	0.0062	-6.1644	16.2236
##	88	-773.623	-13.9640	2.9685	0.0062	-6.1644	16.2236
##	89	-773.623	-13.9640	2.9685	0.0062	-6.1644	16.2236
##	90	-773.559	-13.8670	3.2326	-0.0442	-6.2690	16.2017
##	91	-773.559	-13.8670	3.2326	-0.0442	-6.2690	16.2017
##	92	-773.559	-13.8670	3.2326	-0.0442	-6.2690	16.2017
##	93	-773.559	-13.8670	3.2326	-0.0442	-6.2690	16.2017
##	94	-773.559	-13.8670	3.2326	-0.0442	-6.2690	16.2017
##	95	-773.559	-13.8670	3.2326	-0.0442	-6.2690	16.2017
##	96	-773.511	-13.8042	3.6085	-0.0696	-6.3510	16.1862
##	97	-773.511	-13.8041	3.6085	-0.0696	-6.3510	16.1862
##	98	-773.511	-13.8042	3.6085	-0.0696	-6.3510	16.1862
##	99	-773.511	-13.8042	3.6085	-0.0696	-6.3510	16.1862
##	100	-773.511	-13.8042	3.6085	-0.0696	-6.3510	16.1862
##	101	-773.511	-13.8042	3.6085	-0.0696	-6.3510	16.1863
##	102	-773.484	-13.7862	3.9435	-0.0608	-6.3836	16.1812
##	103	-773.483	-13.7861	3.9435	-0.0608	-6.3836	16.1812
##	104	-773.484	-13.7862	3.9435	-0.0608	-6.3836	16.1812
##	105	-773.484	-13.7862	3.9435	-0.0608	-6.3836	16.1812
##	106	-773.483	-13.7862	3.9435	-0.0608	-6.3836	16.1812
##	107	-773.484	-13.7862	3.9435	-0.0608	-6.3836	16.1812
##	108	-773.464	-13.7889	4.2105	-0.0333	-6.3845	16.1820
##	109	-773.464	-13.7889	4.2105	-0.0333	-6.3845	16.1820
##	110	-773.464	-13.7889	4.2105	-0.0333	-6.3845	16.1820
##	111	-773.464	-13.7889	4.2105	-0.0333	-6.3845	16.1820
##	112	-773.464	-13.7889	4.2105	-0.0333	-6.3845	16.1820
##	113	-773.464	-13.7889	4.2105	-0.0333	-6.3845	16.1820
##	114	-773.444	-13.8013	4.5377	0.0011	-6.3680	16.1864

##	115	-773.444	-13.8013	4.5377	0.0011	-6.3680	16.1864
##	116	-773.444	-13.8013	4.5377	0.0011	-6.3680	16.1864
##	117	-773.444	-13.8013	4.5377	0.0011	-6.3680	16.1864
##	118	-773.444	-13.8013	4.5377	0.0011	-6.3680	16.1864
##	119	-773.444	-13.8013	4.5377	0.0011	-6.3680	16.1864
##	120	-773.425	-13.8185	4.9514	0.0201	-6.3436	16.1928
##	121	-773.425	-13.8185	4.9514	0.0201	-6.3436	16.1928
##	122	-773.425	-13.8185	4.9514	0.0201	-6.3436	16.1928
##	123	-773.425	-13.8185	4.9514	0.0201	-6.3436	16.1928
##	124	-773.425	-13.8185	4.9514	0.0201	-6.3436	16.1928
##	125	-773.425	-13.8185	4.9514	0.0201	-6.3436	16.1928
##	126	-773.409	-13.8356	5.5245	0.0149	-6.3216	16.1998
##	127	-773.409	-13.8356	5.5245	0.0149	-6.3216	16.1998
##	128	-773.409	-13.8356	5.5245	0.0149	-6.3216	16.1998
##	129	-773.409	-13.8356	5.5245	0.0149	-6.3216	16.1998
##	130	-773.409	-13.8356	5.5245	0.0149	-6.3216	16.1998
##	131	-773.409	-13.8356	5.5245	0.0149	-6.3216	16.1998
##	132	-773.400	-13.8431	6.1579	-0.0046	-6.3146	16.2042
##	133	-773.400	-13.8431	6.1579	-0.0046	-6.3146	16.2042
##	134	-773.400	-13.8431	6.1579	-0.0046	-6.3146	16.2042
##	135	-773.400	-13.8431	6.1579	-0.0046	-6.3146	16.2042
##	136	-773.400	-13.8431	6.1579	-0.0046	-6.3146	16.2042
##	137	-773.400	-13.8431	6.1579	-0.0046	-6.3146	16.2042
##	138	-773.396	-13.8421	6.7361	-0.0178	-6.3180	16.2061
##	139	-773.396	-13.8420	6.7361	-0.0178	-6.3180	16.2061
##	140	-773.396	-13.8421	6.7361	-0.0178	-6.3180	16.2061
##	141	-773.396	-13.8421	6.7361	-0.0178	-6.3180	16.2061
##	142	-773.396	-13.8421	6.7361	-0.0178	-6.3180	16.2061
##	143	-773.396	-13.8421	6.7361	-0.0178	-6.3180	16.2061
##	144	-773.394	-13.8386	7.3130	-0.0223	-6.3230	16.2074
##	145	-773.394	-13.8386	7.3130	-0.0223	-6.3230	16.2074
##	146	-773.394	-13.8386	7.3130	-0.0223	-6.3230	16.2074
##	147	-773.394	-13.8386	7.3130	-0.0223	-6.3230	16.2074
##	148	-773.394	-13.8386	7.3130	-0.0223	-6.3230	16.2074
##	149	-773.394	-13.8386	7.3130	-0.0223	-6.3230	16.2074
##	150	-773.393	-13.8358	7.9793	-0.0205	-6.3263	16.2093
##	151	-773.393	-13.8358	7.9793	-0.0205	-6.3263	16.2093
##	152	-773.393	-13.8358	7.9793	-0.0205	-6.3263	16.2093
##	153	-773.393	-13.8358	7.9793	-0.0205	-6.3263	16.2093
##	154	-773.393	-13.8358	7.9793	-0.0205	-6.3263	16.2093
##	155	-773.393	-13.8358	7.9793	-0.0205	-6.3263	16.2093
##	156	-773.392	-13.8352	8.6697	-0.0160	-6.3265	16.2119
##	157	-773.392	-13.8352	8.6697	-0.0160	-6.3265	16.2119
##	158	-773.392	-13.8352	8.6697	-0.0160	-6.3265	16.2119
##	159	-773.392	-13.8352	8.6697	-0.0160	-6.3265	16.2119
##	160	-773.392	-13.8352	8.6697	-0.0160	-6.3265	16.2119
##	161	-773.392	-13.8352	8.6697	-0.0160	-6.3265	16.2119
##	162	-773.392	-13.8359	9.3055	-0.0132	-6.3253	16.2146
##	163	-773.392	-13.8359	9.3055	-0.0132	-6.3253	16.2146
##	164	-773.392	-13.8359	9.3055	-0.0132	-6.3253	16.2146
##	165	-773.392	-13.8359	9.3055	-0.0131	-6.3253	16.2146
##	166	-773.392	-13.8359	9.3055	-0.0132	-6.3253	16.2146
##	167	-773.392	-13.8359	9.3055	-0.0132	-6.3253	16.2146
##	168	-773.392	-13.8366	9.9277	-0.0124	-6.3244	16.2172
##	169	-773.392	-13.8366	9.9277	-0.0124	-6.3244	16.2172
##	170	-773.392	-13.8366	9.9278	-0.0124	-6.3244	16.2172
##	171	-773.392	-13.8366	9.9277	-0.0124	-6.3244	16.2172
##	172	-773.392	-13.8366	9.9277	-0.0124	-6.3244	16.2172
##	173	-773.392	-13.8366	9.9277	-0.0124	-6.3244	16.2172

## 174	-773.392	-13.8369	10.6127	-0.0130	-6.3240	16.2200
## 175	-773.392	-13.8369	10.6127	-0.0130	-6.3240	16.2200
## 176	-773.392	-13.8369	10.6127	-0.0130	-6.3240	16.2200
## 177	-773.392	-13.8369	10.6127	-0.0130	-6.3240	16.2200
## 178	-773.392	-13.8369	10.6127	-0.0130	-6.3240	16.2200
## 179	-773.392	-13.8369	10.6127	-0.0130	-6.3240	16.2200
## 180	-773.392	-13.8369	11.3101	-0.0139	-6.3242	16.2227
## 181	-773.392	-13.8369	11.3101	-0.0139	-6.3242	16.2227
## 182	-773.392	-13.8369	11.3101	-0.0139	-6.3242	16.2227
## 183	-773.392	-13.8369	11.3101	-0.0139	-6.3242	16.2227
## 184	-773.392	-13.8369	11.3101	-0.0139	-6.3242	16.2227
## 185	-773.392	-13.8369	11.3101	-0.0139	-6.3242	16.2227
## 186	-773.392	-13.8367	11.9652	-0.0145	-6.3245	16.2252
## 187	-773.392	-13.8367	11.9652	-0.0145	-6.3245	16.2252
## 188	-773.392	-13.8367	11.9652	-0.0145	-6.3245	16.2252
## 189	-773.392	-13.8367	11.9652	-0.0145	-6.3245	16.2252
## 190	-773.392	-13.8367	11.9652	-0.0145	-6.3245	16.2252
## 191	-773.392	-13.8367	11.9652	-0.0145	-6.3245	16.2252
## 192	-773.392	-13.8366	12.6189	-0.0146	-6.3246	16.2277
## 193	-773.392	-13.8366	12.6189	-0.0146	-6.3246	16.2277
## 194	-773.392	-13.8366	12.6189	-0.0146	-6.3246	16.2277
## 195	-773.392	-13.8366	12.6189	-0.0146	-6.3246	16.2277
## 196	-773.392	-13.8366	12.6189	-0.0146	-6.3246	16.2277
## 197	-773.392	-13.8366	12.6189	-0.0146	-6.3246	16.2277
## 198	-773.392	-13.8366	13.3014	-0.0144	-6.3246	16.2303
## 199	-773.392	-13.8366	13.3014	-0.0144	-6.3246	16.2303
## 200	-773.392	-13.8366	13.3014	-0.0144	-6.3246	16.2303
## 201	-773.392	-13.8366	13.3014	-0.0144	-6.3246	16.2303
## 202	-773.392	-13.8366	13.3014	-0.0144	-6.3246	16.2303
## 203	-773.392	-13.8366	13.3014	-0.0144	-6.3246	16.2304
## 204	-773.392	-13.8366	13.9813	-0.0142	-6.3246	16.2330
## 205	-773.392	-13.8366	13.9813	-0.0142	-6.3246	16.2330
## 206	-773.392	-13.8366	13.9813	-0.0142	-6.3246	16.2330
## 207	-773.392	-13.8366	13.9813	-0.0142	-6.3246	16.2330
## 208	-773.392	-13.8366	13.9813	-0.0142	-6.3245	16.2330
## 209	-773.392	-13.8366	13.9813	-0.0142	-6.3246	16.2330
## 210	-773.392	-13.8367	14.6068	-0.0141	-6.3245	16.2354
## 211	-773.392	-13.8366	14.6068	-0.0141	-6.3245	16.2354
## 212	-773.392	-13.8367	14.6068	-0.0141	-6.3245	16.2354
## 213	-773.392	-13.8367	14.6068	-0.0141	-6.3245	16.2354
## 214	-773.392	-13.8367	14.6068	-0.0141	-6.3245	16.2354
## 215	-773.392	-13.8367	14.6068	-0.0141	-6.3245	16.2354
## 216	-773.392	-13.8367	15.1757	-0.0141	-6.3245	16.2376
## 217	-773.392	-13.8367	15.1757	-0.0141	-6.3245	16.2376
## 218	-773.392	-13.8367	15.1757	-0.0141	-6.3245	16.2376
## 219	-773.392	-13.8367	15.1757	-0.0141	-6.3245	16.2376
## 220	-773.392	-13.8367	15.1757	-0.0141	-6.3245	16.2376
## 221	-773.392	-13.8367	15.1757	-0.0141	-6.3245	16.2376
## 222	-773.392	-13.8367	15.7779	-0.0142	-6	

###	233	-773.392	-13.8367	16.2372	-0.0142	-6.3245	16.2417
##	234	-773.392	-13.8367	16.4583	-0.0142	-6.3245	16.2425
##	235	-773.392	-13.8366	16.4583	-0.0142	-6.3245	16.2425
##	236	-773.392	-13.8367	16.4583	-0.0142	-6.3245	16.2425
##	237	-773.392	-13.8367	16.4583	-0.0142	-6.3245	16.2425
##	238	-773.392	-13.8367	16.4583	-0.0142	-6.3245	16.2425
##	239	-773.392	-13.8367	16.4583	-0.0142	-6.3245	16.2425
##	240	-773.392	-13.8367	16.5341	-0.0142	-6.3245	16.2428
##	241	-773.392	-13.8366	16.5341	-0.0142	-6.3245	16.2428
##	242	-773.392	-13.8367	16.5341	-0.0142	-6.3245	16.2428
##	243	-773.392	-13.8367	16.5341	-0.0142	-6.3245	16.2428
##	244	-773.392	-13.8367	16.5341	-0.0142	-6.3245	16.2428
##	245	-773.392	-13.8367	16.5341	-0.0142	-6.3245	16.2428
##	246	-773.392	-13.8367	18.8800	-0.0142	-6.3245	16.2516
##	247	-773.392	-13.8367	16.7687	-0.0142	-6.3245	16.2437
##	248	-773.392	-13.8367	16.6301	-0.0142	-6.3245	16.2432
##	249	-773.392	-13.8366	16.6301	-0.0142	-6.3245	16.2432
##	250	-773.392	-13.8367	16.6301	-0.0142	-6.3245	16.2432
##	251	-773.392	-13.8367	16.6301	-0.0142	-6.3245	16.2432
##	252	-773.392	-13.8367	16.6301	-0.0142	-6.3245	16.2432
##	253	-773.392	-13.8367	16.6301	-0.0142	-6.3245	16.2432
##	254	-773.392	-13.8367	19.8419	-0.0141	-6.3245	16.2552
##	255	-773.392	-13.8367	16.9745	-0.0142	-6.3245	16.2445
##	256	-773.392	-13.8367	16.7188	-0.0142	-6.3245	16.2435
##	257	-773.392	-13.8367	16.6619	-0.0142	-6.3245	16.2433
##	258	-773.392	-13.8367	16.6425	-0.0142	-6.3245	16.2432
##	259	-773.392	-13.8367	16.6351	-0.0142	-6.3245	16.2432
##	260	-773.392	-13.8367	16.6321	-0.0142	-6.3245	16.2432
##	261	-773.392	-13.8367	16.6309	-0.0142	-6.3245	16.2432
##	262	-773.392	-13.8367	16.6304	-0.0142	-6.3245	16.2432
##	263	-773.392	-13.8366	16.6304	-0.0142	-6.3245	16.2432
##	264	-773.392	-13.8367	16.6305	-0.0142	-6.3245	16.2432
##	265	-773.392	-13.8367	16.6304	-0.0142	-6.3245	16.2432
##	266	-773.392	-13.8367	16.6304	-0.0142	-6.3245	16.2432
##	267	-773.392	-13.8367	16.6304	-0.0142	-6.3245	16.2432
##	268	-773.392	-13.8367	16.6303	-0.0142	-6.3245	16.2432
##	269	-773.392	-13.8366	16.6303	-0.0142	-6.3245	16.2432
##	270	-773.392	-13.8367	16.6303	-0.0142	-6.3245	16.2432
##	271	-773.392	-13.8367	16.6303	-0.0142	-6.3245	16.2432
##	272	-773.392	-13.8367	16.6303	-0.0142	-6.3245	16.2432
##	273	-773.392	-13.8367	16.6303	-0.0142	-6.3245	16.2432
##	274	-773.392	-13.8367	16.6246	-0.0141	-6.3245	16.2429
##	275	-773.392	-13.8367	16.6246	-0.0141	-6.3245	16.2429
##	276	-773.392	-13.8367	16.6247	-0.0141	-6.3245	16.2429
##	277	-773.392	-13.8367	16.6246	-0.0141	-6.3245	16.2429
##	278	-773.392	-13.8367	16.6246	-0.0141	-6.3245	16.2429
##	279	-773.392	-13.8367	16.6			

##	292	-773.392	-13.8367	16.5334	-0.0140	-6.3245	16.2369
##	293	-773.392	-13.8367	16.5334	-0.0140	-6.3245	16.2369
##	294	-773.392	-13.8367	16.5334	-0.0140	-6.3245	16.2369
##	295	-773.392	-13.8367	16.5334	-0.0140	-6.3245	16.2369
##	296	-773.392	-13.8367	16.5334	-0.0140	-6.3244	16.2369
##	297	-773.392	-13.8367	16.5334	-0.0140	-6.3245	16.2370
##	298	-773.392	-13.8367	16.3484	-0.0138	-6.3244	16.2245
##	299	-773.392	-13.8367	16.3484	-0.0138	-6.3244	16.2245
##	300	-773.392	-13.8367	16.3484	-0.0138	-6.3244	16.2245
##	301	-773.392	-13.8367	16.3484	-0.0138	-6.3244	16.2245
##	302	-773.392	-13.8367	16.3484	-0.0138	-6.3244	16.2244
##	303	-773.392	-13.8367	16.3484	-0.0138	-6.3244	16.2245
##	304	-773.392	-13.8367	15.9001	-0.0135	-6.3243	16.1940
##	305	-773.392	-13.8367	15.9001	-0.0135	-6.3243	16.1940
##	306	-773.392	-13.8367	15.9001	-0.0135	-6.3243	16.1940
##	307	-773.392	-13.8367	15.9001	-0.0135	-6.3243	16.1940
##	308	-773.392	-13.8367	15.9001	-0.0135	-6.3243	16.1940
##	309	-773.392	-13.8367	15.9001	-0.0135	-6.3243	16.1940
##	310	-773.392	-13.8368	14.8247	-0.0130	-6.3243	16.1201
##	311	-773.392	-13.8367	14.8247	-0.0130	-6.3243	16.1201
##	312	-773.392	-13.8368	14.8247	-0.0130	-6.3243	16.1201
##	313	-773.392	-13.8368	14.8247	-0.0130	-6.3243	16.1201
##	314	-773.392	-13.8368	14.8247	-0.0130	-6.3242	16.1201
##	315	-773.392	-13.8368	14.8247	-0.0130	-6.3243	16.1201
##	316	-773.392	-13.8368	12.8562	-0.0126	-6.3242	15.9834
##	317	-773.392	-13.8368	12.8562	-0.0126	-6.3242	15.9834
##	318	-773.392	-13.8368	12.8562	-0.0126	-6.3242	15.9834
##	319	-773.392	-13.8368	12.8562	-0.0126	-6.3242	15.9834
##	320	-773.392	-13.8368	12.8562	-0.0126	-6.3242	15.9834
##	321	-773.392	-13.8368	12.8562	-0.0126	-6.3242	15.9834
##	322	-773.392	-13.8367	13.9775	-0.0132	-6.3243	16.0591
##	323	-773.392	-13.8367	13.9775	-0.0132	-6.3243	16.0591
##	324	-773.392	-13.8367	13.9775	-0.0132	-6.3243	16.0591
##	325	-773.392	-13.8367	13.9775	-0.0132	-6.3243	16.0591
##	326	-773.392	-13.8367	13.9775	-0.0132	-6.3243	16.0591
##	327	-773.392	-13.8367	13.9775	-0.0132	-6.3243	16.0591
##	328	-773.392	-13.8367	13.7710	-0.0136	-6.3244	16.0415
##	329	-773.392	-13.8367	13.7710	-0.0136	-6.3244	16.0415
##	330	-773.392	-13.8367	13.7710	-0.0136	-6.3244	16.0415
##	331	-773.392	-13.8367	13.7710	-0.0136	-6.3244	16.0415
##	332	-773.392	-13.8367	13.7710	-0.0136	-6.3244	16.0415
##	333	-773.392	-13.8367	13.7710	-0.0136	-6.3244	16.0415
##	334	-773.392	-13.8366	13.0061	-0.0144	-6.3246	15.9789
##	335	-773.392	-13.8366	13.0061	-0.0144	-6.3246	15.9789
##	336	-773.392	-13.8366	13.0061	-0.0144	-6.3246	15.9789
##	337	-773.392	-13.8366	13.0061	-0.0144	-6.3246	15.9789
##	338	-773.392	-13.8366	13.0			

##	351	-773.392	-13.8366	13.3482	-0.0143	-6.3246	15.9908
##	352	-773.392	-13.8367	14.1188	-0.0143	-6.3245	15.9565
##	353	-773.392	-13.8367	14.1188	-0.0143	-6.3245	15.9565
##	354	-773.392	-13.8367	14.1188	-0.0143	-6.3245	15.9565
##	355	-773.392	-13.8367	14.1188	-0.0142	-6.3245	15.9565
##	356	-773.392	-13.8367	14.1188	-0.0143	-6.3245	15.9565
##	357	-773.392	-13.8367	14.1188	-0.0143	-6.3245	15.9565
##	358	-773.392	-13.8367	16.3763	-0.0141	-6.3244	15.7468
##	359	-773.392	-13.8367	16.3763	-0.0141	-6.3244	15.7468
##	360	-773.392	-13.8367	16.3763	-0.0141	-6.3244	15.7468
##	361	-773.392	-13.8367	16.3763	-0.0141	-6.3244	15.7468
##	362	-773.392	-13.8367	16.3763	-0.0141	-6.3244	15.7468
##	363	-773.392	-13.8367	16.3763	-0.0141	-6.3244	15.7468
##	364	-773.391	-13.8368	18.7508	-0.0141	-6.3243	15.4835
##	365	-773.391	-13.8368	18.7508	-0.0141	-6.3243	15.4835
##	366	-773.391	-13.8368	18.7508	-0.0141	-6.3243	15.4835
##	367	-773.391	-13.8368	18.7508	-0.0141	-6.3243	15.4835
##	368	-773.391	-13.8368	18.7508	-0.0141	-6.3243	15.4835
##	369	-773.391	-13.8368	18.7508	-0.0141	-6.3243	15.4835
##	370	-773.391	-13.8369	22.6623	-0.0140	-6.3242	15.0433
##	371	-773.391	-13.8368	22.6623	-0.0140	-6.3242	15.0433
##	372	-773.391	-13.8369	22.6623	-0.0140	-6.3242	15.0433
##	373	-773.391	-13.8369	22.6623	-0.0140	-6.3242	15.0433
##	374	-773.391	-13.8369	22.6623	-0.0140	-6.3242	15.0433
##	375	-773.391	-13.8369	22.6623	-0.0140	-6.3242	15.0433
##	376	-773.389	-13.8371	32.0819	-0.0139	-6.3239	13.9819
##	377	-773.389	-13.8371	32.0819	-0.0139	-6.3239	13.9819
##	378	-773.389	-13.8371	32.0820	-0.0139	-6.3239	13.9819
##	379	-773.389	-13.8371	32.0819	-0.0139	-6.3239	13.9819
##	380	-773.389	-13.8371	32.0819	-0.0139	-6.3239	13.9819
##	381	-773.389	-13.8371	32.0819	-0.0139	-6.3239	13.9820
##	382	NA	-13.8395	110.5618	-0.0116	-6.3199	5.1373
##	383	-773.375	-13.8373	39.9299	-0.0136	-6.3235	13.0975
##	384	-773.375	-13.8373	39.9299	-0.0136	-6.3235	13.0975
##	385	-773.375	-13.8373	39.9300	-0.0136	-6.3235	13.0975
##	386	-773.375	-13.8373	39.9299	-0.0136	-6.3235	13.0975
##	387	-773.375	-13.8373	39.9299	-0.0136	-6.3235	13.0975
##	388	-773.375	-13.8373	39.9299	-0.0136	-6.3235	13.0975
##	389	NA	-13.8518	488.3924	0.0007	-6.2991	-37.4482
##	390	-980.895	-13.8388	84.7762	-0.0122	-6.3210	8.0429
##	391	-775.191	-13.8380	62.3530	-0.0129	-6.3223	10.5702
##	392	-773.224	-13.8377	51.1415	-0.0133	-6.3229	11.8338
##	393	-773.224	-13.8377	51.1415	-0.0133	-6.3229	11.8338
##	394	-773.224	-13.8377	51.1415	-0.0133	-6.3229	11.8338
##	395	-773.224	-13.8377	51.1415	-0.0133	-6.3229	11.8338
##	396	-773.224	-13.8377	51.1415	-0.0133	-6.3229	11.8338
##	397	-773.224	-13.8377	51.1415	-0.0133	-6.3229	11.8338
##	398	NA	-13.9395	3629.6628	0.1035	-6.1314	-391.5359
##	399	NA	-13.8479	408.9936	-0.0016	-6.3037	-28.5031
##	400	-1014.447	-13.8387	86.9267	-0.0121	-6.3209	7.8001
##	401	-797.077	-13.8382	69.0341	-0.0127	-6.3219	9.8170
##	402	-773.110	-13.8378	55.3970	-0.0131	-6.3226	11.3542
##	403	-773.110	-13.8378	55.3970	-0.0131	-6.3226	11.3542
##	404	-773.110	-13.8378	55.3971	-0.0131	-6.3226	11.3542
##	405	-773.110	-13.8378	55.3970	-0.0131	-6.3226	11.3542
##	406	-773.110	-13.8378	55.3970	-0.0131	-6.3226	11.3542
##	407	-773.110	-13.8378	55.3970	-0.0131	-6.3226	11.3542
##	408	-805.159	-13.6918	68.3486	-0.0216	-6.3849	9.6277
##	409	-773.072	-13.8232	56.6922	-0.0140	-6.3289	11.1815

##	410	-773.072	-13.8232	56.6922	-0.0140	-6.3289	11.1815
##	411	-773.072	-13.8232	56.6922	-0.0140	-6.3289	11.1815
##	412	-773.072	-13.8232	56.6922	-0.0140	-6.3289	11.1815
##	413	-773.072	-13.8232	56.6922	-0.0140	-6.3289	11.1815
##	414	-773.072	-13.8232	56.6922	-0.0140	-6.3289	11.1815
##	415	-772.818	-13.7241	57.4479	-0.0200	-6.3683	10.9019
##	416	-772.817	-13.7241	57.4479	-0.0200	-6.3683	10.9019
##	417	-772.818	-13.7241	57.4479	-0.0200	-6.3683	10.9019
##	418	-772.818	-13.7241	57.4479	-0.0200	-6.3683	10.9019
##	419	-772.818	-13.7241	57.4479	-0.0200	-6.3683	10.9019
##	420	-772.818	-13.7241	57.4479	-0.0200	-6.3683	10.9019
##	421	-772.271	-13.3181	54.2829	-0.0415	-6.4977	10.3163
##	422	-772.271	-13.3181	54.2829	-0.0415	-6.4977	10.3163
##	423	-772.271	-13.3181	54.2829	-0.0415	-6.4977	10.3163
##	424	-772.271	-13.3181	54.2829	-0.0415	-6.4977	10.3163
##	425	-772.271	-13.3181	54.2829	-0.0415	-6.4977	10.3163
##	426	-772.271	-13.3181	54.2829	-0.0415	-6.4977	10.3164
##	427	-772.280	-12.8392	43.9471	-0.0728	-6.6481	10.3603
##	428	-771.288	-13.0792	49.1275	-0.0571	-6.5727	10.3382
##	429	-771.288	-13.0792	49.1275	-0.0571	-6.5727	10.3382
##	430	-771.288	-13.0792	49.1275	-0.0571	-6.5727	10.3382
##	431	-771.288	-13.0792	49.1275	-0.0571	-6.5727	10.3382
##	432	-771.288	-13.0792	49.1275	-0.0571	-6.5727	10.3382
##	433	-771.288	-13.0792	49.1275	-0.0571	-6.5727	10.3383
##	434	-770.495	-13.1092	41.8681	-0.0372	-6.3091	10.0895
##	435	-770.495	-13.1092	41.8681	-0.0372	-6.3091	10.0895
##	436	-770.495	-13.1092	41.8682	-0.0372	-6.3091	10.0895
##	437	-770.495	-13.1092	41.8681	-0.0372	-6.3091	10.0895
##	438	-770.495	-13.1092	41.8681	-0.0372	-6.3091	10.0895
##	439	-770.495	-13.1092	41.8681	-0.0372	-6.3091	10.0895
##	440	-772.399	-12.9622	21.2409	-0.0046	-5.7613	9.4126
##	441	-770.183	-13.0746	37.0044	-0.0295	-6.1800	9.9299
##	442	-770.183	-13.0746	37.0044	-0.0295	-6.1800	9.9299
##	443	-770.183	-13.0746	37.0044	-0.0295	-6.1800	9.9299
##	444	-770.183	-13.0746	37.0044	-0.0295	-6.1800	9.9299
##	445	-770.183	-13.0746	37.0044	-0.0295	-6.1800	9.9299
##	446	-770.183	-13.0746	37.0044	-0.0295	-6.1800	9.9299
##	447	-769.738	-13.2464	21.8315	0.0118	-5.5923	9.6550
##	448	-769.738	-13.2464	21.8315	0.0118	-5.5923	9.6550
##	449	-769.738	-13.2464	21.8315	0.0118	-5.5923	9.6550
##	450	-769.738	-13.2464	21.8315	0.0118	-5.5923	9.6550
##	451	-769.738	-13.2464	21.8315	0.0118	-5.5923	9.6550
##	452	-769.738	-13.2464	21.8315	0.0118	-5.5923	9.6550
##	453	-769.709	-13.2014	22.4710	-0.0026	-5.6552	9.6974
##	454	-769.709	-13.2014	22.4710	-0.0026	-5.6552	9.6974
##	455	-769.709	-13.2014	22.4710	-0.0026	-5.6552	9.6974
##	456	-769.709	-13.2014	22.4710	-0.0026	-5.6552	9.6974
##	457	-769.709	-13.2014	22.4710	-0.0026	-5.6552	9.6974
##	458	-769.709	-13.2014	22.4710	-0.0026	-5.6552	9.6974
##	459	-769.672	-13.0750	21.5539	-0.0180	-5.7268	9.6489
##	460	-769.672	-13.0750	21.5539	-0.0180	-5.7268	9.6489
##	461	-769.672	-13.0750	21.5539	-0.0180	-5.7268	9.6489
##	462	-769.672	-13.0750	21.5539	-0.0180	-5.7268	9.6489
##	463	-769.672	-13.0750	21.5539	-0.0180	-5.7268	9.6489
##	464	-769.672	-13.0750	21.5539	-0.0180	-5.7268	9.6489
##	465	-769.670	-13.0734	20.7571	-0.0113	-5.7052	9.6350
##	466	-769.670	-13.0734	20.7571	-0.0113	-5.7052	9.6350
##	467	-769.670	-13.0734	20.7571	-0.0113	-5.7052	9.6350
##	468	-769.670	-13.0734	20.7571	-0.0113	-5.7052	9.6350

##	469	-769.670	-13.0734	20.7571	-0.0113	-5.7052	9.6350
##	470	-769.670	-13.0734	20.7571	-0.0113	-5.7052	9.6350
##	471	-769.670	-13.0718	20.4630	-0.0103	-5.6980	9.6303
##	472	-769.670	-13.0718	20.4630	-0.0103	-5.6980	9.6303
##	473	-769.670	-13.0718	20.4630	-0.0103	-5.6980	9.6303
##	474	-769.670	-13.0718	20.4630	-0.0103	-5.6980	9.6303
##	475	-769.670	-13.0718	20.4630	-0.0103	-5.6980	9.6303
##	476	-769.670	-13.0718	20.4630	-0.0103	-5.6980	9.6303
##	477	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6301
##	478	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6301
##	479	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6301
##	480	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6301
##	481	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6301
##	482	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6301
##	483	-769.670	-13.0718	20.4528	-0.0105	-5.6977	9.6301
##	484	-769.670	-13.0718	20.4533	-0.0105	-5.6978	9.6301
##	485	-769.670	-13.0718	20.4535	-0.0105	-5.6978	9.6301
##	486	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6301
##	487	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6301
##	488	-769.670	-13.0705	20.4536	-0.0105	-5.6978	9.6301
##	489	-769.670	-13.0731	20.4536	-0.0105	-5.6978	9.6301
##	490	-769.670	-13.0718	20.4556	-0.0105	-5.6978	9.6301
##	491	-769.670	-13.0718	20.4515	-0.0105	-5.6978	9.6301
##	492	-769.670	-13.0718	20.4536	-0.0104	-5.6978	9.6301
##	493	-769.670	-13.0718	20.4536	-0.0106	-5.6978	9.6301
##	494	-769.670	-13.0718	20.4536	-0.0105	-5.6972	9.6301
##	495	-769.670	-13.0718	20.4536	-0.0105	-5.6983	9.6301
##	496	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6310
##	497	-769.670	-13.0718	20.4536	-0.0105	-5.6978	9.6291
##	498	-769.670	-13.0717	20.4566	-0.0105	-5.6979	9.6301
##	499	-769.670	-13.0704	20.4566	-0.0105	-5.6979	9.6301
##	500	-769.670	-13.0730	20.4566	-0.0105	-5.6979	9.6301
##	501	-769.670	-13.0717	20.4587	-0.0105	-5.6979	9.6301
##	502	-769.670	-13.0717	20.4546	-0.0105	-5.6979	9.6301
##	503	-769.670	-13.0717	20.4566	-0.0104	-5.6979	9.6301
##	504	-769.670	-13.0717	20.4566	-0.0106	-5.6979	9.6301
##	505	-769.670	-13.0717	20.4566	-0.0105	-5.6973	9.6301
##	506	-769.670	-13.0717	20.4566	-0.0105	-5.6984	9.6301
##	507	-769.670	-13.0717	20.4566	-0.0105	-5.6979	9.6311
##	508	-769.670	-13.0717	20.4566	-0.0105	-5.6979	9.6292
##	509	-769.670	-13.0716	20.4566	-0.0105	-5.6979	9.6301
##	510	-769.670	-13.0717	20.4587	-0.0105	-5.6979	9.6301
##	511	-769.670	-13.0717	20.4566	-0.0104	-5.6979	9.6301
##	512	-769.670	-13.0717	20.4566	-0.0105	-5.6978	9.6301
##	513	-769.670	-13.0717	20.4566	-0.0105	-5.6979	9.6311
##	514	-769.670	-13.0715	20.4566	-0.0105	-5.6979	9.6301
##	515	-769.670	-13.0716	20.4587	-0.0105	-5.6979	9.6301
##	516	-769.670	-13.0716	20.4566	-0.0104	-5.6979	9.6301
##	517	-769.670	-13.0716	20.4566	-0.0105	-5.6978	9.6301
##	518	-769.670	-13.0716	20.4566	-0.0105	-5.6979	9.6311
##	519	-769.670	-13.0717	20.4607	-0.0105	-5.6979	9.6301
##	520	-769.670	-13.0717	20.4587	-0.0104	-5.6979	9.6301
##	521	-769.670	-13.0717	20.4587	-0.0105	-5.6978	9.6301
##	522	-769.670	-13.0717	20.4587	-0.0105	-5.6979	9.6311
##	523	-769.670	-13.0717	20.4566	-0.0103	-5.6979	9.6301
##	524	-769.670	-13.0717	20.4566	-0.0104	-5.6978	9.6301
##	525	-769.670	-13.0717	20.4566	-0.0104	-5.6979	9.6311
##	526	-769.670	-13.0717	20.4566	-0.0105	-5.6977	9.6301

```

## 527      -769.670   -13.0717  20.4566  -0.0105  -5.6978   9.6311
## 528      -769.670   -13.0717  20.4566  -0.0105  -5.6979   9.6320

## Completed in 804.23 seconds at 17:15:38 22 May 2025

JSSAsecrf <- openCR::openCR.fit(
  caphist,
  type = 'JSSAsecrf',
  mask = habitat_mask,
  ncores = ncores,
  trace = trace
)

## Preparing design matrices
## Warning in autoini(ch1, msk1): 'autoini' failed to find g0; setting initial g0
## = 0.1
## Maximizing likelihood...
## Eval      Loglik    lambda0      phi        f    superD      sigma
## 1      -1491.500    -2.2504    0.8473   -1.2040   -8.7127    8.6194
## 2      -1491.500    -2.2504    0.8473   -1.2040   -8.7127    8.6194
## 3      -1491.500    -2.2504    0.8473   -1.2040   -8.7127    8.6194
## 4      -1491.500    -2.2504    0.8473   -1.2040   -8.7127    8.6194
## 5      -1491.500    -2.2504    0.8473   -1.2040   -8.7127    8.6194
## 6      -1491.500    -2.2504    0.8473   -1.2040   -8.7127    8.6194
## 7      -1491.499    -2.2504    0.8473   -1.2040   -8.7127    8.6194
## Warning in log(pdot): NaNs produced
## 8      40000000000.000   -120.9078  -4.7790   23.2421  -10.2765   89.2990
## Warning in log(pdot): NaNs produced

## 9      40000000000.000   -120.9077  -4.7790   23.2421  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 10     40000000000.000   -120.9078  -4.7790   23.2421  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 11     40000000000.000   -120.9078  -4.7790   23.2421  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 12     40000000000.000   -120.9078  -4.7790   23.2421  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 13     40000000000.000   -120.9078  -4.7790   23.2421  -10.2765   89.2991
## Warning in log(pdot): NaNs produced
## 14     40000000000.000   -120.9077  -4.7790   23.2421  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 15     40000000000.000   -120.9078  -4.7789   23.2421  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 16     40000000000.000   -120.9078  -4.7790   23.2444  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 17     40000000000.000   -120.9078  -4.7790   23.2421  -10.2764   89.2990
## Warning in log(pdot): NaNs produced
## 18     40000000000.000   -120.9078  -4.7790   23.2421  -10.2765   89.3079
## Warning in log(pdot): NaNs produced
## 19     40000000000.000   -120.9076  -4.7790   23.2421  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 20     40000000000.000   -120.9077  -4.7789   23.2421  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 21     40000000000.000   -120.9077  -4.7790   23.2444  -10.2765   89.2990
## Warning in log(pdot): NaNs produced
## 22     40000000000.000   -120.9077  -4.7790   23.2421  -10.2764   89.2990
## Warning in log(pdot): NaNs produced
## 23     40000000000.000   -120.9077  -4.7790   23.2421  -10.2765   89.3079
## Warning in log(pdot): NaNs produced
## 24     40000000000.000   -120.9078  -4.7788   23.2421  -10.2765   89.2990

```

```

## Warning in log(pdot): NaNs produced
## 25 40000000000.000 -120.9078 -4.7789 23.2444 -10.2765 89.2990
## Warning in log(pdot): NaNs produced
## 26 40000000000.000 -120.9078 -4.7789 23.2421 -10.2764 89.2990
## Warning in log(pdot): NaNs produced
## 27 40000000000.000 -120.9078 -4.7789 23.2421 -10.2765 89.3079
## Warning in log(pdot): NaNs produced
## 28 40000000000.000 -120.9078 -4.7790 23.2467 -10.2765 89.2990
## Warning in log(pdot): NaNs produced
## 29 40000000000.000 -120.9078 -4.7790 23.2444 -10.2764 89.2990
## Warning in log(pdot): NaNs produced

## 30 40000000000.000 -120.9078 -4.7790 23.2444 -10.2765 89.3079
## Warning in log(pdot): NaNs produced

## 31 40000000000.000 -120.9078 -4.7790 23.2421 -10.2763 89.2990
## Warning in log(pdot): NaNs produced

## 32 40000000000.000 -120.9078 -4.7790 23.2421 -10.2764 89.3079
## Warning in log(pdot): NaNs produced

## 33 40000000000.000 -120.9078 -4.7790 23.2421 -10.2765 89.3168
## Completed in 50.08 seconds at 17:16:36 22 May 2025

JSSAsecr1 <- openCR::openCR.fit(
  caphist,
  type = 'JSSAsecr1',
  mask = habitat_mask,
  ncores = ncores,
  trace = trace
)

## Preparing design matrices
## Warning in autoini(ch1, msk1): 'autoini' failed to find g0; setting initial g0
## = 0.1
## Maximizing likelihood...
## Eval      Loglik  lambda0      phi  lambda  superD      sigma
## 1      -1491.480   -2.2504   0.8473   0.0000  -8.7372   8.6194
## 2      -1491.480   -2.2504   0.8473   0.0000  -8.7372   8.6194
## 3      -1491.481   -2.2504   0.8473   0.0000  -8.7372   8.6194
## 4      -1491.480   -2.2504   0.8473   0.0000  -8.7372   8.6194
## 5      -1491.480   -2.2504   0.8473   0.0000  -8.7372   8.6194
## 6      -1491.480   -2.2504   0.8473   0.0000  -8.7372   8.6194
## 7      -1491.480   -2.2504   0.8473   0.0000  -8.7372   8.6194
## Warning in log(pdot): NaNs produced
## Warning in log(pdot): NaNs produced
## 8      NA      -120.8444 -21.8743  81.4409  -8.7628  89.9538
## 9      -1215.505  -14.1098  -1.4249   8.1441  -8.7398  16.7528
## 10     -1215.504  -14.1098  -1.4249   8.1441  -8.7398  16.7528
## 11     -1215.505  -14.1098  -1.4249   8.1441  -8.7398  16.7528
## 12     -1215.505  -14.1098  -1.4249   8.1441  -8.7398  16.7528
## 13     -1215.504  -14.1098  -1.4249   8.1441  -8.7398  16.7528
## 14     -1215.505  -14.1098  -1.4249   8.1441  -8.7398  16.7528
## 15     -1500.927  -10.8084  -1.3240   5.7799  -5.6200  16.6612
## 16     -1067.444  -13.0628  -1.3929   7.3943  -7.7504  16.7238
## 17     -1067.444  -13.0628  -1.3929   7.3943  -7.7504  16.7238
## 18     -1067.444  -13.0628  -1.3929   7.3943  -7.7504  16.7238
## 19     -1067.445  -13.0628  -1.3929   7.3944  -7.7504  16.7238
## 20     -1067.444  -13.0628  -1.3929   7.3943  -7.7504  16.7238
## 21     -1067.444  -13.0628  -1.3929   7.3943  -7.7504  16.7238

```

##	22	-75625.304	-8.1195	-1.1985	-0.6458	-1.7737	16.4722
##	23	-989.935	-12.5685	-1.3734	6.5903	-7.1527	16.6986
##	24	-989.935	-12.5685	-1.3734	6.5903	-7.1527	16.6986
##	25	-989.935	-12.5685	-1.3734	6.5903	-7.1527	16.6986
##	26	-989.935	-12.5685	-1.3734	6.5903	-7.1527	16.6986
##	27	-989.935	-12.5685	-1.3734	6.5903	-7.1527	16.6986
##	28	-989.935	-12.5685	-1.3734	6.5903	-7.1527	16.6986
##	29	-1263.782	-11.6081	-1.1910	-0.3923	-5.5635	16.3910
##	30	-896.406	-12.2925	-1.3210	4.5841	-6.6961	16.6102
##	31	-896.406	-12.2925	-1.3210	4.5841	-6.6961	16.6102
##	32	-896.406	-12.2925	-1.3210	4.5841	-6.6961	16.6102
##	33	-896.406	-12.2925	-1.3210	4.5841	-6.6961	16.6102
##	34	-896.406	-12.2925	-1.3210	4.5841	-6.6961	16.6102
##	35	-896.406	-12.2925	-1.3210	4.5841	-6.6961	16.6102
##	36	-1278.982	-11.6254	-0.8120	-11.9237	-5.7691	15.7248
##	37	-888.135	-12.0783	-1.1575	-0.7186	-6.3983	16.3258
##	38	-888.137	-12.0782	-1.1575	-0.7186	-6.3983	16.3258
##	39	-888.135	-12.0783	-1.1575	-0.7186	-6.3983	16.3258
##	40	-888.135	-12.0783	-1.1575	-0.7186	-6.3983	16.3258
##	41	-888.136	-12.0783	-1.1575	-0.7186	-6.3983	16.3258
##	42	-888.135	-12.0783	-1.1575	-0.7186	-6.3983	16.3258
##	43	-797.222	-12.3385	-1.8075	2.0181	-7.1453	16.4433
##	44	-797.221	-12.3385	-1.8075	2.0181	-7.1453	16.4433
##	45	-797.222	-12.3385	-1.8075	2.0181	-7.1453	16.4433
##	46	-797.222	-12.3385	-1.8075	2.0181	-7.1453	16.4433
##	47	-797.221	-12.3385	-1.8075	2.0181	-7.1453	16.4433
##	48	-797.222	-12.3385	-1.8075	2.0181	-7.1453	16.4433
##	49	-774.746	-12.3573	-2.1077	0.7964	-7.2652	16.3755
##	50	-774.746	-12.3573	-2.1077	0.7964	-7.2652	16.3755
##	51	-774.746	-12.3573	-2.1077	0.7964	-7.2652	16.3755
##	52	-774.746	-12.3573	-2.1077	0.7964	-7.2652	16.3755
##	53	-774.746	-12.3573	-2.1077	0.7964	-7.2652	16.3755
##	54	-774.746	-12.3573	-2.1077	0.7964	-7.2652	16.3755
##	55	-773.240	-12.4626	-2.0620	0.6764	-7.0628	16.3971
##	56	-773.240	-12.4626	-2.0620	0.6764	-7.0628	16.3971
##	57	-773.240	-12.4626	-2.0620	0.6764	-7.0628	16.3971
##	58	-773.240	-12.4626	-2.0620	0.6764	-7.0628	16.3971
##	59	-773.240	-12.4626	-2.0620	0.6764	-7.0628	16.3971
##	60	-773.240	-12.4626	-2.0620	0.6764	-7.0628	16.3971
##	61	-772.456	-12.6440	-1.8859	0.7445	-6.7610	16.4413
##	62	-772.456	-12.6440	-1.8859	0.7445	-6.7610	16.4413
##	63	-772.456	-12.6440	-1.8859	0.7445	-6.7610	16.4413
##	64	-772.456	-12.6440	-1.8859	0.7445	-6.7610	16.4413
##	65	-772.456	-12.6440	-1.8859	0.7445	-6.7609	16.4413
##	66	-772.456	-12.6440	-1.8859	0.7445	-6.7610	16.4414
##	67	-772.133	-12.7620	-1.7475	0.7481	-6.6555	16.4577
##	68	-772.133	-12.7620	-1.7475	0.7481	-6.6555	16.4577
##	69	-772.133	-12.7620	-1.7475	0.7481	-6.6555	16.4577
##	70	-772.133	-12.7620	-1.7475	0.7481	-6.6555	16.4577
##	71	-772.133	-12.7620	-1.7475	0.7481	-6.6555	16.4577
##	72	-772.133	-12.7620	-1.7475	0.7481	-6.6555	16.4577
##	73	-771.023	-13.3542	-0.9223	0.7577	-6.1802	16.5294
##	74	-771.023	-13.3542	-0.9223	0.7577	-6.1802	16.5294
##	75	-771.023	-13.3542	-0.9223	0.7577	-6.1802	16.5294
##	76	-771.023	-13.3542	-0.9223	0.7577	-6.1802	16.5294
##	77	-771.023	-13.3542	-0.9223	0.7577	-6.1802	16.5294
##	78	-771.023	-13.3542	-0.9223	0.7577	-6.1802	16.5295
##	79	-770.776	-13.5894	-0.4687	0.7524	-6.0000	16.5523
##	80	-770.776	-13.5893	-0.4687	0.7524	-6.0000	16.5523

##	81	-770.776	-13.5894	-0.4687	0.7524	-6.0000	16.5523
##	82	-770.776	-13.5894	-0.4687	0.7524	-6.0000	16.5523
##	83	-770.776	-13.5894	-0.4687	0.7524	-6.0000	16.5523
##	84	-770.776	-13.5894	-0.4687	0.7524	-6.0000	16.5523
##	85	-770.600	-13.7486	-0.0010	0.7527	-5.9044	16.5598
##	86	-770.600	-13.7486	-0.0010	0.7527	-5.9044	16.5598
##	87	-770.600	-13.7486	-0.0010	0.7527	-5.9044	16.5598
##	88	-770.600	-13.7486	-0.0010	0.7527	-5.9044	16.5598
##	89	-770.600	-13.7486	-0.0010	0.7527	-5.9044	16.5598
##	90	-770.600	-13.7486	-0.0010	0.7527	-5.9044	16.5598
##	91	-770.440	-13.8011	0.4409	0.7514	-5.9172	16.5479
##	92	-770.440	-13.8011	0.4409	0.7514	-5.9172	16.5479
##	93	-770.440	-13.8011	0.4409	0.7514	-5.9172	16.5479
##	94	-770.440	-13.8011	0.4409	0.7514	-5.9172	16.5479
##	95	-770.440	-13.8011	0.4409	0.7514	-5.9172	16.5479
##	96	-770.440	-13.8011	0.4409	0.7514	-5.9172	16.5479
##	97	-770.267	-13.7410	0.9498	0.7468	-6.0484	16.5118
##	98	-770.267	-13.7410	0.9498	0.7468	-6.0484	16.5118
##	99	-770.267	-13.7410	0.9498	0.7468	-6.0484	16.5118
##	100	-770.267	-13.7410	0.9498	0.7468	-6.0484	16.5118
##	101	-770.267	-13.7410	0.9498	0.7468	-6.0483	16.5118
##	102	-770.267	-13.7410	0.9498	0.7468	-6.0484	16.5118
##	103	-770.195	-13.6286	1.2683	0.7436	-6.1904	16.4767
##	104	-770.195	-13.6285	1.2683	0.7436	-6.1904	16.4767
##	105	-770.195	-13.6286	1.2683	0.7436	-6.1904	16.4767
##	106	-770.195	-13.6286	1.2683	0.7436	-6.1904	16.4767
##	107	-770.195	-13.6286	1.2683	0.7436	-6.1903	16.4767
##	108	-770.195	-13.6286	1.2683	0.7436	-6.1904	16.4767
##	109	-770.185	-13.5892	1.3650	0.7499	-6.2281	16.4666
##	110	-770.185	-13.5891	1.3650	0.7499	-6.2281	16.4666
##	111	-770.185	-13.5892	1.3650	0.7499	-6.2281	16.4666
##	112	-770.185	-13.5892	1.3650	0.7499	-6.2281	16.4666
##	113	-770.185	-13.5892	1.3650	0.7499	-6.2281	16.4666
##	114	-770.185	-13.5892	1.3650	0.7499	-6.2281	16.4666
##	115	-770.184	-13.5878	1.4069	0.7545	-6.2275	16.4654
##	116	-770.184	-13.5878	1.4069	0.7545	-6.2275	16.4654
##	117	-770.184	-13.5878	1.4069	0.7545	-6.2275	16.4654
##	118	-770.184	-13.5878	1.4069	0.7545	-6.2275	16.4654
##	119	-770.184	-13.5878	1.4069	0.7545	-6.2275	16.4654
##	120	-770.184	-13.5878	1.4069	0.7545	-6.2275	16.4654
##	121	-770.184	-13.5938	1.4424	0.7561	-6.2233	16.4652
##	122	-770.184	-13.5938	1.4424	0.7561	-6.2233	16.4652
##	123	-770.184	-13.5938	1.4424	0.7561	-6.2233	16.4652
##	124	-770.184	-13.5938	1.4424	0.7561	-6.2233	16.4652
##	125	-770.184	-13.5938	1.4424	0.7561	-6.2233	16.4652
##	126	-770.184	-13.5938	1.4424	0.7561	-6.2233	16.4652
##	127	-770.183	-13.6051	1.5062	0.7568	-6.2174	16.4646
##	128	-770.183	-13.6051	1.5062	0.7568	-6.2174	16.4646
##	129	-770.183	-13.6051	1.5062	0.7568	-6.2174	16.4646
##	130	-770.183	-13.6051	1.5062	0.7568	-6.2174	16.4646
##	131	-770.183	-13.6051	1.5062	0.7568	-6.2174	16.4646
##	132	-770.183	-13.6051	1.5062	0.7568	-6.2174	16.4646
##	133	-770.183	-13.6123	1.5527	0.7564	-6.2152	16.4638
##	134	-770.183	-13.6123	1.5527	0.7564	-6.2152	16.4638
##	135	-770.183	-13.6123	1.5527	0.7564	-6.2152	16.4638
##	136	-770.183	-13.6123	1.5527	0.7564	-6.2152	16.4638
##	137	-770.183	-13.6123	1.5527	0.7564	-6.2152	16.4638
##	138	-770.183	-13.6123	1.5527	0.7564	-6.2152	16.4639
##	139	-770.183	-13.6135	1.5634	0.7558	-6.2153	16.4635

```
## 140      -770.183      -13.6135      1.5634      0.7558      -6.2153      16.4635
## 141      -770.183      -13.6135      1.5634      0.7558      -6.2153      16.4635
## 142      -770.183      -13.6135      1.5634      0.7558      -6.2153      16.4635
## 143      -770.183      -13.6135      1.5634      0.7558      -6.2153      16.4635
## 144      -770.183      -13.6135      1.5634      0.7558      -6.2153      16.4635
## 145      -770.183      -13.6133      1.5638      0.7558      -6.2158      16.4635
## 146      -770.183      -13.6132      1.5638      0.7558      -6.2158      16.4635
## 147      -770.183      -13.6133      1.5638      0.7558      -6.2158      16.4635
## 148      -770.183      -13.6133      1.5638      0.7558      -6.2158      16.4635
## 149      -770.183      -13.6133      1.5638      0.7558      -6.2157      16.4635
## 150      -770.183      -13.6133      1.5638      0.7558      -6.2158      16.4635
## 151      -770.183      -13.6131      1.5626      0.7558      -6.2157      16.4635
## 152      -770.183      -13.6131      1.5626      0.7558      -6.2157      16.4635
## 153      -770.183      -13.6131      1.5626      0.7558      -6.2157      16.4635
## 154      -770.183      -13.6131      1.5626      0.7558      -6.2157      16.4635
## 155      -770.183      -13.6131      1.5626      0.7558      -6.2157      16.4635
## 156      -770.183      -13.6131      1.5626      0.7558      -6.2157      16.4635
## 157      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 158      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 159      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 160      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 161      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 162      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 163      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 164      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 165      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 166      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 167      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 168      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4635
## 169      -770.183      -13.6130      1.5623      0.7558      -6.2157      16.4635
## 170      -770.183      -13.6131      1.5625      0.7558      -6.2157      16.4635
## 171      -770.183      -13.6131      1.5623      0.7559      -6.2157      16.4635
## 172      -770.183      -13.6131      1.5623      0.7558      -6.2156      16.4635
## 173      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4651
## 174      -770.183      -13.6129      1.5623      0.7558      -6.2157      16.4635
## 175      -770.183      -13.6130      1.5625      0.7558      -6.2157      16.4635
## 176      -770.183      -13.6130      1.5623      0.7559      -6.2157      16.4635
## 177      -770.183      -13.6130      1.5623      0.7558      -6.2156      16.4635
## 178      -770.183      -13.6130      1.5623      0.7558      -6.2157      16.4651
## 179      -770.183      -13.6131      1.5626      0.7558      -6.2157      16.4635
## 180      -770.183      -13.6131      1.5625      0.7559      -6.2157      16.4635
## 181      -770.183      -13.6131      1.5625      0.7558      -6.2156      16.4635
## 182      -770.183      -13.6131      1.5625      0.7558      -6.2157      16.4651
## 183      -770.183      -13.6131      1.5623      0.7560      -6.2157      16.4635
## 184      -770.183      -13.6131      1.5623      0.7559      -6.2156      16.4635
## 185      -770.183      -13.6131      1.5623      0.7559      -6.2157      16.4651
## 186      -770.183      -13.6131      1.5623      0.7558      -6.2155      16.4635
## 187      -770.183      -13.6131      1.5623      0.7558      -6.2156      16.4651
## 188      -770.183      -13.6131      1.5623      0.7558      -6.2157      16.4668
```

```
## Warning in openCR::openCR.fit(caphist, type = "JSSAsecr1", mask = habitat_mask,
##: variance calculation failed for some beta parameters; confounding likely
```

```
## Completed in 258.85 seconds at 17:21:01 22 May 2025
```

```
# === Estimate density ===
density_estimates_JSSAsecrb <- predict(JSSAsecrb, type = 'D')
density_estimates_JSSAsecrf <- predict(JSSAsecrf, type = 'D')
density_estimates_JSSAsecr1 <- predict(JSSAsecr1, type = 'D')
(superD_JSSAsecrb <- density_estimates_JSSAsecrb$superD * study_area_ha)
```

```

##      estimate SE.estimate      lcl      ucl
## 1 1476.389      1002.67 390.0485 5588.345

(superD_JSSAsecrf <- density_estimates_JSSAsecrf$superD * study_area_ha)

##      estimate SE.estimate      lcl      ucl
## 1 15.16129          0 15.16129 15.16129

(superD_JSSAsecr1 <- density_estimates_JSSAsecr1$superD * study_area_ha)

##      estimate SE.estimate      lcl      ucl
## 1      879.6      514.9326 279.2399 2770.722

aic <- AIC(JSSAsecrb, JSSAsecrf, JSSAsecr1)

# === General details ===
setup <- list(utm_resolution = utm_resolution,
              buffer = buffer)
opencr_results <-
  list(
    JSSAsecrb = JSSAsecrb,
    JSSAsecrf = JSSAsecrf,
    JSSAsecr1 = JSSAsecr1,
    density_estimates_JSSAsecrb = density_estimates_JSSAsecrb,
    density_estimates_JSSAsecrf = density_estimates_JSSAsecrf,
    density_estimates_JSSAsecr1 = density_estimates_JSSAsecr1,
    superD_JSSAsecrb = superD_JSSAsecrb,
    superD_JSSAsecrf = superD_JSSAsecrf,
    superD_JSSAsecr1 = superD_JSSAsecr1,
    aic = aic
  )

readr::write_rds(x = opencr_results, file = file.path(write_path, "opencr_results.
rds"), compress = "xz")

```