Impact of global warming on the European whale pump

A literature review on the influence of global warming on the great whale pump in European aquatic ecosystems.

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A literature review on the influence of global warming on the whale pump of great whales in European aquatic ecosystems.

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Preface

This report reviews the importance of whales in the earth's marine ecosystems as broadly as possible. Whales have a bigger impact on the world than is widely known, so the main goal of this report is to inspire others to preserve whale species in Europe. One of the target groups of this research are European biologists that have yet to find out how important whales are in this world. In addition, all interested parties are welcome to study this report. This report is especially interesting for Stichting Rugvin, which has been active in the world of preserving cetaceans in the Netherlands for about twenty years. Since its establishment, more research was conducted and the protection of cetaceans in the Dutch waters started in 2004.

I would like to thank Nynke Osinga and Frank Zanderink from Stichting Rugvin for inspiring and supporting me in writing this report, supplying me with information and putting me into the network of amazing people with an abundance of knowledge. I would like to thank Danny Merién for providing feedback, motivation and inspiration during the writing process. Lastly I thank my friend Djeli Lindhout for supporting and motivating me with writing this report.

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Abstract

This thesis is a literature review on the impact of global warming on the great whale pump in Europe. Global warming is known to have an effect on different ecosystems around the world. However, what is largely unknown is the impact of global warming on marine systems and specifically large whales that have a major role within these systems. This report attempts to gather information and create understanding where information is missing through a literature study. In addition, the report seeks to encourage others to identify the impacts of global warming on large whales and marine ecosystems. Great whales transfer nutrients like iron and carbon by feeding at depths and defaecating and urinating at low-latitude areas. It is known that this great whale pump positively affects nutrient dispersal in different pelagic layers. It thus provides an important ecosystem service by sustaining productivity to core feeder species like phytoplankton, which are at the bottom of the food chain. It is yet unknown how global warming affects this process. The results of this study showed that global warming leads to an increase in sea surface temperature (SST), with negative effects on sea ice, habitat availability and distribution, food availability and the overall health of great whales. Even though information on whales and the influence of global warming is lacking, it is known that specific processes such as ocean nutrification, ocean acidification and the whale pump will be influenced by global warming. It is expected that whales with larger distribution ranges will be less impacted than those with smaller ones. Habitat range shifts are likely to occur in all great whale species. Distinguishing the effects of current threats on cetaceans is hard, since there is a multitude of threats acting at the same time. Anthropogenic threats undoubtedly pressure their survival, which leads to more stress. This report concludes that global warming will cause changes in marine ecosystems, which could impact great whales in Europe. Information on great whales and the influence of global warming on marine processes is scarce. It is necessary to conduct more research towards great whales and their ability to adapt to habitat changes, to estimate the actual impact of global warming affects great whales.

Deze scriptie is een literatuurstudie over het effect van de opwarming van de aarde op de walvispomp van grote walvissen in Europa. Het is bekend dat de opwarming van de aarde een effect heeft op verschillende ecosystemen over de hele wereld. Wat echter grotendeels onbekend is, is het effect op mariene systemen en specifiek op grote walvissen die binnen deze systemen een belangrijke rol spelen. Dit verslag tracht informatie te verzamelen en inzicht te verschaffen in ontbrekende informatie door een literatuurstudie. Bovendien wil het verslag anderen aanmoedigen om de gevolgen van de opwarming van de aarde voor grote walvissen en mariene ecosystemen te achterhalen. Grote walvissen brengen voedingsstoffen zoals ijzer en koolstof over door zich op diepte te voeden en op lage hoogte te poepen en te urineren. Het is bekend dat deze grote walvispomp de verspreiding van voedingsstoffen in verschillende pelagische lagen positief beïnvloedt. Het levert dus een belangrijke ecosysteemdienst door de productiviteit te ondersteunen van belangrijke voedersoorten zoals fytoplankton, die onderaan de voedselketen staan. Het is onbekend hoe de opwarming van de aarde dit proces beïnvloedt. De resultaten van deze studie geven dat dit leidt tot een stijging van de zeeoppervlaktetemperatuur (SST), met negatieve gevolgen voor zee-ijs, beschikbaarheid en verspreiding van habitats, voedselbeschikbaarheid en algemene gezondheid van grote walvissen. Hoewel informatie over walvissen en de invloed van de opwarming van de aarde ontbreekt, is bekend dat specifieke processen zoals de voeding van de oceaan, de verzuring van de oceaan en de walvispomp door de opwarming van de aarde zullen worden beïnvloed. Verwacht wordt dat walvissen met een groter verspreidingsgebied minder gevolgen zullen ondervinden dan walvissen met een kleiner verspreidingsgebied. Bij alle grote walvissoorten zullen zich waarschijnlijk verschuivingen in het verspreidingsgebied voordoen. Het is moeilijk om de effecten van de huidige bedreigingen op walvisachtigen te onderscheiden, aangezien er vele bedreigingen tegelijk optreden. Antropogene bedreigingen zetten de overleving onder druk, wat tot meer stress leidt. In dit verslag wordt geconcludeerd dat de opwarming van de aarde veranderingen in de mariene ecosystemen veroorzaakt, die gevolgen kunnen hebben voor de grote walvissen in Europa. Informatie over grote walvissen en de invloed van de opwarming van de aarde op mariene processen is schaars. Er moet meer onderzoek worden verricht naar grote walvissen en hun vermogen om zich aan te passen aan habitatveranderingen, om de werkelijke impact van de opwarming van de aarde op grote walvissen in te kunnen schatten.

Keywords:
Whale Pump; Sea Surface Temperature; SST; Global Warming; Great Whales

Contents

List of abbreviations

EEA	European Environment Agency
IUCN	International Union for Conservation of Nature
MPA	Marine Protected Area
MLD	Mixed-Layer Depth
SST	Sea Surface Temperature

1 Introduction

The ocean plays an important role in the earth's ecosystems that maintain a liveable habitat for all species on the planet (Winton, Takahashi, & Held, 2009; Johnson *et al.*, 2022). Several ecosystem models have recently shown shifts in temperature, circulations, oxygen content, stratification, ocean acidification and nutrient input. These are proven to be associated with climate change, global warming and the modifying of marine ecosystem structures (Winton, Takahashi, & Held, 2009; Doney *et al.*, 2012; Jochum *et al.,* 2012; Barlow, Kahru, & Mitchell, 2008; Lindsey, Scott, & Simmon, 2010; Levin, & Le Bris, 2015). These changes possibly have a negative impact on biodiversity and key ocean cervices that influence a healthy planet (Levin, & Le Bris, 2015). Abiotic and biotic ocean conditions are currently changing due to climatic alterations (Ratnarajah, & Hodgson-Johnston, 2014). Changes in climate have effects on ocean surface processes, such as the observed warming trends of upper ocean temperatures that occurred the past four decades (Smith, et. al., 2009). In response to this, changes in dynamics within populations of marine species occur. For example, many marine predators rely on fish communities and the majority of marine organisms (e.g. fish) rely on phytoplankton as one of their main food sources (Ratnarajah, & Hodgson-Johnston, 2014). Thus, it can be concluded that alterations of these climate changes not only directly affect the ocean and its cycles, but its inhabitants as well (Gallagher *et al.*, 2021).

Cetaceans are the ocean's largest inhabitants. This group of marine top-predators consist of several whale, dolphin and porpoise families. Most European cetaceans are listed Vulnerable or Endangered by the International Union for Conservation of Nature (IUCN) (Johnson *et al.*, 2022). Certain cetaceans are especially vulnerable to climate related changes. This is due to the fact that some whale families and their food have limited habitat ranges that rely on abiotic (e.g. sea ice cover, salinity, acidity, ocean circulation, climate patterns) and biotic (e.g. food availability) conditions (Simmonds, & Eliot, 2009).

An example of important cetaceans are great whales. Great whales are a combination of one suborder and one subspecies of whales; baleen whales (*Mysticeti*) and the sperm whale (*Physeter macrocephalus*). Their ecological role used to be undervalued, yet it is now more commonly known that great whales transfer nutrients by feeding at depths and defaecating at low-latitude areas (Roman, & McCarthy, 2010). This is a great distinction from other marine organisms like fish, since they mostly feed and release nutrients at the same aquatic layer as they live in (Roman, & McCarthy, 2010). After death, whale carcasses sink to the ocean floor, where large amounts of carbon are released into the deep sea and stored on the ocean floor, which provides food and habitat for endemic invertebrates (Roman *et al*., 2014). Because of this, great whales are of great importance to the ocean's biodiversity. They provide an important ecosystem service by sustaining productivity in regions where they occur in high densities, by distributing nutrients through their defaecation process (Marangi *et al.,* 2021; Johnson *et al.*, 2022; Savoca *et al.*, 2021). The process of spreading nutrients like sulphur, iron, carbon and nitrogen in the euphotic zone of the ocean is often referred to as the whale pump (Roman, & McCarthy, 2010; Johnson *et al.*, 2022). The whale pump works for all whale species. Whales feed at lower parts of the ocean and then migrate upwards into the euphotic zone to defaecate (Johnson *et al.*, 2022). The plumes of whale defaecation near the surface of the ocean spreads several concentrated nutrients locally (Roman *et al.,* 2014). The most important nutrients whales disperse through the whale pump are nitrogen and iron (Johnson *et al.*, 2022). Additionally, they also spread carbon, sulphur and small amounts of heavy metals (Marangi, Airoldi, Beneduce, & Zaccone, 2021). In the euphotic zone of the Gulf of Maine, whales and seals may be restoring 2.4×10^4 metric tons of nitrogen per year, which is more than what all rivers combined are able to replenish (Roman, & McCarthy, 2010). The faeces of four species of the baleen whale family (Blue, Pygmy blue, Humpback and Fin whale) is proven to contain a high liquid iron content that acts as a fertilizer for surface waters (Nicol *et al.,* 2010; Ratnarajah, & Hodgson-Johnston, 2014). Besides that, iron is an important nutrient for marine life, since it serves as an electron carrier and a catalyst in the process of photosynthesis in phytoplankton (Ratnarajah, & Hodgson-Johnston, 2014). Great whales are of significant importance to the whale pump in Europe (N. Osinga, personal communication, 2022; Bannister, 2008). Their body size is the largest, they have a great historical abundance, high metabolic demands, large migration ranges, deep diving behaviour and their global distribution is well known in Europe (Roman *et al*., 2014). Apart from that, nutrient enrichments from the whale pump are important in the process of increasing species richness and overall density of organisms (Jochum *et al.,* 2012). Therefore, it can be concluded that whale faeces create a more productive ecosystem (Ratnarajah, & Hodgson-Johnston, 2014).

One group of species that benefit from the whale nutrient pump is phytoplankton, which is a collection of thousands of photosynthetic algae species (Winder, & Sommer, 2012). It is one of the main food sources for all marine life and thus a key factor in marine ecosystems (Ratnarajah, & Hodgson-Johnston, 2014; Winder, & Sommer, 2012). Phytoplankton also has the ability to absorb great amounts of carbon dioxide through photosynthesis, which is then transformed into oxygen as one of the by-products. This process makes them the primary producers of oxygen on the planet (Lindsey, Scott, & Simmon, 2010; Hallegraeff, 2010; Ratnarajah, & Hodgson-Johnston, 2014). Lindsey, Scott, & Simmon (2010) discovered that phytoplankton can consume carbon dioxide through photosynthesis equivalently as much as forests; this means about ten gigatonnes of carbon being transferred from the atmosphere into the earth's waters every year. Any change in these numbers could significantly influence the phytoplankton's productivity, which then influences biodiversity, food supply and the pace of global warming (Lindsey, Scott, & Simmon, 2010). The growth of these microscopic organisms depends on the availability of sunlight, carbon dioxide and nutrients (Lindsey, Scott, & Simmon, 2010), with whales being one of the main sources of these nutrients (Barlow, Kahru, & Mitchell, 2008). Phytoplankton are responsible for almost half of the global net primary production and are proven to be the primary energy source for aquatic ecosystems (Winder, & Sommer, 2012; Field *et. al.,* 1998). These organisms have been negatively affected by the changes in upper ocean temperatures due to stratification (Smith *et al*., 2009), which is the separation of water layers based on water density due to temperature and salinity differences (Li *et al.,* 2020). Stratification affects the availability of nutrients for the reproduction cycle of these organisms (Smith *et al.*, 2009). On top of this, these photosynthetic cells' dynamics have proven to influence annual variations in temperature, mixing of the water column, consumption and resource availability (Winder, & Sommer, 2012). Buesseler *et al.* (2020) recently discovered that the oceanic biological pump, which phytoplankton plays a major role in, captures twice as much carbon as previously thought. Since the growth and survival of phytoplankton partially depends on whale faeces, it can be concluded that whales are of great importance and indirectly influence the core of the whole aquatic ecosystem and its marine processes (Ratnarajah, & Hodgson-Johnston, 2014).

Apart from this, whales migrate globally across ocean basins to breed and feed (Johnson *et al*., 2022). Each species has their own migration route, which relies on their food, habitat, wintering and breeding preference (Johnson *et al.*, 2022). In addition to this, Johnson *et al.* (2022) found that these networks are large and span across different ocean basins. Climate change could impact the dynamics of these habitats and thus could cause shifts in their species range (Maxwell, Gjerde, Conners, & Crowder, 2020). This could possibly affect the whale pump. Both climate change and global warming have a threatening influence on the environment of marine mammals (Avila, Kaschner, & Dormann, 2018). It is yet unknown to what extent global warming will influence the whale pump on great whales (N. Osinga, personal communication, 2022). Therefore, the main question that will be answered in this report is: *What are the consequences of global warming on the whale pump of baleen whales* (*Mysticeti sp.*) *and the sperm whale* (*Physeter macrocephalus*) *in Europe?*

To answer this question, several subjects need to be researched which are related to great whale species, the whale pump, European waters, defaecation, nutrient contents, marine processes that are influenced by the whale pump, great whale migratory patterns, global warming and climate change in Europe. In response to this, four sub-questions are created to answer the main question of this thesis report:

I. What is the geographical distribution of great whales in Europe?
II. What are the effects of the whale pump on European waters?
III. What aspects of the whale pump are influenced by European marine ecosystems?
IV. How does global warming affect great whales in Europe?

These questions will be answered through a qualitative literary study. After answering these questions, a conclusion will be drawn based on the findings and thus the main research question can then be answered. It is widely known that whales play a big role in marine processes (Ratnarajah, & Hodgson-Johnston, 2014). Therefore, it is important to know the effect of global warming on whales for policy makers in the field of climate and conservation, as well as institutes that help protect whales like Stichting Rugvin which take measures to protect European waters. The focus of this research will be on great whales; the sperm whale and all baleen whales occurring in European waters, which consists of nine species in total (OceanCare, 2021). The main goal of this report is to gather all information regarding great whales and the effects of global warming on the European whale pump. It is expected that global warming will have changing effects on the ocean's temperature and processes, which in turn will have a negative effect on the species' habitat distribution and food availability of great whales.

2 Methodology

To answer the research question of this report, a qualitative literature review was performed. Information was also gathered through meetups with Nynke Osinga and Frank Zanderink, who are both biologists working for and founders of Stichting Rugvin. The information gathered from both was checked and backed up by literature.

2.1 Study species

This report includes the great whales of Europe, which consists of the following two families; baleen whales (*Mysticeti)* and the sperm whale *(Physeter macrocephalus)*. These families consist of 9 species that evidentially occur in European waters as described by OceanCare (2021). They are used in this report since they are considered large whales in Europe, which have most effect on the whale pump (N. Osinga, personal communication, 2022). The eight baleen whale species used in this research are: Bowhead whale *(Balaena mysticetus),* North Atlantic right whale *(Eubalaena glacialis),* Common minke whale *(Balaenoptera acutorostrata),* Sei whale *(Balaenoptera borealis),* Bryde's whale *(Balaenoptera edeni)*, Blue whale *(Balaenoptera musculus),* Fin whale *(Balaenoptera physalus)* and Humpback whale *(Megaptera novaengliae).* Apart from this, the Sperm whale (*Physeter macrocephalus)* is also included in this report since it is an important large whale species with great influence in Europe.

2.2 Literature research

The main search engines that were used to find reliable scientific literature are Google Scholar and Science Direct. Green-I and the Wageningen University library were used as well, yet less frequently. Apart from that, documents from the database of Stichting Rugvin were available to gather information about several whale related topics. Preferably, the resources should not be older than 20 years. However, if necessary and no new resources could be found, a resource older than 20 years could also be used to support the information. Resources over 30 years old were not considered up-to-date. To find new resources, Google was used to broaden the search spectrum and gather information from instances like Greenpeace, International Union for Conservation of Nature (IUCN) and organisations alike. To answer the sub-questions, literature research has been conducted to find the answers. Per question, certain keywords were used to find corresponding information. These are described below in table 1. Every time 'faeces/poo' is written it indicates that both options have been explored.

Table 1: Search terms used

TOPIC	SEARCH TERMS
GEOGRAPHICAL DISTRIBUTION OF GREAT WHALES IN EUROPE	Baleen whales, sperm whale, baleen whale species, whales Europe, geographical distribution whales, distribution sperm whale, distribution baleen whales, distribution whales Europe, cetaceans Europe, migratory patterns whales, migratory route whales,

	migration whales, migration baleen whale, migration sperm whale, migration cetaceans Europe.
EFFECTS OF WHALE PUMP ON EUROPEAN WATERS	Whale faeces/poo, whales marine ecosystem, whale faeces/poo marine ecosystem, whale pump, importance of whales, marine ecosystem Europe, whale poo, whale nutrient distribution, whale faeces/poo climate change, whale faeces/poo climate, distribution whale faeces/poo Europe, influence whale faeces/poo climate, marine process climate change, marine climate change, marine global warming, marine influence global warming, whale faeces/poo global warming, whale poo/faeces temperature rise, whale poo/faeces phytoplankton, whale faeces/poo carbon dioxide, whale faeces/poo CO2, phytoplankton food, whale pump phytoplankton, phytoplankton global warming, phytoplankton climate change.
HOW THE WHALE PUMP IS INFLUENCED BY WATER	Whale pump Europe, great whale defaecation, whale pump marine ecosystems, whale pump, highlights whale pump, European water cycle, European ocean cycle.
HOW GLOBAL WARMING AFFECTS WHALES	Climate change Europe, climate change water, climate change oceans, effect climate Europe, global warming Europe, global warming water, ocean temperature, rise temperature Europe, effects temperature water Europe, global warming cetaceans, global warming marine life, global warming Europe, global warming whales.

After researching these topics, the abstract of every found report was skimmed through. When the information seemed to fit this research, the original report was saved in a different document and in Zotero. Afterwards it was critically further inspected by reading the summary, introduction and results. A short summary of all the required information for this report with some keywords were then written down to easily access this data later. The data validity was checked by looking for several different resources stating similar information. To ensure even more validity, an analysis on the information was executed through a comparative study with the information retrieved from experts of Stichting Rugvin. These experts have great knowledge of whales in Europe, the whale pump and the importance of whales in the oceans. Meetups with these people were scheduled to check in on the progress, the information and to add resources to this report on the whale related topics they excel in, like listed above.

3 Results

The currently available data regarding the following topics are described; geographical distributions of great whales in Europe, the effects of the whale pump regarding great whales in Europe, the effect of global warming on European waters and the effect of the whale pump on marine ecosystems in Europe.

3.1 Geographical distribution of great whales in Europe

To recognise in which seas great whales occur, it is important to have an overview of all European seas. Europe consists of four great waters; The North-east Atlantic Ocean, the Mediterranean Sea, the Black Sea and the Baltic Sea (Fig 1). The North-east Atlantic Ocean is divided into different regions; The Barents Sea, the Norwegian Sea, the Iceland Sea, the Celtic Seas, the Bay of Biscay and the Iberian Coast, the Greater North Sea (including Kattegat and the English Channel) and the Macaronesia. The Mediterranean Sea consists of the Western Mediterranean Sea, the Ionian Sea and the Central Mediterranean Sea, the Adriatic Sea, and the Aegan-Levantine Sea. Both the Black Sea and the Baltic Sea are not divided in sub-areas (European Environment Agency (EEA), 2021).

Figure 1: Map of the European regional seas with their different regions (EEA, 2021).

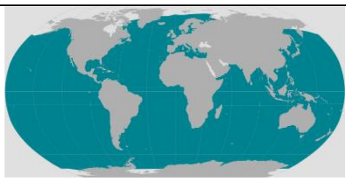
Throughout all four seas, whales are found abundantly (Johnson et al., 2022). The Mediterranean Sea is rich in great whale species. The sperm, Bryde's and fin whale are present. The common minke and humpback whales are occasionally spotted. The sei was sighted with minimal exceptions (OceanCare, 2021). The Hellenic Trench, found in the Mediterranean Sea, serves as a biodiversity hotspot for whales and other marine species. It is a core migrating, feeding and breeding habitat for several species. Sperm whales can be found in larger numbers in this area.

Around 2500 individuals live in the Mediterranean Sea and between 200 to 250 sperm whales currently live in the eastern region (OceanCare, 2021). In the North-east Atlantic Ocean, the humpback, sei, fin and blue whale are found in waters from the southeast U.S. to Greenland. These baleen whales are especially widely distributed during winter throughout all regions. However, due to its declining population, these whales are currently mostly present in the eastern coastal areas of America (NOAA Fisheries, 2022)[7]. Even though some whale species do reside in the Black Sea, no great whale species are present (Fontaine *et al.,* 2012; OceanCare, 2020). This is due to the fact that the Black Sea transitioned from a freshwater ecosystem to a marine ecosystem and is not accessible for great whales (Fontaine *et al.,* 2012). The Black Sea is also a land-locked, deep and isolated ecosystem, which makes it impossible for new whale species to establish here naturally in the future (Llope *et al.,* 2011). The Baltic Sea has no native great whales permanently inhibiting its water. Occasionally the minke whale, fin whale and humpback whale appear in the southern part of the sea (Teilmann, Galatius, & Sveegaard, 2017).

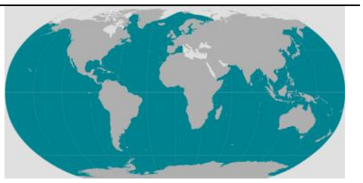
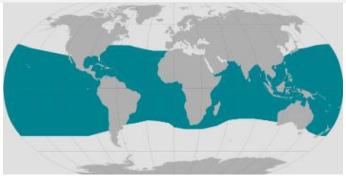
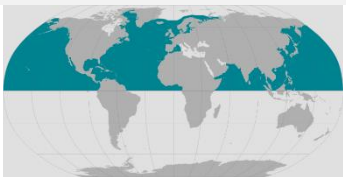
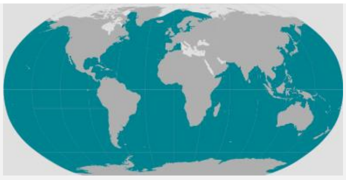
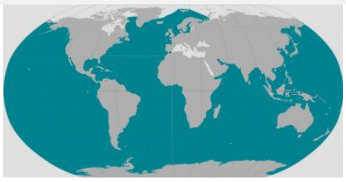
Apart from being native in certain areas, whales tend to migrate horizontally across several water bodies. All whales travel between breeding and feeding areas across ocean basins on national and international scale. Some of these migrations are year-round, others occur seasonally (Johnson *et al.*, 2022). Fin, sperm, blue and humpback whales travel globally (Johnson *et al.*, 2022). Blue whales, like most great whale species, forage at high productivity feeding areas and then migrate to lower productivity areas to breed and defaecate (Roman *et al.,* 2014). Humpback whales migrate similarly between tropical and polar latitudes throughout different seasons (Pomilla, & Rosenbaum, 2005). Baleen whales transport nutrients latitudinally from food rich summer feeding grounds of polar oceans to food scarce, yet safer tropical waters. They fast through birth and lactation in the tropics and thus burn their summer fat stores, leaving waste products in warm coastal waters (Ecotone, 2014).

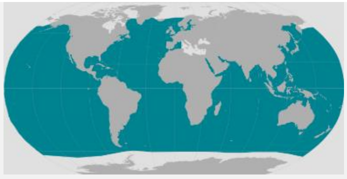
All great whales migrate seasonally between feeding areas and breeding areas (NOAA Fisheries, 2022)[1-4,6-10]. A more detailed overview of all great whale species and their correlating habitat ranges throughout the European waters can be found in Table 2. A more detailed overview of global spatial distribution ranges of most great whale species can be found in Appendix I.

Table 2. Great whale species and their correlating habitat range in Europe (OceanCare, 2021; NOAA Fisheries[1-4,6-10], 2022)

COMMON NAME	SCIENTIFIC NAME	HABITAT RANGE EUROPE	EUROPEAN DISTRIBUTION
SPERM WHALES *(PHYSETERIDAE)*			
SPERM WHALE	*Physeter macrocephalus*	Occurs throughout all European seas except the Black and Baltic Seas.	 (*NOAA Fisheries, 2022)*[1]

BALEEN WHALES *(MYSTICETI)*

BLUE WHALE	*Balaenoptera musculus*	Occurs from the Arctic waters of northern Siberia and Norway to the Canary Islands. Not found in the Mediterranean, Baltic and Black Seas.	 (*NOAA Fisheries, 2022)* [2]
BOWHEAD WHALE	*Balaena mysticetus*	Occurs in coasts of Norway, Russia, Svalbard, Barents Sea, east Greenland, Norway and Iceland. Lives almost exclusively in Seas covered with ice seasonally.	 (*NOAA Fisheries, 2022)* [3]
BRYDE'S WHALE	*Balaenoptera edeni*	Occurs around Madeira and the Canary Islands. Usually live around the equator in all oceans from 40 degrees north to 40 degrees south.	 (*NOAA Fisheries, 2022)* [4]
COMMON MINKE WHALE	*Balaenoptera acutorostrata*	Occurs through all European Seas except the Black and Baltic Seas. Occasionally spotted in the Mediterranean.	 (*NOAA Fisheries, 2022)* [6]
FIN WHALE	*Balaenoptera physalus*	Occurs from Arctic waters around the Svalbard Islands to the Canary Islands. This includes the Mediterranean and North Sea. Not found in the Black Sea.	 (*NOAA Fisheries, 2022)* [7]
HUMPBACK WHALE	*Megaptera novaengliae*	Occurs throughout the European seas from Siberia to the Canary Islands. Not found in the Baltic and Black Seas. Occasionally ranges in Mediterranean.	 (*NOAA Fisheries, 2022)* [8]
NORTH ATLANTIC RIGHT WHALE	*Eubalaena glacialis*	Occurs in waters from sast Greenland to northwest Africa, north Norway and Iceland. Due to current ongoing threats, this species is considered heavily threatened and has a small distribution area.	 (*NOAA Fisheries, 2022)* [9]

SEI WHALE	*Balaenoptera borealis*	Occurs through the northeast Atlantic waters from North Norway to Canary Islands, including the North Sea. Not found in the Baltic, Mediterranean (apart from minimal exceptions) and Black Seas.	 (*NOAA Fisheries, 2022)* [10]

3.2 Effects of the great whale pump on European waters

Whales inhibit different oceanic layers. Adult great whale species feed on food resources available in the deeper layers of the European ocean (Ecotone, 2014). The whale pump starts below the base of the euphotic zone. In order to breathe, whales must rise from below the base of the euphotic zone to the upper parts of the ocean to reach the surface. They defaecate and urinate in the higher water column of the ocean and release faecal plumes rich in nutrients. These nutrients disperse, enriching the upper water column (Kanwisher, & Ridgway, 1983; Roman, & McCarthy, 2010). After this process, whale species return to deeper layers to restart the whale pump.

One of the nutrients whales disperse is NH_4^+, for which cetaceans are responsible for delivering 77% of this nutrient in the Gulf of Maine (Roman *et al.,* 2014). Whales thus play an important role in nitrogen (N) recycling in surface waters. Baleen whales excrete up to 15 kg per day more N compared to other whale species. Apart from fertilizing NH_4^+ and carbon (C), great whales also recycle iron (Fe) and other limiting nutrients (e.g. sulphate) (Roman, & McCarthy, 2010). Each great whale sequesters 33 tons of CO_2 after death. Iron is a scarce and essential nutrient in marine ecosystems that is mainly derived from whale defaecation (Ecotone, 2014).

The release of nutrients enhances primary production by phytoplankton, which enhances the CO_2 absorption by a process of dissolving these greenhouse gases (Roman *et al.,* 2014). Microbes and phytoplankton living near the surface level are capable of utilizing the secreted NH_4^+. A study of marine phytoplankton growth showed positive photosynthetic results when whale faeces of pygmy blue whale was added to two different phytoplankton species, which supports the importance of whales in marine nutrient cycles (Smith *et al.,* 2013).

Major decreases in great whale population sizes have effects on the marine ecosystem. An example of this has been reported for the Black Sea. Between 1960 and 1990, the recession of apex marine predators resulted in a decrease of flexibility of the ecosystem in Black Sea. This instability resulted in a trigger of great eutrophication (bottom-up effect) and the collapse of fishery stocks as a trophic cascade (top-down effect). Models show the deletion of apex predators in marine ecosystems leads to reorganisation of the food web, yet it does not prevent a trophic cascade from happening (Llope *et al.,* 2011). Great whales are important apex predators in marine ecosystems.

3.3 Aspects of the great whale pump that are influenced by European marine ecosystems

The whale pump is influenced by marine ecosystems. Three aspects that are mostly affected in European waters are food availability and sea surface temperature. Each of these aspects is discussed separately below.

3.3.1 Food availability

The whale pump occurs through feeding, urinating and defaecating of great whales. Throughout Europe, these processes are important aspects of the whale pump that are influenced by marine ecosystems. In general, adult great whale species forage on krill, squid, crustaceans, several fish species and zooplankton throughout the deeper layers of the European ocean (Ecotone, 2014; Fleming, Clark, Calambokidis, & Barlow, 2015; Borrell, Abad-Oliva, Gómez-Campos, & Aguilar, 2012; Roman, & McCarthy, 2012; Busquets-Vass et al., 2017; Windsland, Lindstrom, Nilssen & Haug, 2007). Some great whales solely forage on one of the above; fin whales in northwest Spain dominate krill (Borrell, Abad-Oliva, Gómez-Campos, & Aguilar, 2012), along with blue whales in the northeast Pacific (Fleming, Clark, Calambokidis, & Barlow, 2015) and the common minke whale in Norway (Windsland, Lindstrom, Nilssen & Haug, 2007). This foraging process occurs in deeper parts of the ocean. Randing from 100 meters below the surface for most whale species to approximately 200 meters for blue whales (Ecotone, 2014; Roman et al., 2014). Stomach samples showed that an average of 69% of all whale species eat one prey item only and 23% eat two different species of prey. This report also states that these whales forage on prey which is most abundant in their area (Windsland, Lindstrom, Nilssen & Haug, 2007). The feeding process of whales is a circular process. The prey animals that whales consume (e.g. fish and squid), feed on phytoplankton. In return, the growth of phytoplankton depends on the whales' nutrient enrichment in upper oceanic regions as discussed in paragraph 3.2 (Ecotone, 2014).

A significant shift in spatial use has been detected before and after 2010; this research shows that these great whales were more frequently found in higher latitudes after 2010 (NOAA Fisheries, 2020). NOAA Fisheries (2020) also shows that blue whales migrated further towards the southern part of this ocean than expected. The sperm, bowhead, Bryde's, common minke, and North Atlantic right whale are also found in this area (OceanCare, 2021). The North Atlantic right whale increased its time spent in the Mid-Atlantic region since 2010 (NOAA Fisheries, 2017).

3.3.2 Sea surface temperature

Tittensor *et al.* (2010) found that sea surface temperature (SST) is the only environmental predictor relating to biodiversity among marine mammals. Apart from the SST, habitat availability and historical factors also influence the coastal species' diversity. In a study conducted by Fleming, Clark, Calambokidis and Barlow (2015) humpback whales show a variance in diet with a high and low SST. Their diet consists almost solely of krill with cooler SSTs, whereas with higher SSTs their diet tends to be dominated by schooling fish. Their preference is related to food availability, which in return relates to the local SST. Whales thus respond to changes in ecosystems by changing their diet within different trophic levels (Fleming, Clark, Calambokidis, & Barlow, 2015).

A study by Chambault *et al.* (2018) repors that bowhead whales change movement patterns as a response to a shift in SST. After tracking 98 bowhead whales by satellite, to research the environmental drivers, it was concluded that the whales follow a narrow range of SSTs and that they were found at higher latitudes due to increasing SSTs. The diving patterns differ seasonally, yet most aggregations changed during spring and summer. The SST is predicted to undergo an increase that will expose whales to profound changes, which could possibly lead to extensive habitat loss (Chambault *et al.,* 2018).

3.4 How global warming affects great whales in Europe

The unique ecologies and the complexity of life cycles of marine mammals make it difficult to predict their responses on climate change and global warming. The most important aspects that are affected by global warming are the marine climates, food availability, ocean acidification, sea ice and the spatial distribution of great whales. These topics can influence marine ecosystem functioning and structures in return.

3.4.1 Marine Climates SST

Marine climates are predicted to change due to global warming. Marine ecosystems will mostly be impacted by changing sea surface temperature (SST). Global temperature changes affect global-average sea levels through thermal expansion with an increasing SST. It is estimated that by the year 2100, the majority of sea-level rise will be caused by this process. Changes in ocean temperature and human impacts could possibly lead to a rearrangement of ocean life (Tittensor *et al.,* 2010). The effects of past alterations of temperature on the life cycle phenology, movements, abundance and distribution of marine organisms have shown to impact plankton, fish, seabirds and cetaceans (Lambert *et al.,* 2010). It was reported that an increase in SST results in a decrease in phytoplankton in mid to low latitudes (Behrenfelt *et al.,* 2006). The fraction of small phytoplankton increases, which results in a decrease of energy flow to the higher trophic levels (Morán *et al.,* 2010). Many marine habitats and species like great whales are highly sensitive to increases in SST (EEA, 2022). On average, the SST is expected to rise between 0.9 °C and 2.9 °C by 2100, this increase is 30% slower than the rise of the mean surface air temperature (Arias, P., Bellouin, N., Coppola, E., Jones, R., Krinner, G., Marotzke, J., ... & Zickfeld, K. (2021).

The Mediterranean Sea is especially vulnerable to SST rise caused by global warming (Pace, Tizzy, & Mussi, 2015). Since the Mediterranean region lies in a transitional zone between continental and sub-tropical temperate climates, it is more sensitive to climatic dynamics. Apart from that, the only connection between the Mediterranean Sea and the open ocean is a shallow and narrow stream of water; The Strait of Gibraltar. The shape of this water limits water exchanges severely (Lionello *et al.,* 2012). Its STT is estimated to rise 0.35 °C per decade, with a peak in spring and seasonal variability (Shaltout, & Omstedt, 2014). Some parts of the Mediterranean Sea display an even higher warming SST trend, like the Black Sea with an increase of 0.51°C per decade (Shaltout, & Omstedt, 2014). The Baltic Sea is expected to increase by 4°C in the northern parts and 2°C in the southern parts in the next decade (Helcom, 2013).

The predicted increase in SST will enhance stratification in the upper levels of the ocean (Coma *et al.,* 2009). Enhanced stratification will decrease ocean ventilation, affect ocean carbon and heat uptake, affect tropical storm formations and strength and lastly affect water mass formation. Apart from this, changes in ocean circulation patterns are expected and research shows that these patterns are currently slowing down (Rahmstorf, *et al.,* 2015). Changes in SST also result in a decrease of vertical mixing of water. This additionally affects ocean circulation drastically (Pace, Tizzy, & Mussi, 2015). An increase in stratification also leads to increased light efficiency and reduced nutrient supply, therefore the mixed-layer depth (MLD) will be shallower (Bopp *et al.,* 2001).

A rising SST is accompanied by more frequent and intense marine heatwaves which causes more frequent algal blooms in European seas (Smale *et al.,* 2017). Glibert *et al.* (2014) investigated the influence of temperature rising on algal blooms around the globe. Algal blooms will increase with higher water temperatures and the possibility of harmful algae blooms (HAB) then increases in coastal areas of the North-Western European Sea and the Baltic Sea. Since some algae (e.g. HAB algae) are harmful and kill fish, spread toxins and alter ecosystem functions, this results in negative impacts on aquaculture, ecosystems and human health (Gilbert *et al.,* 2014; Oliver, Donat, & Burrows, 2018). In 2014, marine heatwaves and algal blooms led to high levels of vibriosis infections along the coasts of the North Sea and Baltic Sea (Baker-Austin *et al.,* 2016). These *Vibrio* bacteria are responsible for severe infections for both animals and humans with a possible fatal end, such as cholera, wound infections and gastroenteritis (Vezzulli, Colwell & Pruzzo, 2013). Global temperature changes affect global-average sea levels through thermal expansion with an increasing SST. It is estimated that by the year 2100, the majority of sea-level rise will be caused by this process. When changes in ocean temperature and human impacts possibly lead to a rearrangement of ocean life (Tittensor *et al.,* 2010).

3.4.2 Food availability

The consequences of a shallower MLD are a decrease in nutrient supply for phytoplankton (Stambler, 2012), since this group of organisms mostly occurs in the mixed layer area (Bopp et al., 2001). Phytoplankton is one of the main food sources for all marine life and thus a key factor in marine ecosystems (Ratnarajah, & Hodgson-Johnston, 2014; Winder, & Sommer, 2012). It is estimated that with a 10 °C temperature rise, phytoplankton will increase its growth rate by 37% (Doney *et al.,* 2012). Marine food webs tend to have high trophic interaction richness (Dunne, Williams, & Martinez, 2004). Zooplankton are grazer species (e.g. protozoa, copepods, crabs, fish larvae, krill and jellyfish) that feed off phytoplankton (Jaspers, Acuña, & Brodeur, 2015). Several of these species function as both prey for apex predators like great whales and predators to lower trophic levels (Gómez-Villota, 2007). Warmer ocean temperatures increase basal metabolic rates, resulting in less energy availability for reproduction and growth. Ocean warming has mismatching consumer-prey effects on species within different trophic levels. Higher trophic levels are usually more affected than lower trophic levels, yet the complexion of networks and interactions make it difficult to predict specific effects (Doney *et al.,* 2012).

In the report of Mazzariol *et al.* (2011) evidence is found of starvation in seven stranded sperm whales. Even though their cause of death is scientifically researched, it is assumed that the starvation caused the mobilization high concentrations of pollutants found in the animals to be activated and impaired their nervous and immune functions (Pace, Tizzy, & Mussi, 2015).

3.4.3 Ocean acidification

Seawater increasingly absorbs carbon dioxide (CO_2) as a result of global warming. This results into ocean acidification and a higher salinity level, which amplifies the effects of global warming (Pace, Tizzy, & Mussi, 2015; Lionello *et al.*, 2012). These decreases in pH and O_2 levels occur in intermediate and moderate waters. It is expected that the primary production increases in a warmer ocean. It is however possible that other factors like oxygen availability, chemistry and food availability will limit production and growth (Doney *et al.,* 2014). Reductions in primary production will occur in the tropics and in the North Atlantic (Bopp *et al.,* 2013). Changes in ocean primary production on long-term base influence the global carbon cycle and thus influence marine life. Since 1980, the annual primary production decreased over 6% and 70% of the decrease was found in high latitudes (Gregg, Conkright, Ginoux, O'Reilly, & Casey, 2003).

Phytoplankton is responsible for half of the net primary production (Behrenfeld *et al.,* 2001). Even though the growth of phytoplankton depends on temperature, light conditions and vertical diffusion (Bopp *et al.,* 2001), a more recent report by Morán, López-Urrutia, Calvo-Díaz and Li (2010) shows that temperature alone explains 73% of cell size variance of phytoplankton despite differences in inorganic nutrient loadings and trophic status. Bopp *et al*. (2001) used two different models to track the marine productivity response to global warming and found that an increase in greenhouse gases leads to increased stratification and thus a reduction in nutrient supply and an increase in light efficiency. Marine export production drops 6% in general with a concentration of twice as much CO_2 in the ocean, yet regional changes occur. The stress of acidification and a reduction in energy flow on the first trophic level, which are primary producers and detritus, flow into the second trophic level (herbivores) and the third level (carnivores).

If ocean acidification alone occurs, a positive effect on herbivores and carnivores is predicted (Ullah, Nagelkerken, Goldenberg & Fordham, 2018). Eutrophic coastal systems usually consist of surface water with higher pH levels due to primary production. Below the pycnocline, pH levels are reduced by respiratory demand and the production of CO_2 (Doney *et al.,* 2012).

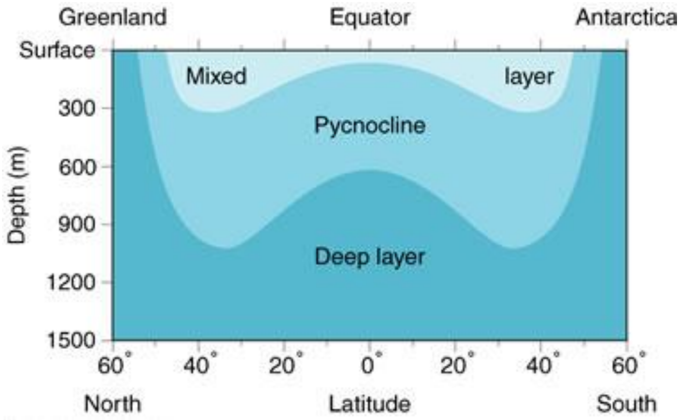


Figure 2: The three marine layers with their corresponding depths on different latitudes around the globe (Ocean Motion, 2006).

3.4.4 Sea ice

Sea ice is influenced by marine ecosystems. Another consequence of global temperature rises is melting of mountain glaciers, which also results in rising sea levels (Hulme, 2002). Several great whale species rely on sea ice. It provides critical habitat and protection from predators (Johnson *et al.*, 2022). Bowhead whales use ice to protect themselves from killer whale attacks at higher latitudes. Due to the loss of sea ice, whales are currently more exposed to longer open water periods, resulting in increasing opportunities for killer whales to attack bowhead whales (NOAA Fisheries[1], 2022; NOAA Fisheries[5], 2022 Matthews, Breed, LeBlanc, & Ferguson, 2020). This influences current population sizes negatively. Another report related to sea ice shows that humpback whales occurring in Disko Bay are to follow the sea-ice edge during spring and winter. In fall and summer, they were found in open ice-free waters. Humpback whales from Foxe Basin tended to stay in their area near to sea ice. It is unknown why these animals differ in distribution, yet it is expected that it may be due to birthing season (Chambault *et al.,* 2018).

According to previously mentioned findings by Chambault *et al.* (2018), statistical models indicate that bowhead whales in the Arctic are exposed to altered stratification, thermal stress and vertical transport of water masses due to the loss of sea ice in this area. In response to this, these whales possibly suffer from extensive habitat loss. A study conducted by Heide-Jorgenson *et al.* (2010) shows a clear relationship between increasing offshore distances and decreasing sea-ice cover of beluga whales in west Greenland, suggesting the expansion of spatial distribution of whales due to habitat loss and annual ice recession.

3.4.5 Spatial distribution

Climate change and variability have an effect on species distribution and abundance (Azzellino, Gaspari, Airoldi, & Lanfredi, 2008). Quantifying marine biodiversity patterns is a costly and challenging process, since most taxa are not easy to be seen. A wide range of species are highly mobile and distribute themselves throughout the open oceans with large ranges (Tittensor *et al.,* 2010). Two of the most important threats to Mediterranean cetaceans relate to degradation due to climate alterations and habitat loss (Pace, Tizzy, & Mussi, 2015). Research performed in the western Ligurian Sea evidently shows change in cetacean distribution due to climate variability where certain cetaceans avoided marine circumstances with a deviation of 3°C from the seasonal average temperatures (Azzellino, Gaspari, Airoldi, & Lanfredi, 2008). Cetaceans are found in diverse habitats and are considered wide ranging organisms due to their behavioural range shifts, thus changes in marine ecosystems are expected to have an impact on these cetaceans (Pace, Tizzy, & Mussi, 2015). Whale abundance peaks consistently on mid-latitudes in all oceans (Tittensor *et al.,* 2010). Climate change also changes prey abundance, distribution and type, since ocean warming impacts the timing of important events like migration (Johnson *et al.*, 2022).

Organisms respond to climate change shifts and other condition shifts through behaviour and physiological adaptations. When physiologically possible, individuals either adjust their physiology to the new conditions or change through adaptation over generations. If the individuals are intolerable, migration, change in phenology or extinction and death result from these changes. These shifts are usually stressful and cause suboptimal performance; mortality, smaller size, reduced growth and reduced reproduction are likely to occur (Doney *et al.,* 2012). Range shifts towards more dangerous areas could occur. A relatively large number of sperm whales reside in the eastern part of the Mediterranean Sea. This part is known for its relatively high number of whale strandings. Around 50% of the stranded animals have scarring from propellers or ships. This indicates that shipping traffic is threat for the whales. In addition, Cuvier's beaked whales suffer from strandings here due to naval sonar exercises. High density underwater noise pollution and ship traffic impacts cetaceans throughout all waters in Europe. It leads to whale displacement, disturbance, temporary and permanent hearing loss and direct mortality (Johnson *et al.,* 2022).

4 Discussion

The primary goal of this report is to provide a literary report on the effect of global warming on great whale species residing in European waters. Since cetaceans are generally not well studied, the amount of information on great whales was less available than expected. Marine life and its ecosystems have been researched relatively little compared to terrestrial life. This makes it more difficult to predict possible ecosystem changes for oceans. More information on the relationship between spatial distribution and on their ability to adapt to changes in water temperature could have given more insight on the future of great whale health.

It is known that whale defaecation and urination have positive effects on phytoplankton growth, since research showed positive photosynthetic results when faeces were added in a lab as described in chapter 3.2. This means that whales could potentially affect marine phytoplankton positively. However, this is thus far one of the few reports conducted on the effects of whale faeces and thus more information could clarify the greatness of this positive effect. A decrease in nutrient supply through whales as a result of ocean warming could result in less phytoplankton, decreasing the number of organisms on different trophic levels that function as whale prey.

Even though crucial information of how whales are affected by global warming is lacking, white beaked dolphins have shown to be negatively influenced by this phenomenon. Salvadeo *et al.* (2010) discovered a decrease in seasonal occurrence from the cool season between 1980 and 2000, a decrease in average group sizes and a decrease in sightings. During this research, sperm, fin, Bryde's, blue and the humpback whale encountered in the study area. These great whales, along with other cetaceans, did not show a similar decline. White beaked dolphins also have different habitat preferences. Since 2010, the North Atlantic right whale increased the time it spent in the Mid-Atlantic region. This is likely to be a response to changes in food resources and prey availability.

Apart from global warming, several other threats to whales surfaced whilst researching the effects of climate change. Since there are currently many factors that negatively influence great whale populations , the possibility exists that the effects of climate change are enhanced by these threats. That makes distinguishing the effects of the current threats on cetaceans hard, since there is a multitude of threats acting at the same time, e.g. by-catch in fishing gear, pollutants, pathogen exposure, ship vessel accidents, and underwater noise. For instance, anthropogenic threats like ship vessels, by-catch of fishing and hunting undoubtedly influence whale health most by adding pressure to their survival and adding negative effects on marine ecosystems; the deletion of apex predators like great whales in marine ecosystems leads to trophic cascades (Johnson *et al.*, 2022; Llope *et al.,* 2011). In addition to this, the report of Mazzariol *et al.* (2011) found evidence of starvation in seven stranded sperm whales. Even though their cause of death is scientifically researched, it is assumed that the starvation caused the mobilization high concentrations of pollutants found in the animals to be activated and impaired their nervous and immune functions (Pace, Tizzy, & Mussi, 2015). It is also known that whales forage on prey that is most abundant in their area. The possibility that whales will change their choice of prey due to climate change is yet not researched.

Habitat range shifts may occur due to global warming through SST rising. The average SST is expected to rise between 0.9 and 2.9 by 2100, as discussed in chapter 3.4.1. This might have consequences for great whales that are connected to habitat range shifts. The MLD will be shallower due to stratification, which could lead to less food availability and thus to additional habitat range shifts. In figure 2, the latitudinal difference in depths of the pycnocline is displayed.

It shows that the MLD is shallower around the equator and deeper around 40 degree latitudes. Shallower MLD means less space for phytoplankton to live. This impacts whales by reducing the availability for their food sources (secondary trophic level) to feed on phytoplankton (primary producers), thus less food available for great whales in areas where the MLD is shallower. Even though some great whale species (e.g. North Atlantic right whale) are restricted to certain areas, sperm whales are likely to have the greatest feeding range of any species on earth. This could possibly indicate that sperm whales are more resilient to global warming than species with smaller habitat ranges (NOAA, 2022)[6]. If this statement is correct, the possibility exists that great whales with broad habitat ranges are less likely to be affected by global warming, yet scientific research is lacking in this area so it is not clear whether or not this is true.

The effects of HABs caused by a rising SST on great whales has not been researched yet, but it is expected that great whales could be affected negatively by these algal blooms, its corresponding infections and heatwaves.

A standard methodology for literary studies is applied to this thesis. Even though this report cannot answer all questions equally as extensively, this type of study is a suitable approach to gather more knowledge on the subject. Research on cetacean and great whales have only started to increase in the past 20 years. This creates knowledge gaps in their adaptiveness to changes, deeper insights in foraging behaviour and the reasoning behind their distribution apart from feeding and breeding. There is little information on their adaptations to changing marine ecosystems, which makes it hard to predict their response to global warming.

This report shows the importance of conducting more research towards great whales and their relationship to marine ecology. It is therefore of high value to future research towards great whale and marine health, which is conducted by institutes like Universities, Greenpeace and Stichting Rugvin. It is necessary to fill the knowledge gaps this report created, since global warming will undoubtedly influence great whales and these species are of great importance to the foundation of ocean life.

5 Conclusion

This research aims to examine the influence of global warming on great whales residing in European waters, specifically the bowhead whale, North Atlantic right whale, common minke whale, sei whale, Bryde's whale, blue whale, fin whale, humpback whale and sperm whale. It is important to research the effects of global warming on apex-predators like great whales. Their importance in complex marine ecosystems is large and the need to protect these species is increasing.

The main question of this research was *'What are the consequences of global warming on the whale pump of baleen whales* (*Mysticeti sp.*) *and the sperm whale* (*Physeter macrocephalus*) *in Europe?'* and can be answered as followed through the four sub questions:

What is the geographical distribution of great whales in Europe? Great whales distribute themselves throughout the Baltic Sea, The North-east Atlantic Ocean and the Mediterranean Sea, travelling between feeding and breeding areas latitudinally.

What are the effects of the whale pump on European waters? The whale pump is important for spreading nutrients like nitrogen, carbon, iron and sulphates throughout different pelagic layers in the ocean. This enhances primary production and CO_2 absorption by dissolving greenhouse gases. Whales contribute to these processes by feeding in deeper layers ocean and defaecating and urinating in higher layers.

What aspects of the whale pump are influenced by European marine ecosystems? The aspects of the whale pump that are most influenced by the European marine ecosystems are food availability, SST and sea ice. The SST influences food availability and whales adapt their migration patterns due to a changes in SST, which will result in extensive habitat loss. Sea ice provides critical habitat, provide food resources and serve as protection from predators. A loss in sea ice results in altered stratification, thermal stress and vertical transport of water.

How does global warming affect great whales in Europe? Global warming results in change in SST, such as thermal expansion and enhanced stratification. All European seas will be affected by a rising SST. Increases in SST affects phytoplankton populations, which is one of the main food resources of the great whales' prey. Apart from phytoplankton, many marine habitats and species are highly sensitive to increases in SST. Additionally, harmful algal blooms will occur, harming and killing fish, spreading toxins and altering ecosystems. Trophic interaction will change and result in mismatching consumer-prey effects. These aspects could possibly negatively affect food availability and health for great whales. A reduction in primary production due to the loss of phytoplankton caused by ocean acidification will lead to stress in second and third trophic levels, thus stress great whales. An increase in stratification also leads to increased light efficiency and reduced nutrient supply, therefore the MLD will be shallower and result in less food availability. In the past decades, climate change and variability has altered cetacean species distribution and abundance. Ocean warming will also affect shifts in timing of important events such as migration and breeding on the long run. Range shifts are assumed to happen on short term, especially to more dangerous areas due to habitat stress. It is likely that sperm whales are less affected by global warming than species with smaller ranges. Alterations like these are usually stressful and cause immediate suboptimal performance for all whales.

The answer to the main research question *'What are the consequences of global warming on the whale pump of baleen whales* (*Mysticeti sp.*) *and the sperm whale* (*Physeter macrocephalus*) *in Europe?'* is as followed: it can be concluded that predicting marine responses on global warming is challenging due to the complex ecosystems and marine processes. Most projections predict changes in marine food webs through range shifts and extinction on all trophic levels, though it is unclear how impactful these will be. Undoubtedly global warming will have altered and negative effects on spatial distribution, habitats and food availability of great whales through a rising SST. Food availability will decrease and habitat ranges will shift and decline, especially for great whale species with smaller range sizes. Even though overexploitation is proven to be most responsible for alterations in functioning of several ecosystems, it is expected that global warming will amplify these effects, especially on marine ecosystems.

The information gathered in this report is relevant for future research related to climate change, marine ecosystems and great whales. This information could be beneficial for governments, marine biologists and instances like Stichting Rugvin and Greenpeace by providing information on whale health, which could lead to creating new measures to protect whales from global warming. It can also be used to create awareness for the importance of whales in the world's ecosystems to protect them more in Europe.

Recommendations

During this research, the lack of information on the specific effects of climate change on great whales and cetaceans in general has surfaced. Since whale species are quite important factors in sustaining healthy marine ecosystems, further research needs to be executed to gather knowledge which helps to sustain a biodiverse ocean. This includes investing in short term solutions such as tagging, tracking and monitoring all whale species and their behaviour, which can be executed by organisations like Stichting Rugvin and marine research centres. Phytoplankton abundance, population density and its algal blooms are research topics that can predict the health of ocean waters on long terms. This can be done by corporations and organisations like Stichting Rugvin and Greenpeace through tracking algal blooms, phytoplankton population densities and marine ecosystem changes through temperature shifts.

Measurements need to be taken to assure the effects of global warming is minimized for oceans. Examples of these measurements are lowering CO_2 and other greenhouse gasses, so ice will not melt as quickly, ocean acidification and SST rising are minimized.

Whale health is related to phytoplankton health and thus research on these topics helps predict the success of whale species. It has also become clear that anthroponotic stressors such as overfishing, hunting and ship vessel accidents are changing the composition of whales and other marine species. It is important to examine these topics and act on anthropological threats in order to sustain healthy whale populations and healthy ecosystems. This could be executed through creating new or stricter rules for whale protection against anthroponotic stressors. To prevent whale loss, the most important point that needs to be spread globally, is the importance of whales in the world's ecosystem.

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Appendix

Appendix I: Global spatial distribution of most great whale species (Johnson *et al.,* 2022*)*