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# The potential role of Posidonia oceanica for mitigating acidification on coastal waters of Europe

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# Affidavit

I, **MARIA BLOMENHOFER, BA**, hereby declare

1. that I am the sole author of the present Master's Thesis, "THE POTENTIAL ROLE OF POSIDONIA OCEANICA FOR MITIGATING ACIDIFICATION ON COASTAL WATERS OF EUROPE", 85 pages, bound, and that I have not used any source or tool other than those referenced or any other illicit aid or tool, and
2. that I have not prior to this date submitted the topic of this Master's Thesis or parts of it in any form for assessment as an examination paper, either in Austria or abroad.

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**Abstract:**

Ocean acidification is a major environmental concern that has significant ecological., economic, and social implications. The plantation and restoration of seagrass meadows in coastal waters, specifically Posidonia oceanica, is one possible method to combat ocean acidification and has the potential to have a significant positive impact on the marine environment and the overall state of the biosphere. As there has been a decline of Posidonia oceanica of about 30% in the Mediterranean Sea over the past three decades to about 1.2 mio ha in the Mediterranean Sea, the positive effects of the sea grass have diminished due to anthropogenic influence. Still, its importance as a carbon sink should not be underestimated. By using recent literature and different studies that have been analysed of the capacity of sea grass to mitigate the impacts of ocean acidification and the effects on the marine ecosystems, supported by several experiments that have been conducted, this thesis demonstrated the importance of Posidonia oceanica. The experiments showed that seagrass ecosystems have higher pH than ecosystems without seagrass, with a mean difference of 0.43. As the pH is interlocked with the $CO_2$-levels and the oxygen levels, also experiments on these factors have been conducted. In general, the concentration of oxygen with P. oceanica present is 2mg/L higher than without. Equally, the $CO_2$ concentration was lower with P. oceanica present. The Posidonia oceanica meadows present in the Mediterranean Sea are able to fixate about 13,3 mio tons of $CO_2$, which is equal to 0,3% of Europeans $CO_2$ emissions. About 2,8 mio tons of $CO_2$ are sequestered by the sea grass, which is about 0,07% of European $CO_2$ emissions. Furthermore, recent plantation efforts show the successful restoration of seagrass meadows and their overall benefits for the regional environment. Overall, this paper provides valuable insights into the potential role of seagrass meadows in mitigating ocean acidification and improving marine biosystems while providing specific numbers to support its findings.

# 1. INTRODUCTION

The escalating environmental degradation of our oceans, characterized by coral bleaching, mass fish mortality, and oil spills, is not a fictitious dystopia, but a stark reality that is emblematic of anthropogenic climate change. The acidification of the ocean, a direct result of the influx of $CO_2$ from human activities, has rendered the marine ecosystem increasingly vulnerable to the deleterious effects of climate change (Orr *et al.*, 2005). The unprecedented levels of $CO_2$ uptake in the ocean, resulting from industrial emissions and greenhouse gases, have profound effects on land and in the sea. With the ongoing progression of the climate crisis, the development of innovative technologies to address its symptoms and potential causes has become urgent. This thesis sets its focus on the shore waters of the Mediterranean Sea and aims to explore the mechanisms of ocean acidification, its impact on the marine biosystem, and the urgent need for immediate and sustained action to mitigate the ecological consequences of anthropogenic climate change (Caldeira and Wickett, 2003). The uptake of $CO_2$ in the ocean reaches unparalleled levels that have far-reaching effects on all parts of the biosphere, land, and sea. As the climate crisis advances, so does the technology and the development of methods to combat the symptoms and the potential causes of the crisis – one of which will be discussed in this thesis. Sea grass as a habitat and due to its chemical and physical effects may have far reaching feedback mechanisms that on one side increases the pH level and influences biological systems around it. Meadows, sea grass and other marine plants have come up in many scientific discussions during the last few years as the focus in the climate crisis shifts from land to sea. According to a search on Google Schoar, there has been a significant increase in the number of publications discussing seagrass meadows and other marine vegetation in recent years. For example, a search conducted on Google Scholar for the period of January 2023 until May 2023 yielded 1860 publications on that topic.

Posidonia oceanica, with the nickname "lungs of the Mediterranean Sea" is connected to over a third of all species existing in the region for either breeding ground purposes, habitat, nutrition or as a hunting ground. Unfortunately, within the past 4 years, about 50% of it were lost in the Northern Adria, and about 30% overall in the Mediterranean Sea whereas the definite reason for it is still not known. While many guess that it has been lost due to a change in temperature, which is caused by the climate change and the warming of the overall atmosphere (Marbà, Díaz-Almela, *et al.*, 2014), some researchers, like Manuel Marinelli by the research and preservation institute Project Manaia think of an overfeeding of nutrients and the following destruction of the plant more likely. Overfeeding nutrients in combination with higher $CO_2$ levels, invasive species as feedbacks to changes in climate disable the successful reforestation of sea grass (Marbà and Duarte, 2010). Posidonia oceanica is of utmost importance to the balance of the marine ecosystem as it acts as a potent and resilient carbon sink, much more effective than rainforests. As a carbon sink and a potential buffer to ocean acidification it acts as the last barrier to cross for the Mediterranean Sea to reach its tipping points and a horrific loss of marine life. One of the reasons we are about to cross the barrier is ocean acidification. The effectiveness of Posidonia oceanica in Mediterranean shore waters regarding ocean acidification mitigation will be the topic of this master thesis.

## 1.1 BACKGROUND INFORMATION ON OCEAN ACIDIFICATION AND ITS EFFECTS ON MARINE ECOSYSTEMS

Ocean acidification is a major environmental threat. Due to increasing levels of carbon dioxide in the atmosphere, the ocean experiences a pH reduction as it balances out the $CO_2$ emissions (Caldeira and Wickett, 2003). Due to this uptake, the $CO_2$ concentration increases in the water, which leads to a decrease of pH in the ocean which is the process of acidification (Orr *et al.*, 2005). Since the beginning of the industrial era it has already decreased by approximately 0,1 units while the projected decrease is up to additional -0,5 units until the end of this century (Fabry *et al.*, 2008).
The high $CO_2$ emissions have their source in human activities like the burning of fossil fuels, deforestation, decreasing the capability of carbon sinks and other industrial processes (Caldeira and Wickett, 2003). This effect has a significant impact on the marine environment and the overall climate (Gattuso *et al.*, 2015).

### 1.1.1 Impacts on Marine Organisms

One of the effects of ocean acidification is the reduced ability of marine organisms to build and maintain their skeletons and shells, which are made of calcium carbonate

(Caldeira and Wickett, 2003). The growth and survival of coral reefs, shellfish, and the overall fish populations are being affected by ocean acidification (Fabry *et al.*, 2008). Especially coral reefs are highly vulnerable to ocean acidification as the decline in the pH of the ocean affects their ability to effectively produce calcium carbonate and to maintain their structure (Fabry *et al.*, 2008). This leads to a decline in the health of coral reefs and contributes to their degradation and eventual disappearance, which again has overarching negative effects on the availability of habitats for other marine organisms (Gattuso *et al.*, 2015). Ocean acidification also affects shellfish, such as mussels and oysters in their survival and growth. The larvae of these organisms are unable to form their shells properly in a more acidic environment, leading to a steady decline of their population and health (Orr *et al.*, 2005). In addition, adult shellfish lose their ability to repair their shells in case of breakages or for the overall maintenance. Fish populations are affected in the development of their eggs and larvae, and it can impact their behavior, metabolism, and immune system (Fabry *et al.*, 2008). This can lead to a decline in the health and survival of fish populations, which has significant implications for the marine food chain and the overall health of the ocean ecosystem (Gattuso *et al.*, 2015). It is obvious that the decrease in ocean-pH has far reaching impacts on marine life, but also life on land is affected by this environmental degradation.

### 1.1.2 Economic and Social Impacts

Human life depends on the ocean, not only in coastal regions but due to globalization and the interconnectivity of human life and economy, humanity across the globe is affected by ocean acidification and the decline of marine health. The decline in the health of coral reefs and the decline in fish populations threaten the livelihoods of coastal communities that depend on fishing and tourism as these ecosystems are relevant tourist destinations and therefore income sources for many countries (Gattuso *et al.*, 2015).

The decline in the health of shellfish populations has also significant implications for the fishing industry as they are a valuable food source and a cultural good for many coastal communities (Orr *et al.*, 2005). The decline in the health of shellfish populations due to ocean acidification threatens the livelihoods of people in fishing industries in regards of their income and overall monetary power, which may as well lead to potential food security issues in affected communities (Gattuso *et al.*, 2015).

### 1.1.3 Mitigating Ocean Acidification

The first factor that must be reduced to mitigate ocean acidification is, of course the emission of $CO_2$ and other greenhouse gases into the atmosphere (Caldeira and Wickett, 2003). Reducing the burning of fossil fuels, increasing the use of renewable energy sources, and reducing deforestation and afforestation are suitable strategies (Gattuso *et al.*, 2018). The international community has recognized the importance of reducing emissions to mitigate ocean acidification which resulted in agreements such as the Paris Agreement, but unfortunately, the steps taken were not enough (United Nations General Assembly, 2015).

Another possibility would be the restoration and political protection of coastal ecosystems such as seagrass meadows and mangrove forests, that help to reduce the impact of ocean acidification on the marine environment (Orr *et al.*, 2005). As coastal ecosystems act as carbon sinks, absorbing and storing carbon from the atmosphere and reducing the impact of ocean acidification on the marine environment they could be a reliable possibility to reduce the regional $CO_2$ concentration (Gattuso *et al.*, 2018).

One such coastal ecosystem is the seagrass meadow, specifically the seagrass species Posidonia oceanica. This species of seagrass is particularly effective at mitigating the impact of ocean acidification on the marine environment (Orr *et al.*, 2005). Seagrass meadows not only are able to act as a carbon sink, but also provide a habitat for a variety of marine organisms which on the other hand mitigate ocean acidification in a feedback mechanism (Gattuso *et al.*, 2015).

In conclusion, ocean acidification is a major environmental concern that has significant ecological., economic, and social implications. Combatting ocean acidification requires the reduction of $CO_2$ emissions and greenhouse gases, as well as the protection and restoration of coastal ecosystems. Only functioning ecosystems can act as carbon sinks in their full capacity, which is essential for a successful mitigation of ocean acidification. The plantation and restoration of seagrass meadows, specifically Posidonia oceanica, seems to be one possible method to combat ocean acidification regionally and has the potential to have a significant positive impact on the marine environment and the state of the marine ecosystem in the Mediterranean Europe.

## 1.2 SIGNIFICANCE OF THE RESEARCH

The significance of research on methods to combat ocean acidification is increasingly important given the growing threat of this phenomenon to marine ecosystems and the organisms that depend on them. Ocean acidification is a major environmental challenge that can have severe impacts on the health and functioning of marine ecosystems and at the end on human life. The negative effects of ocean acidification on marine ecosystems and their organisms have been well documented in recent years. For example, research has shown that ocean acidification can lead to decreased calcification in some species of phytoplankton, corals, and other marine organisms that rely on calcium carbonate for building their shells and skeletons (Kroeker *et al.*, 2013). This reduction in calcification can have cascading impacts on the entire food web, as these organisms play critical roles in providing food and habitats for other species (Byrnes, 2016). In addition to its impacts on individual species, ocean acidification can also lead to changes in ecosystem structure and function. For example, research has shown that ocean acidification can alter the composition and abundance of phytoplankton communities, leading to changes in the productivity and functioning of marine ecosystems (Feely *et al.*, 2010). These changes can also have significant impacts on the services that these ecosystems provide, such as the provision of food and livelihoods for coastal communities (Cooley and Doney, 2009). Given these severe and far-reaching impacts of ocean acidification, it is essential to identify and implement effective methods to mitigate its results on the marine ecosystem. This is where research on methods to combat ocean acidification becomes crucial. By investigating the potential of different strategies to mitigate the impacts of ocean acidification, researchers can help to inform and guide efforts to conserve and protect marine ecosystems and the organisms that depend on them.

One promising approach to combat ocean acidification is the restoration and protection of seagrass habitats, such as Posidonia oceanica. Seagrasses are a critical component of many coastal ecosystems, providing vital habitats for a variety of species and helping to maintain the overall health and functioning of these ecosystems (Duarte, Hendriks, *et al.*, 2013). In addition, research has shown that seagrasses can play a key role in mitigating ocean acidification through their ability to sequester carbon dioxide from the atmosphere and store it in the sediment (Fourqurean *et al.*, 2012). By promoting the restoration and protection of seagrass habitats, researchers and managers can help to improve the resilience of these ecosystems to ocean acidification and other stressors. This is a pressing global issue that is having a significant impact on marine ecosystems, and the ramifications of inaction are far-reaching and severe. With the oceans serving as a critical component in regulating the Earth's climate and supporting a vast array of marine life, it is imperative that steps are taken to mitigate the effects of ocean acidification.

Especially the degradation of seagrass beds caused by ocean acidification has a cascading effect on the health of marine ecosystems, as well as contributing to further climate change (Hsieh, Tew and Meng, 2023; Lubchenco and Haugan, 2023). Given the urgency of this issue, it is imperative that research is conducted into effective methods for combating ocean acidification. There are several reasons for the significance of this thesis. Firstly, it will contribute to a deeper understanding of the mechanisms behind ocean acidification and the ways in which it is impacting marine life. This knowledge will be crucial in developing targeted and effective mitigation strategies. It will also play a critical role in advancing the development and implementation of innovative and cost-effective technologies and methods for mitigating the effects of ocean acidification. These methods may include the planting and cultivation of Posidonia Oceanica, as well as the implementing and developing alternative methods for carbon capture and storage. The research will also be significant due to the potential benefits for communities that rely on the oceans and its biodiversity and physiochemical composition for their livelihoods. The preservation and restoration of seagrass and other habitats could provide a range of economic and social benefits, like an increased fishing yield, higher water quality, and cleaner air.

Additionally, the research will contribute to a more sustainable future by analyzing ways to reduce the amount of $CO_2$ that is emitted into the atmosphere and therefore also mitigating the far-reaching effects of climate change. Successful implementation of effective ocean acidification mitigation measures is critical for the future state of health of the environment and at the end for securing a sustainable way of living for all coming generations. This importance of the research is also shown in the increase in research on that topic. As awareness about the concern of vegetated coastal habitats as the most intense carbon sinks in the biosphere rise, so does the number of papers written on the subject increase (Duarte, Middelburg and Caraco, 2005). 30 studies published in 2005, to 110 in 2012 to well over 400 in 2022: this shows how important the topic is becoming for the scientific community.

The growing threat of ocean acidification to marine ecosystems and the organisms that depend on them underlines the need for effective and science-based strategies to mitigate the impacts of high carbon emissions. By investigating the potential of different methods, their effectiveness can be calculated in managing the chemical composition and the carbon storage capability of the ocean. Due to the urgency of the issue it is imperative that research is conducted into effective and innovative solutions. Furthermore, this research can identify gaps in current knowledge and possibly provide a basis for further research. This will advance the development and implementation of effective mitigation strategies and ultimately play a critical role in securing a sustainable future for all.

## 1.3 Objectives

### Research question

While investigating the topic of seagrass in ocean acidification mitigation, several research questions came to mind, but one raised a special interest especially as it had not yet been discussed by other scholars to a proper extent. The research question is as follows:

*What is the effectiveness of seagrass to mitigate ocean acidification and the current restoration efforts as a means to address ocean acidification, and what factors need to be taken into consideration when developing and implementing sea grass restauration strategies for sustainable and successful outcomes?*

This study is in the format of a master's thesis to gain further knowledge about the usage of Posidonia oceanica as a countermeasure against ocean acidification. The study will be directed on a sea grass species endemic to the Mediterranean region, namely Posidonia oceanica. The specific goals of this work are:

- The conduction of a comprehensive review of the available literature to deepen the understanding of the importance of sea grass in the mitigation of ocean acidification and its impact on marine ecosystems (Guo *et al.*, 2021)
- Investigate how technologies such as artificial reefs and underwater cultures can be leveraged in combination with seagrass management and restoration to maximize the effectiveness of using seagrass to combat ocean acidification (Unsworth *et al.*, 2019)

- A review of current technologies and methods to address ocean acidification, including the use of seagrass, to assess the effectiveness and sustainability of seagrass management and restoration (Duarte, Hendriks, *et al.*, 2013)

These goals will allow to assess the effectiveness and sustainability of using seagrass to combat ocean acidification and to study how different technologies and methods can help improve the process of seagrass management and recovery.

# 2 LITERATURE REVIEW

This chapter firstly explains the effects of ocean acidification and its causes to show the urgency of the problem. Several different methods of combatting ocean acidification are followed by a review of relevant literature on the use of sea grass and the importance of a functioning biological marine system for successful buffering of carbon uptakes. The focus will be on recent literature and the different aspects that have been analysed of the capacity of sea grass to mitigate ocean acidification and its impacts on marine ecosystems.

## 2.1 OVERVIEW OF OCEAN ACIDIFICATION AND ITS CAUSES

Ocean acidification is a current environmental issue that not only affects the world's oceans but also life on land. It is interconnected with the symptoms and the sources for the climate crisis, though not equally frequently discussed. Ocean acidification is primarily caused by the sea water's absorption of atmospheric carbon dioxide ($CO_2$). The carbon dioxide ($CO_2$) from the atmosphere dissolves in seawater and reacts with the ions in the water. The chemical reaction between $CO_2$ and water molecules results in the production of carbonic acid, which dissociates into hydrogen ions (H+) and bicarbonate ions ($HCO^-$) in seawater, causing a decrease in the concentration of carbonate ions ($CO_3^{2-}$). The result of these chemical reactions is a decrease in seawater pH and an increase in its acidity (Gattuso and Hansson, 2011). In summary, the higher the $CO_2$ concentration in the atmosphere, the higher becomes the $CO_2$ concentration in the sea water which lowers the pH level and leads to ocean acidification.

1. $CO_2$ (g) + $H_2O$ (l) → $H_2CO_3$
2. $H_2CO_3$ → $H^+ + HCO_3^-$
3. $HCO_3^-$ → $H^+ + CO_3^{2-}$

In the experimental part of the master thesis not only the pH level is considered, but also the dissolved oxygen and the $CO_2$ levels as all of these chemical factors are intertwined. As to say, one of the consequences of ocean acidification is the decrease in dissolved oxygen levels in seawater. As $CO_2$ is absorbed by seawater, the concentration of hydrogen ions in the water increases, which then leads to a decrease in the pH of the water. This decrease in pH can lead to a reduction in the solubility of oxygen. This decrease in dissolved oxygen levels can have serious consequences for the marine ecosystem as marine life requires oxygen to survive remain in balance (Breitburg *et al.*, 2018).

Another effect of ocean acidification is the increase of the $CO_2$ level in seawater. This increase in $CO_2$ concentration has a profound effect on the ability of marine organisms to form and maintain their shells and skeletons, as mentioned previously. The decrease in carbonate ion concentration reduces the availability of this ion for marine organisms, making it difficult for them to build their shells (Gattuso and Hansson, 2011). This shift in the balance of these ions has many possible effects, ultimately leading to their decline or extinction (Doney *et al.*, 2009).

The increased concentration of $CO_2$ in seawater also affects the carbon cycle and the ability of marine ecosystems to store carbon. Seawater absorbs approximately 25% of the $CO_2$ emitted by human activities each year (Sabine *et al.*, 2004). For example, a decrease in carbonate ion availability can affect the photosynthetic activity of phytoplankton, which plays an imminent role in the global carbon cycle by sequestering carbon dioxide from its surroundings (Riebesell *et al.*, 2009). However, the increase in $CO_2$ concentration alters the balance between the uptake and release of $CO_2$ by marine ecosystems, potentially leading to a decrease in the ocean's capacity to store carbon (Gattuso *et al.*, 2015). The changes in pH levels, oxygen levels, and $CO_2$ concentrations are interconnected, and their effects on marine ecosystems are complex and often context dependent, whereas the temperature is an important factor. The main subject of this master thesis, Posidonia oceanica, demonstrates this dependency. Studies suggest that seagrass meadows can help mitigate the impacts of ocean acidification by buffering the pH levels in their vicinity and increasing oxygen production through photosynthesis (Unsworth *et al.*, 2019). Conversely, other studies suggest that ocean acidification can lead to the loss of seagrass meadows, which can further exacerbate the effects of ocean acidification by reducing the amount of oxygen produced through photosynthesis (Cai *et al.*, 2011). Increasing the amount of sea grass therefore proposes to be beneficial for ocean acidification by provoking a positive feedback loop, just as its loss decreases the pH and the overall balancing structure of the ecosystem.

The reduction in the availability of carbonate ions, which are crucial for the formation of calcium carbonate shells and skeletons of many marine organisms such as corals, molluscs, and some planktonic species furthers this process (Doney *et al.*, 2009). The decrease in carbonate ions availability leads to the process called ocean acidification, which can result in the dissolution of these structures and make it harder for organisms to grow and survive.

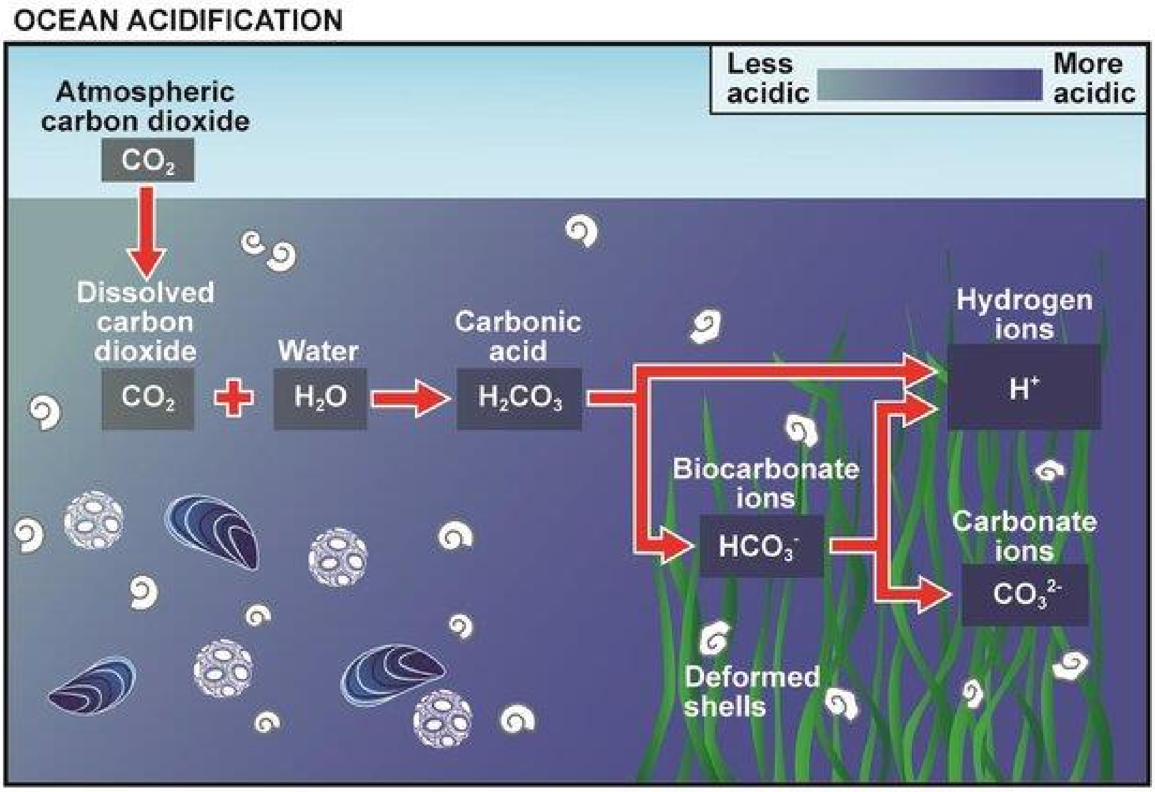


*Figure 1: Ocean acidification mechanism (Birchenough, Williamson and Turley, 2017)*

## 2.2 CARBON SEQUESTRATION MECHANISM

Not only the process of the acidification is relevant, but also the carbon cycle and the counteracting sequestration mechanism is of importance to understand the crucial role of Posidonia oceanica and other ocean vegetation.

The sequestration process involves the uptake and storage of $CO_2$ through various mechanisms, impacting the overall carbon balance in the oceans. This subchapter explores the exact $CO_2$ sequestration capacity of Posidonia oceanica, the distribution of carbon compounds within the ocean, and the differences observed in $CO_2$ concentrations across different ocean layers. Posidonia oceanica is a marine angiosperm that forms extensive underwater meadows along the Mediterranean coastline. These meadows act as important carbon sinks by efficiently sequestering atmospheric $CO_2$ through photosynthesis. The seagrass takes up $CO_2$ from the water column and converts it into organic matter, a process known as dissolved inorganic carbon (DIC) fixation. DIC consists of $CO_2$, bicarbonate ions ($HCO_3$-), and carbonate ions ($CO_3$ 2-). The exact CO2 sequestration capacity of Posidonia oceanica can vary depending on factors such as environmental conditions, meadow density, and biomass. Research conducted by Marbà et al. (2015) estimated that seagrass meadows can sequester approximately 6.7 metric tons of carbon per hectare per year. This value includes both above- and below-ground biomass, indicating the substantial potential of Posidonia oceanica in carbon storage.

In addition to DIC, the distribution of carbon compounds in the ocean is further characterized by dissolved organic carbon (DOC) and particulate organic carbon (POC). DOC refers to the fraction of carbon that exists in a dissolved form, such as dissolved sugars, amino acids, and other organic molecules. POC, on the other hand, represents carbon compounds that are associated with solid particles, including phytoplankton, zooplankton, and detritus. The concentration and distribution of these carbon compounds vary across different layers of the ocean. In surface waters, the highest concentrations of DIC, DOC, and POC are often observed due to the input of organic matter from primary production and external sources such as rivers. Deeper into the ocean, the concentration of DIC generally decreases, while DOC and POC levels tend to decrease more gradually. This vertical gradient in carbon distribution reflects the interplay between biological processes, physical mixing, and sinking particles. The differences in $CO_2$ concentrations across ocean layers are influenced by several factors, including biological activity, temperature, and pressure. In surface waters, where primary production is highest, the uptake of $CO_2$ through photosynthesis by marine plants, including seagrasses like Posidonia oceanica, leads to a decrease in $CO_2$ concentration. Conversely, deeper ocean layers often exhibit higher $CO_2$ concentrations due to the respiration of organic matter and reduced light availability for photosynthesis.

The process of carbon sequestration in Posidonia oceanica involves not only the absorption of dissolved $CO_2$ in the water column, but also its functioning as a biological pump. Posidonia oceanica and other vegetation represent an important and relatively recent addition in the discussion about carbon sinks. The biological pump involves the transfer of carbon from the surface ocean to the deep ocean, through the sinking of organic matter and its subsequent storage of carbon in sediments.

## 2.3 Methods to Combat Ocean Acidification

To address the issue of ocean acidification, various mitigation strategies, such as reducing $CO_2$ emissions and sequestering carbon in marine ecosystems, have been proposed (Turley and others, 2010; Gao and Xu, 2018). In this chapter, I will discuss how different methods can be used to combat ocean acidification, that directly influence the marine ecosystem. This is relevant for the thesis as it provides an overview over other possible methods to combat ocean acidification and to stress the importance of restoring Posidonia oceanica as a functioning biological method.

### 2.3.1 Artificial Reef Construction

Artificial reefs can help mitigate ocean acidification in several ways. First, they provide a hard substrate for the attachment and growth of marine organisms, such as corals or other marine structures, which can help increase the absorption of atmospheric $CO_2$ through photosynthesis (Byrne et al., 2018). This increases the carbon sink potential of coastal marine ecosystems.

Second, artificial reefs can act as buffers by releasing calcium carbonate, which can help counteract the decrease in pH caused by ocean acidification (Diaz, Nestlerode and Diaz, 2017). They provide an additional buffer for ocean acidification and the introduction of $CO_2$ into the ocean. The higher the buffer potential of an ecosystem, the more mitigation and rebound potential it has, which balances the overall effects of $CO_2$ emissions.

Third, artificial reefs can provide a refuge for vulnerable species that may be adversely affected by ocean acidification (Byrne et al., 2018). Several studies have investigated the potential of artificial reefs as a tool to mitigate the impacts of ocean acidification. For example, a study by Diaz et al. (2017) found that artificial reefs constructed from waste materials, such as concrete and ceramic tiles, increased the pH of surrounding seawater by up to 0.3 units, which could help offset the effects of ocean acidification. Conversely, by Potts et al. (2014) found that artificial reefs constructed from calcium carbonate-rich minerals, such as limestone and dolomite, could help counteract the decrease in pH caused by ocean acidification. However, the effectiveness of artificial reefs in mitigating ocean acidification may depend on several factors, including the type of reef construction, the materials used during the process, and the environmental conditions in the region of the reef (Byrne et al., 2018). For example, artificial reefs that are designed unsuitable for the region or constructed from materials of lower quality may have little or no mitigation potential regarding ocean acidification (Krieger *et al.*, 2018). In addition, artificial reefs may have unintended and unforeseen consequences, like an alternation of local hydrodynamics, which may cause sedimentation, or introduce invasive species to the ecosystem (Baine *et al.*, 2017). Another study by Kuffner et al. (2017) investigated the potential of artificial reef structures to alleviate the negative effects of ocean acidification. The researchers conducted a three-year field experiment in the Florida Keys to determine the influence of reef structure and location on carbonate chemistry. The study found that artificial reef structures, particularly those with complex topography and greater surface area, can enhance local alkalinity and thus increase the pH of surrounding waters. This effect was observed to be stronger in areas with higher rates of biological activity, as the biological processes associated with the reefs can further enhance alkalinity.

The use of artificial reefs to mitigate ocean acidification has also been explored in other parts of the world. In the coastal waters of Japan, for example, the construction of artificial reefs has been shown to increase local fish populations and enhance the buffering capacity of seawater against acidification (Ishimatsu, Hayashi and Kikkawa, 2014). Similarly, a study by Manzello et al. (2012) in the Caribbean found that artificial reefs made of limestone rubble can enhance local pH by increasing alkalinity through the dissolution of calcium carbonate.

In addition to their potential to enhance seawater chemistry, artificial reefs also provide critical habitat for marine organisms. In a previous study by Kuffner et al. (2013), artificial reefs were found to harbour a greater diversity and abundance of marine life compared to natural reefs. The study suggests that artificial reefs may serve as a refuge for marine organisms that are negatively impacted by ocean acidification and other stressors. The results of these studies may be promising, but there are still limitations and challenges associated with the use of artificial reefs as a method of mitigating ocean acidification. The effectiveness of artificial reefs may vary depending on factors such as their design, location, and maintenance. Furthermore, the long-term impacts of artificial reefs on marine ecosystems and seawater chemistry are still not well understood. Despite these challenges, artificial reefs show promise as a tool to mitigate the impacts of ocean acidification. Further research is needed to optimize the design and construction of artificial reefs for this purpose, and to evaluate the long-term effectiveness of artificial reefs in mitigating the impacts of ocean acidification (Byrne *et al.*, 2018; Potts, Henley and Widdicombe, 2014).

In conclusion, the physical ocean acidification method of artificial reef construction seems promising under certain circumstances. The construction of artificial reefs with a complex topography and greater surface area has been shown to enhance local alkalinity and increase the pH of surrounding waters. Furthermore, artificial reefs can provide critical habitats for various marine organisms and may serve as a refuge for those negatively impacted by ocean acidification and excessive carbon intake. However, more research is needed to fully understand the effectiveness of artificial reefs as a mitigation strategy and to address the potential limitations and challenges associated with their use.

### 2.3.2 Restoration of Marine Forests

Parallel to the reef construction, restoring marine forests has emerged as a promising method to mitigate the effects of ocean acidification on marine ecosystems. Marine forests, such as kelp forests, seagrass meadows, and mangrove forests, play a crucial role in sequestering carbon and regulating the pH of surrounding water bodies (Duarte, Hendriks, *et al.*, 2013). With the rise in atmospheric $CO_2$ levels, these ecosystems have become vulnerable to the detrimental effects of ocean acidification (Hendriks, Duarte and Álvarez, 2014). Physical restoration of marine forests offers an effective means of combating the effects of ocean acidification by enhancing the carbon sequestration potential and pH regulation capacity of these ecosystems. Marine forests are highly productive ecosystems that provide habitat and food for a diverse range of marine organisms (Cavanaugh *et al.*, 2014). However, as these regions are declining rapidly in their size and healthiness due to ocean acidification, which reduces the availability of carbonate ions that are essential for shell-forming organisms also the photosynthesis of primary producers is hindered (Cai *et al.*, 2011). Physical restoration of marine forests has been shown to enhance the photosynthesis and carbon sequestration capacity of these ecosystems, thus improving their overall health and resilience to the impacts of ocean acidification (Cavanaugh *et al.*, 2014).

One of the most effective physical restoration methods for marine forests is transplantation. This involves the manual relocation of fragments or whole plants of the target species to degraded or damaged areas, where they can establish new populations and restore ecosystem function (Bulleri and Chapman, 2010). Transplantation has been successfully used to restore seagrass meadows, kelp forests, and mangrove forests in various regions of the world (McLeod, Chmura, Bouillon, Salm and Björk, 2011; Nielsen *et al.*, 2014; Serrano *et al.*, 2016).

The use of artificial structures such as coral nurseries, artificial reefs, and oyster reefs. These structures can enhance the recruitment and growth of target species, provide refuge and habitat for associated fauna, and improve ecosystem function and resilience (Bayraktarov *et al.*, 2016). For example, the use of artificial reefs has been shown to enhance the recruitment and growth of coral species, thus restoring degraded coral ecosystems, and mitigating the impacts of ocean acidification (Hock *et al.*, 2017).

Additionally, to the use of artificial structures, the transplantation of seagrass meadows has deemed to be particularly successful in restoring ecosystem function and mitigating the effects of ocean acidification. Seagrass meadows are among the most productive and efficient carbon sequestration ecosystems on the planet (Duarte, Losada, *et al.*, 2013). As, Posidonia oceanica meadows have been declining due to various anthropogenic activities such as dredging, coastal development, and eutrophication (Orth *et al.*, 2006), there have been efforts to counteract these developments. For example, the transplantation of seagrass meadows has been shown to be an effective method for restoring degraded or damaged seagrass ecosystems. Transplanted seagrass meadows have been found to sequester carbon at rates comparable to those of natural meadows, indicating their potential to mitigate the effects of ocean acidification (McLeod, Chmura, Bouillon, Salm, Björk, *et al.*, 2011). Posidonia oceanica is only one kind of sea grass where efforts have been shown to restore it, which will be discussed later on.

In conclusion, physically restoring marine forests in their variety seems to be an effective method of countering the effects of ocean acidification and its symptoms. Transplantation and the use of artificial structures have been discussed as having great potential in restoring degraded or damaged marine ecosystems and enhancing the carbon sequestration and pH regulation capacity of the system. However, further research is needed to better understand the long-term impacts of the restoration process as it may enhance invasive species and decrease the biodiversity in the region (Lopez-Mosquera *et al.*, 2019).

### 2.3.3 Ocean fertilization

Not only the use of physical mitigation methods, but also the use of chemical properties of the ocean and pH reducing mechanisms can be used to address ocean acidification.

Enhancing ocean alkalinity through ocean fertilization with minerals like iron or silica to promote phytoplankton growth. As mentioned before, phytoplankton, using photosynthesis, increases the oxygen levels and therefore the pH-level. This method aims to increase the capacity of the ocean to absorb $CO_2$ and reduce the acidity of seawater. Adding minerals and the connected increase of the number of phytoplankton not only removes $CO_2$ from the atmosphere but also increases the pH of the surrounding seawater, thereby reducing ocean acidification. Iron and silica are two of the most used minerals for ocean fertilization, as they are essential nutrients for phytoplankton growth. A study conducted by Lenton and Vaughan (2009), suggests that the application of iron fertilization in the Southern Ocean could potentially sequester as much as 1.3 billion tons of carbon per year which is the $CO_2$ emitted by China per year, therefore greatly decreasing the carbon surplus. Another study by Lovenduski et al. (2016) examined the impact of iron fertilization on the marine carbon cycle and found that it can enhance the uptake of atmospheric $CO_2$ by the ocean, leading to a reduction in the amount of $CO_2$ in the atmosphere.

However, there are also potential risks associated with ocean fertilization. One major concern is that it may lead to the growth of harmful algae blooms, which can have negative impacts on marine ecosystems and human health. Algae blooms are the exponential increase of algae in a region, which not only imbalances the ecosystem but also hinders other marine life from getting enough oxygen. Another concern is that the long-term effects of ocean fertilization are still largely unknown, as the process is still quite undeveloped and there is a risk that it may have unintended consequences such as changes in ocean circulation or the composition of marine communities(González-Dávila *et al.*, 2016). Despite the potential benefits of ocean fertilization, there are also ethical and legal considerations that need to be considered. For example, the use of this method could raise questions about ownership of the ocean and the potential for exploitation by wealthy nations or corporations (Miller, Saito and Deutsch, 2008). It is difficult for unanimous treatment of international oceans, which is why the mitigation of ocean acidification is such a large-scale and long-during issue.

In conclusion, ocean fertilization with minerals such as iron or silica is a promising approach to combat ocean acidification. However, it is important to carefully consider the potential risks and benefits of this method, as well as its ethical and legal implications. Further research is needed to better understand the long-term impacts of ocean fertilization on marine ecosystems and the global carbon cycle, as well as to develop effective regulations to ensure the responsible use of this method on a large scale.

#### *2.3.3.1 Limestone addition*

The addition of limestone also has been proposed as a solution to ocean acidification. Limestone addition aims to raise the pH of seawater, which can help to offset the effects. Limestone addition is a chemical method used to increase the alkalinity of seawater, thereby reducing the acidity caused by the absorption of atmospheric $CO_2$. The process involves adding crushed limestone to seawater, which reacts with $CO_2$ to form bicarbonate and carbonate ions, ultimately increasing the alkalinity of the water. The bicarbonate and carbonate ions then react with the excess hydrogen ions in the water, reducing its acidity.

1. $CO_2\ (g) + H_2O\ (l) \rightleftharpoons H_2CO_3\ (aq)$
2. $CaCO_3\ (s) + H_2CO_3\ (aq) \rightarrow Ca(HCO_3)_2\ (aq) + CO_2\ (g)$

Studies have shown that limestone addition can effectively increase the pH of seawater and reduce its acidity (Chen *et al.*, 2019). Limestone addition also has been found to have positive effects on various marine organisms, including corals, shellfish, and calcifying plankton, which just as the reforestation method succeeds in a positive feedback loop and the overall balancing of the chemical and biological composition of marine life. For example, a study conducted in Australia found that limestone addition increased the growth rate of corals and improved their overall health and survival (Cook *et al.*, 2016). Similarly, another study found that the addition of crushed limestone to shellfish aquaculture systems improved the growth and survival of oysters, clams, and mussels (Gazeau *et al.*, 2018). Moreover, research has shown that limestone addition can increase the growth and productivity of phytoplankton, which are essential to the food chain of many marine ecosystems (Kline et al., 2018), and again for the increase of ocean pH.

Despite the positive effects of limestone addition on marine ecosystems, some scholars have raised concerns about the long-term effects of this method as it may also increase the levels of dissolved inorganic carbon (DIC) in seawater, which could lead to the growth of non-calcifying phytoplankton species and reduce the diversity of marine life (Brennan et al., 2018). Additionally, the long-term effects of limestone addition on marine biodiversity are not yet fully understood, and further research is needed to assess the potential risks and benefits of this method (Hendriks, Duarte and Álvarez, 2018). The methods and potential effects need to be evaluated intensively before implementing them. Due to this reason, choosing the potentially least invasive method is crucial. The evaluation of the methods in their effectiveness is of utmost importance to not further the decrease of biodiversity in marine life.

Research on the effectiveness of limestone addition in combating ocean acidification is still in its early stages, and there is much that is not yet understood about the process and the potential effects. Despite the potential benefits of limestone addition, some researchers and conservationists have expressed concerns about its long-term effectiveness and potential negative impacts on marine ecosystems. Some studies have reported positive effects of limestone addition on marine ecosystems, while others have shown no significant benefits or even negative effects (Hendriks, Duarte and Álvarez, 2018). Others suggest that the dissolution of limestone particles may release metals and other contaminants into the surrounding water, leading to toxicity issues and further environmental damage (Ivanina, Sukharov and Sokolova, 2017). One study even found that limestone addition may have a limited impact on reducing ocean acidification on a global scale, as the amount of limestone required would be prohibitively large, reducing the relevance of the method as a single solution to ocean acidification (Petersen, Holmer and Duarte, 2018). Moreover, the cost-effectiveness of limestone addition as a method for combatting ocean acidification has not yet been fully assessed, which would be also a factor in the implementation process on the international level.

Furthermore, it is important to note that limestone addition alone may not be sufficient in combatting ocean acidification. Other strategies, such as reducing carbon emissions and promoting renewable energy sources, must also be implemented to address the main cause of the problem and the climate crisis. In addition, it is crucial to consider the economic and logistical feasibility of implementing large-scale limestone addition projects, particularly in remote or ecologically sensitive areas. Despite these challenges, limestone addition remains a promising strategy in the fight against ocean acidification. With ongoing research and development, it may become a viable option for protecting vulnerable marine ecosystems and supporting the industries that depend on them.

### 2.3.4 Social methods

Not only externally introduced and additive methods can be used to mitigate ocean acidification, but also different behaviours, strategies and an increased awareness of the problem are feasible strategies. In this section, I will present different strategies on how behavioural changes can be effective in regards of ocean acidification.

#### *2.3.4.1 Sustainable fishing and aquaculture practices*

Sustainable fishing and agriculture practices have been suggested as a potential solution to mitigate ocean acidification and its impact on marine ecosystems (Duarte, Losada, *et al.*, 2013). This section will examine the effectiveness and feasibility of these practices on an international level. Sustainable fishing practices can help reduce the impact of ocean acidification by promoting healthy marine ecosystems. Overfishing can lead to the decline of important species in the food web, resulting in a decrease in their natural predators and an increase in their prey, including organisms that are susceptible to ocean acidification (Halpern *et al.*, 2015). Sustainable fishing practices, such as limiting fishing quotas and implementing fishing gear that minimizes bycatch, can help maintain a healthy marine ecosystem and ensure that the ocean can absorb more $CO_2$ (Duarte, Losada, *et al.*, 2013).

In addition to sustainable fishing practices, sustainable agriculture practices can also play a role in mitigating ocean acidification. Agriculture contributes to ocean acidification through the release of nitrogen and phosphorus from fertilizers that stimulate the growth of algae, which, when they die, are consumed by bacteria that release $CO_2$ (Gattuso *et al.*, 2015). Sustainable agriculture practices, such as reducing fertilizer use, improving irrigation efficiency, and promoting crop rotation, can help reduce the amount of nitrogen and phosphorus runoff and thus the amount of $CO_2$ released into the atmosphere and absorbed by the ocean (Duarte, Losada, *et al.*, 2013). While both sustainable fishing and agriculture practices show promise in mitigating ocean acidification, their effectiveness and feasibility on an international level depend on several factors. One such factor is the political will and commitment of governments to implement and enforce sustainable practices (Pihlajamäki *et al.*, 2017). This requires a shared understanding of the importance of marine conservation and the willingness to make long-term investments in sustainable fishing and agriculture practices. Another factor is the economic cost of implementing these practices, which may be higher than traditional methods in the short term. However, the long-term benefits, such as increased productivity and resilience, may outweigh the costs (Duarte, Losada, *et al.*, 2013). The feasibility of sustainable fishing and agriculture practices on an international level also depends on the local context and the specific challenges faced by different regions. For example, some regions may face more significant challenges in implementing sustainable agriculture practices due to their unique climate and soil conditions (Halpern *et al.*, 2015). Similarly, sustainable fishing practices may be more challenging to implement in regions where fishing is a critical source of income and livelihoods (Pihlajamäki *et al.*, 2017).

In conclusion, sustainable fishing and agriculture practices offer a potential solution to mitigate the impact of ocean acidification on marine ecosystems. Sustainable fishing practices can help promote a healthy marine ecosystem and reduce $CO_2$ absorption, while sustainable agriculture practices can reduce the amount of nitrogen and phosphorus runoff that contributes to ocean acidification. However, their effectiveness and feasibility on an international level depend on several factors, including political will, economic cost, and regional context. Further research is needed to explore these factors and develop effective and feasible strategies for mitigating the impact of ocean acidification on a global scale.

### 2.3.5 Industrial Methods

This chapter explores industrial methods such as Carbon Capture and Storage (CCS) and the use of alternative materials and eco-friendly processes in mitigating ocean acidification. Carbon Capture and Storage (CCS) technology is an effective approach to reducing $CO_2$ emissions from large industrial sources, which is quite similar to the biological carbon sequestration process by marine vegetation. This method involves capturing $CO_2$ emissions from power plants and other industrial facilities before they are released into the atmosphere. Instead, the captured $CO_2$ is stored underground in geologic formations (Leung, Caramanna and Maroto-Valer, 2014). By preventing $CO_2$ from entering the atmosphere, CCS helps limit the amount of $CO_2$ absorbed by the ocean, thereby mitigating ocean acidification. Recent advancements in CCS technology have made it a more feasible option for large-scale implementation. In addition to CCS, the use of alternative materials in industrial processes can significantly reduce $CO_2$ emissions and mitigate ocean acidification. The cement industry, for instance, is a major contributor to $CO_2$ emissions due to the production of Portland cement clinker, a key ingredient in concrete (Andrew, 2018). By substituting traditional cementitious materials with low-carbon alternatives like fly ash or slag, $CO_2$ emissions from the cement industry can be significantly reduced (Scrivener, John and Gartner, 2018). This shift towards alternative materials not only helps mitigate ocean acidification but also contributes to overall sustainability in the construction sector.

Technological advancements in CCS have been significant in recent years. The development of more efficient and cost-effective carbon capture technologies has made CCS a viable option for large-scale implementation (Leung, Caramanna and Maroto-Valer, 2014). However, challenges related to the storage and transportation of captured $CO_2$ still need to be addressed to ensure the safe and sustainable implementation of CCS. The use of alternative materials in industrial processes, such as low-carbon cementitious materials, requires further research and development. The availability and suitability of these materials need to be assessed, considering factors such as their performance, cost, and environmental impact. Additionally, the acceptance and adoption of alternative materials by industries and regulatory bodies are essential for successful implementation. Furthermore, the chemical industry plays a vital role in industrial $CO_2$ emissions. Adopting eco-friendly processes, such as green chemistry, can be a valuable strategy in mitigating ocean acidification. Green chemistry aims to minimize the environmental impact of chemical processes by designing products and processes that reduce or eliminate the use and generation of hazardous substances (Anastas and Warner, 1998). By implementing green chemistry principles, the chemical industry can reduce its carbon footprint and contribute to the mitigation of ocean acidification.

The implementation of these industrial methods to mitigate ocean acidification requires a comprehensive evaluation of their effectiveness and feasibility. Key aspects to consider include technological advancements, economic viability, and environmental impact. These methods must be carefully assessed for their potential benefits and drawbacks to ensure that they provide long-term solutions to the problem of ocean acidification.

Financial considerations are also significant when evaluating the feasibility of these industrial methods. The costs associated with implementing CCS, using alternative materials, and adopting eco-friendly processes need to be carefully analyzed. Economic incentives and government support can play a crucial role in encouraging industries to invest in these mitigation strategies.

Furthermore, the environmental impact of these methods must be thoroughly assessed. While CCS has the potential to reduce $CO_2$ emissions and mitigate ocean acidification, the storage of captured $CO_2$ in geologic formations requires careful monitoring to prevent any unintended leakage or environmental harm (Leung, Caramanna and Maroto-Valer, 2014). It is essential to consider the long-term stability and integrity of storage sites to ensure the effectiveness of CCS as a mitigation strategy.

Similarly, the use of alternative materials in industrial processes should undergo life cycle assessments to evaluate their overall environmental footprint. Although these materials may offer reduced $CO_2$ emissions during production, their extraction, processing, and disposal should be carefully managed to minimize any negative ecological impacts (Scrivener, John and Gartner, 2018). Additionally, the availability and sourcing of alternative materials must be evaluated to ensure sustainable practices that do not lead to other environmental concerns, such as habitat destruction or resource depletion.

To assess the effectiveness of these industrial methods in mitigating ocean acidification, comprehensive monitoring and evaluation programs are necessary. Long-term studies should be conducted to measure the actual reduction in $CO_2$ emissions and the subsequent impact on ocean pH levels and carbonate chemistry. Monitoring the health and abundance of marine organisms, such as calcifying organisms that are particularly vulnerable to ocean acidification, can provide valuable insights into the success of mitigation efforts. These monitoring programs should encompass a wide range of geographical regions and include both controlled experimental settings and real-world applications.

In conclusion, industrial methods such as Carbon Capture and Storage (CCS), the use of alternative materials, and the adoption of green chemistry practices have the potential to significantly mitigate ocean acidification resulting from $CO_2$ emissions. These methods require careful evaluation of their technological feasibility, economic viability, and environmental impact. They serve as an alternative to biological methods if their effectiveness has been diminished due to human influences. Collaboration between industry, academia, and policymakers is essential to drive research and development, promote sustainable practices, and create the necessary incentives for industries to adopt these mitigation strategies.

Continued monitoring and research are crucial to assess the long-term effectiveness of these methods in mitigating ocean acidification. By implementing and refining these industrial methods, we can strive to reduce $CO_2$ emissions, limit ocean acidification, and preserve the health and biodiversity of marine ecosystems.

### 2.3.6 Social Methods to Mitigate Ocean Acidification

Using methods that engage people and the social plane in larger definition play a crucial role in mitigating ocean acidification by engaging the public and raising awareness of the issue. Through education and promoting sustainable behaviors, societies can mobilize collective action and drive positive change.

One effective approach to raising awareness of ocean acidification is through public education campaigns. These campaigns aim to inform individuals about the causes, consequences, and urgency of ocean acidification. Utilizing various media platforms such as television, radio, print, and social media, these campaigns can effectively reach a wide audience and disseminate information (Gattuso *et al.*, 2015). By increasing public knowledge and understanding, these campaigns can help shift public opinion, generate support for policy changes, and encourage individuals to take action.

In addition to education campaigns, promoting sustainable consumption habits is another important social method to mitigate ocean acidification. Encouraging individuals to adopt environmentally friendly behaviors in their daily lives can contribute to reducing $CO_2$ emissions, the main driver of ocean acidification. For example, promoting reduced meat consumption can help decrease the demand for livestock production, which is a significant source of greenhouse gas emissions (Girod, van Vuuren and Hertwich, 2013). Similarly, advocating for energy conservation practices and the use of public transportation can reduce carbon emissions associated with energy consumption and transportation sectors.

Moreover, fostering sustainable practices in various industries and sectors can significantly contribute to mitigating ocean acidification. For instance, engaging businesses and industries in adopting environmentally friendly practices, such as reducing their carbon footprint, implementing sustainable waste management systems, and investing in renewable energy sources, can have a substantial impact on reducing $CO_2$ emissions (Hoegh-Guldberg *et al.*, 2019). Collaborative initiatives between governments, businesses, and civil society organizations can promote sustainable practices and drive systemic changes towards a low-carbon and environmentally conscious economy.

Social methods to mitigate ocean acidification also involve fostering community engagement and empowering local communities. By involving communities that depend on marine resources for their livelihoods, such as fishermen and coastal communities, in decision-making processes, their knowledge and experiences can contribute to more effective and locally relevant solutions. Local initiatives, such as community-based marine protected areas or sustainable fishing practices, can be implemented with the active participation and support of local communities, leading to more sustainable and resilient marine ecosystems (Cinner, Daw and McClanahan, 2009).

Furthermore, collaboration and partnerships between different stakeholders, including scientists, policymakers, non-governmental organizations (NGOs), and local communities, are essential for successful mitigation efforts. These partnerships can facilitate the exchange of knowledge, resources, and expertise, leading to more comprehensive and effective solutions. By working together, stakeholders can develop innovative strategies, share best practices, and advocate for policy changes that prioritize the protection and restoration of marine ecosystems.

In conclusion, social methods play a vital role in mitigating ocean acidification by engaging the public, raising awareness, and promoting sustainable behaviors. Education campaigns can inform individuals about the issue and inspire action, while promoting sustainable consumption habits can contribute to reducing $CO_2$ emissions. Engaging businesses, industries, and local communities, as well as fostering collaboration between stakeholders, are crucial for driving systemic changes and implementing sustainable practices. By combining social methods with scientific and policy efforts, we can work towards a more resilient and sustainable future for our oceans.

### 2.3.7 Economic and Political Methods to Mitigate Ocean Acidification

Ocean acidification is a complex issue that requires a comprehensive approach involving various economic and political methods. These methods aim to create incentives and policies that promote the reduction of $CO_2$ emissions, which is the primary driver of ocean acidification.

At the national level, governments play a crucial role in implementing policies to mitigate $CO_2$ emissions. One effective method is the implementation of carbon pricing mechanisms, such as carbon taxes or cap-and-trade systems. These mechanisms create economic incentives for industries and individuals to reduce their carbon footprint by imposing a cost on $CO_2$ emissions (Stiglitz, Sen and Fitoussi, 2009). Additionally, governments can provide incentives and subsidies for renewable energy sources, such as solar and wind power, to promote their adoption and reduce reliance on fossil fuels. Energy-efficiency standards for buildings, vehicles, and industrial processes can also contribute to reducing $CO_2$ emissions.

Internationally, countries can collaborate through multilateral agreements and initiatives to address ocean acidification. The Paris Agreement, adopted in 2015 under the United Nations Framework Convention on Climate Change (UNFCCC), sets a global goal to limit global warming to well below 2°C above pre-industrial levels (UNFCCC, 2015). Achieving this goal would significantly mitigate the impacts of ocean acidification by reducing the amount of $CO_2$ entering the atmosphere.

Economic instruments and financial mechanisms can also play a crucial role in addressing ocean acidification. The Green Climate Fund, established under the UNFCCC, provides financial support to developing countries for climate change mitigation and adaptation projects (Green Climate Fund, 2021). This fund can support initiatives that help countries transition to low-carbon economies and implement strategies to mitigate the impacts of ocean acidification.

Furthermore, public awareness and engagement are vital components of addressing ocean acidification. Social methods involve educating the public about the causes and consequences of ocean acidification and promoting sustainable behaviors. Public education campaigns, utilizing various media platforms, can raise awareness and mobilize collective action (Gattuso *et al.*, 2015). Encouraging sustainable consumption habits, such as reducing meat consumption, conserving energy, and using public transportation, can contribute to reducing $CO_2$ emissions and mitigating ocean acidification (Girod, van Vuuren and Hertwich, 2013).

In conclusion, mitigating ocean acidification requires a combination of economic and political methods at national and international levels. By implementing policies, creating incentives, promoting renewable energy, raising public awareness, and providing financial support, we can work towards reducing $CO_2$ emissions and safeguarding the health and functioning of our oceans. Collaboration and cooperation among nations are essential to effectively address this global challenge and protect the future of our marine ecosystems.

## 2.4 Overview of Posidonia Oceanica

Posidonia oceanica is a seagrass species that is endemic to the Mediterranean Sea, where it forms extensive meadows in shallow coastal waters (Ruiz *et al.*, 2019). It is considered one of the most important species of seagrass due to its ecological and economic significance. In this chapter, I will discuss the biological and ecological aspects of Posidonia oceanica, and the challenges associated with its conservation and management. Posidonia oceanica, also called Neptungras, is a perennial plant that grows on sandy or muddy bottoms in the coastal regions of the Mediterranean Sea, where it forms large meadows that can reach depths of up to 40 meters. The plant has a horizontal rhizome system that anchors it to the sediment and produces a vertical shoot that can reach up to one meter in height. The leaves are ribbon-like and can be up to one meter long. The plant has different compartments, which differs it from algae. Just like other types of grass it has roots, leaves, and a trunk to connect it whereas algae need suction plates and solid structures to grow on. It has a reproductive cycle of seven years and produces flowers and seeds, but it primarily asexually through the rhizome system. It extracts the seeds, which then float to the surface, releasing an oil. At the surface, they have a 1-3% chance of survival. Large numbers of seeds get stranded, which then can be picked up and planted manually, which increases the survival rate to over 90% (Marinelli, personal communication, 2023).

*Figure 2: Sea grass meadow close up*

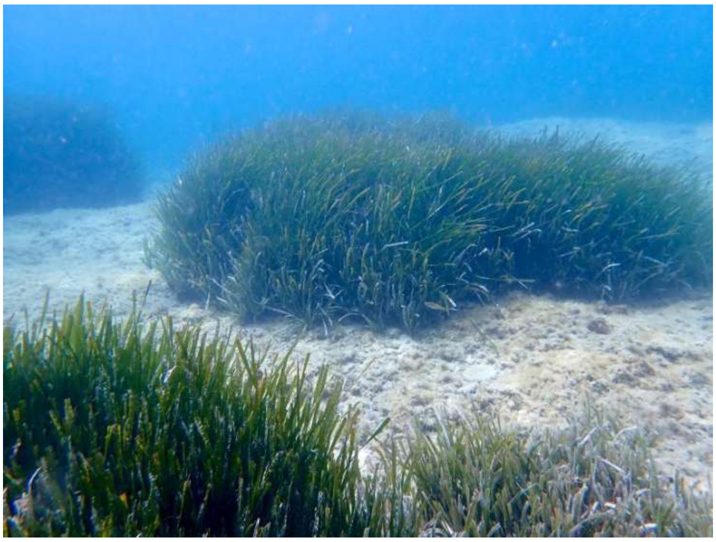

*Figure 3: Sea grass meadow*

It is a long-lived plant that can survive for several decades, sometimes even centuries, and plays a crucial role in Mediterranean coastal ecosystems by providing habitat, supporting biodiversity, and contributing to carbon sequestration (Marbà, Duarte, *et al.*, 2014).

Table 1: Posidonia oceanica distribution in the Mediterranean Sea (Telesca *et al.*, 2015)

| | **Mediterranean Sea** | **Western basin** | | **Eastern basin** | |
|---|---|---|---|---|---|
| **Coastline length (km)** | 46,000 | 11,621 | 25% | 34,379 | 75% |
| **Coastline length with *P. oceanica* (km)** | 11,907 | 6,201 | 14% | 5,706 | 12% |
| **Coastline length without *P. oceanica* (km)** | 12,622 | 3,925 | 9% | 8,697 | 19% |
| **Coastline length without data (km)** | 21,471 | 1,494 | 3% | 19,977 | 43% |
| **Total area of *P. oceanica* (ha)** | 1,224,707 | 510,715 | 41.7% | 713,992 | 58.3% |

The ecological importance of Posidonia oceanica lies in its role as a foundation species that provides a habitat for a diverse community of organisms. The meadows support a high abundance and diversity of fish and invertebrates, including commercially important species such as sea bream and octopus (Marbà, Arias-Ortiz, *et al.*, 2015). It is a foundation species that creates complex habitats that support high biodiversity and biomass, providing food, shelter, hunting, and nursery grounds for a wide range of fish and invertebrate species (Garrabou *et al.*, 2019). Its leaves, which are rich in carbon, also contribute to the sequestration of atmospheric carbon dioxide and the storage of organic carbon in sediments, making it an important player in the global carbon cycle and the fight against climate change (Favery *et al.*, 2013). The carbon gets stored in the rhizome, where it remains even after the plant has died. It therefore is a long-lasting and very effective carbon sink. The plant also plays an important role in the carbon and nitrogen cycles of marine ecosystems. It is estimated that Posidonia oceanica meadows sequester up to 7% of the carbon fixed in the Mediterranean Sea, making it a significant contributor to the mitigation of climate change (Duarte, Hendriks and Moore, 2010). Additionally, the plant's root system helps to stabilize sediments and prevent erosion, which is particularly important in areas with high wave energy. Posidonia oceanica as a key species for the Mediterranean Sea, provides a wide range of ecological., economic, and cultural services (Mannino, Calvo and La Mantia, 2020). However, it is threatened by multiple stressors, including coastal development, overfishing, eutrophication, and climate change, which have led to significant declines in its abundance and distribution over the past few decades (Marbà and Duarte, 2010). From an economic perspective, Posidonia oceanica is a source of income and employment for many coastal communities, particularly in the tourism and fisheries sectors (Balestri, Gennaro and Acunto, 2018). It provides aesthetic and recreational values, such as swimming, diving, and boating, and supports traditional artisanal fishing practices that are part of the Mediterranean cultural heritage (Katsanevakis *et al.*, 2012). Moreover, it has the potential to generate new economic opportunities through the development of sustainable aquaculture practices, the production of biofuels and bioplastics (Patti, Jackson and Rose, 2018), and the provision of ecosystem services such as carbon sequestration and coastal protection (Santana-Garcon, Roca and Barbera, 2018). The seagrass is also known for its high production of oxygen and its ability to reduce sediment erosion. The plant's leaves slow down the water currents, which reduces the sediment erosion caused by the flow of water (Marbà, Holmer, *et al.*, 2014). Furthermore, the seagrass beds provide a habitat for many species, including commercially important fish, invertebrates, and endangered species such as sea turtles and seahorses (Lirman and Cropper, 2003).

However, Posidonia oceanica is facing various threats, including overfishing, coastal development, pollution, and climate change (Buia, Gambi and Zupo, 2016). In particular, ocean acidification is a significant threat to seagrass meadows and marine ecosystems worldwide (Martin, Diaz-Almela and Grau, 2013). As carbon dioxide levels increase in the ocean, the pH decreases, making the water more acidic. This can have negative impacts on seagrass growth and survival (Hall-Spencer et al., 2008). Unfortunately, there has been a vast loss of vegetated coastal ecosystems during the past years due to anthropogenic interference, chemical imbalances and high emissions. Despite these challenges, there have been efforts to restore Posidonia oceanica meadows in areas where they have been damaged or lost. For example, in the Mediterranean Sea, seagrass restoration projects have been continuously reintroducing it in areas where the seafloor has been disturbed by human activities (Marbà and Duarte, 2010). These efforts have included transplanting seagrass shoots and monitoring the success of restoration efforts over time. This is one of the processes where the research project comes into place, which will be further elaborated on in the next chapter.

Overall, the role of Posidonia oceanica in the mitigation of ocean acidification is an important area of research. By better understanding how seagrass can help to mitigate the impacts of ocean acidification, we can work towards preserving and restoring seagrass meadows in areas where they have been lost or damaged. Furthermore, exploring the use of seagrass in combination with other technologies and methods, such as artificial reefs and underwater cultures, can help to maximize the effectiveness of using seagrass to combat ocean acidification (Unsworth *et al.*, 2019).

# 3 Methodology

In the following chapter, I will elaborate on the methodology used in the thesis. The chapter will be structured as follows: in the first section the overall research design and approach is introduced. This I followed by possible ethical considerations and potential impacts of the study being done as well as joining the research vessel.

## 3.1 Research design and approach

The research design and approach for this study involve a mixed methods approach, which includes a literature review of pre-existing data and research. The literature review will involve conducting a comprehensive review of available literature on the importance of Posidonia oceanica in the mitigation of ocean acidification and its impact on marine ecosystems. Academic online databases were used to gather peer-reviewed literature available until April 2023 by following a complex search string involving specific keywords, combined with the evaluation of their specific relevance and possible new information. Grey literature has been included as an important source for research-relevant information. In addition to the literature review, ethnographic research will be conducted by taking part in the mitigation process and evaluating the effort and effectiveness of using seagrass to combat ocean acidification. This will include participating in a seagrass management and restoration project in collaboration with Project Manaia, a non-profit organization dedicated to protecting and restoring marine ecosystems and the conduction of an analytic review of the available data. The information provided during the research boat will be screened, evaluated in its correctness, and included as additional information to strengthen the points being made within the thesis. During the project, an analysis of the data collected during the last years on the sustainability, effectiveness, and mitigation potential of Posidonia oceanica will be completed. This analysis will aim to gain further insight into the effectiveness and sustainability of seagrass management and restoration efforts and will focus on aspects such as the challenges and opportunities of implementing seagrass management and restoration in different contexts, the best practices for seagrass management and restoration, such as water temperature, light availability, and sedimentation rates. Planting methods will be carefully selected to ensure the best possible survival rates, and monitoring protocols will be established to track the growth and survival of the seagrass over time. Data analysis will involve the use of statistical methods to assess the effectiveness and sustainability of seagrass management and restoration efforts.

Overall, this mixed-methods approach will allow us to gain a comprehensive understanding of the effectiveness and sustainability of seagrass management and restoration efforts for mitigating ocean acidification. We will be able to identify best practices and key challenges associated with these efforts and make recommendations for future research and policy action to promote the protection and restoration of seagrass ecosystems.

## 3.2 Ethical considerations

When doing experimental studies, especially externally of laboratories, there are ethical considerations to be aware of. One major concern was finding a research possibility that ensures sustainability and a non-invasive approach when doing the experiments as well as making up for the potential impacts on the environment. To counter these concerns, I have done a lot of research and chose Project Manaia as a research vessel. The project and each of its participants ensured that the research vessel used solar panels as electricity and energy provider. To ensure a minimal pollution into the marine environment, there was a wastewater repurposing system which completely eliminated all sources of pollution and only discharged water that was safe for the environment. There were several mechanisms on board that encouraged saving energy and water, to sustain an environmentally friendly experience. Another important aspect was that the research vessel paid specific attention to not anchoring in sea grass or other marine environments except for sand beds. Additionally, the motor was used for only 10% of the distance whereas the rest has been covered with sailing. On the research vessel, only vegan food was allowed to not increase our $CO_2$ footprint. The experiments were completed in a non-invasive way with materials and solutions that were then discharged into waste properly.

## 3.3 Reliability and validity

Ensuring the trustworthiness and genuineness of research is crucial for producing accurate and credible findings. This study recognizes the importance of thoroughly examining these aspects to guarantee the precision and believability of its results. In this segment, I will describe the methods employed to reduce possible bias and constraints. One potential form of bias is the principle of reporting favouritism, where studies with substantial findings are more likely to be published than those without significant results as they fit the expected outcomes of the study. To counteract this bias, a comprehensive search that includes both published and unpublished research without any preconceived outcomes exclusion criteria will be conducted. This specific approach ensures that all relevant studies, regardless of their findings, are included, thus reducing the risk of the occurrence of reporting bias.

## 3.4 Limitations of the study

Ensuring the trustworthiness and genuineness of research is crucial for producing accurate and credible findings. This study recognizes the importance of thoroughly examining these aspects to guarantee the precision and believability of its results. In this segment, I will describe the methods employed to reduce possible bias and constraints. One potential form of bias is the principle of reporting favouritism, where studies with substantial findings are more likely to be published than those without significant results as they fit the expected outcomes of the study. To counteract this bias, a comprehensive search that includes both published and unpublished research without any preconceived outcomes exclusion criteria will be conducted. This specific approach ensures that all relevant studies, regardless of their findings, are included, thus reducing the risk of the occurrence of reporting bias. Furthermore, measures will be taken to ensure validity, such as using standardized collection methods when pooling together diverse sets of data. This approach makes it easier to compare across varying datasets, ultimately yielding far superior results than before while still maintaining transparency regarding limitations.

Additionally, this study focuses solely on Posidonia oceanica, and other seagrass species may not share similarities, making the findings irrelevant elsewhere. Therefore, future research should take caution when applying the findings to other species or contexts, and appropriate policy action should occur safely and efficiently given the available knowledge structures.

# 4 RESULTS

## 4.1 OVERVIEW OF THE STATE OF POSIDONIA OCEANICA IN THE STUDY AREA

Due to its vast importance for the region and the balancing of the marine ecosystem, Posidonia oceanica has been a protected species for the most part of the last century with harsh consequences if impaired. According to Pergent et al. (2019), the current state of Posidonia oceanica in the Mediterranean Sea is a matter of concern. Despite being a key species for the coastal ecosystem, its populations have been declining rapidly over the past few decades. The authors report that the area covered by Posidonia meadows has decreased by 13.5% between 1996 and 2016, with the greatest losses observed in the western Mediterranean. This trend is attributed to a combination of anthropogenic impacts, including coastal development, pollution, and overfishing, as well as natural disturbances such as storms and disease outbreaks. The health of remaining meadows is also threatened by warming waters, ocean acidification, and the spread of invasive species (Migliaccio *et al.*, 2020). In light of these challenges, there is an urgent need for conservation efforts and effective management strategies to protect and restore Posidonia meadows in the Mediterranean Sea.

Table 2: Ovserved changes in areas covered by Posidonia oceanica meadows in the Mediterranean Sea between 1996 and 2020 (Marbà, Arias-Ortiz, *et al.*, 2015; Cormaci, Furnari et alongi, 2019; Greenpeace, 2020).

| **Region** | **1996 (km²)** | **2020 (km²)** | **% Change** | **Sources** |
|---|---|---|---|---|
| **Balearic Islands** | 248 | 208 | -16.1% | Marbà et al., 2015; Greenpeace, 2020 |
| **Ligurian Sea** | 10 | 3 | -70% | Cormaci et al., 2019; Greenpeace, 2020 |
| **Northern Adriatic Sea** | 20 | 5 | -75% | Cormaci et al., 2019; Greenpeace, 2020 |
| **Northwestern Mediterranean Sea** | 566 | 385 | -32.0% | Marbà et al., 2015; Greenpeace, 2020 |
| **Total** | 844 | 601 | -28.8% | |

The health and geographic distribution of Posidonia oceanica has been a topic of concern in the Mediterranean region. Recent studies have highlighted the importance of monitoring this seagrass species due to its ecological and economic value (Buia et al., 2019). According to several reports, Posidonia oceanica has experienced a decline in its coverage and health status in the Mediterranean Sea over the last few decades (Marbà and Duarte, 2010; Pergent et al., 2019). The causes of this decline are mainly related to human activities, such as coastal development, pollution, and overfishing (Pergent et al., 2019).
Table 2 presents data on the current status of Posidonia oceanica in the Mediterranean Sea, based on recent research. It is important to note that the information presented in this table is not exhaustive, as there are many ongoing studies on this species. Nevertheless, the data provides an overview of the current situation of Posidonia oceanica in the region.

Table 3: Current status of Posidonia oceanica in the Mediterranean Sea (Buia, Gambi and Pergent-Martini, 2019; Pergent-Martini, Buia and Gambi, 2019; Tsirika, Katsanevakis and Pergent-Martini, 2020)

| **Region** | **Health status** | **Coverage (%)** | **References** |
|---|---|---|---|
| **Balearic Islands** | Good | 45-55 | Buia et al. (2019) |
| **Sardinia** | Declining | 25-35 | Pergent-Martini et al. (2019) |
| **Sicily** | Declining | 30-40 | Pergent-Martini et al. (2019) |
| **Cyprus** | Good | 50-60 | Tsirika et al. (2020) |

As given in Table 2, the health status of Posidonia oceanica varies among regions, with some areas showing a decline in coverage and health status. For instance, Pergent-Martini et al. (2019) reported a decline in the coverage of Posidonia oceanica in Sardinia and Sicily, with values ranging from 25% to 35%. The authors also noted a decline in shoot density and leaf length. In contrast, Buia et al. (2019) reported good health status and coverage of Posidonia oceanica in the Balearic Islands, with coverage ranging from 45% to 55%.
In Cyprus, a recent study by Tsirika et al. (2020) reported good health status and coverage of Posidonia oceanica, with coverage ranging from 50% to 60%. The authors noted that the presence of this seagrass species is mainly concentrated in shallow waters, with a mean depth of 5.2 m.

During research over the last 8 years, the scientists on Project Manaia found similar results regarding the state of Posidonia oceanica. Over the last years, regular transect analysis have been done in different parts of the Mediterranean Sea, which can be seen in the appendix.

## 4.2 Experimental Part: Assessment of the Capacity of Posidonia Oceanica to Mitigate Ocean Acidification

### 4.2.1 Effect of Posidonia Oceanica on water pH

Seagrass beds have been shown to play an important role in mitigating the effects of ocean acidification by reducing the acidity of seawater through photosynthesis. This experiment investigated the ability of seagrass to mitigate the effects of ocean acidification by measuring the pH of seawater in areas with and without seagrass beds. Previous research has shown that seagrass beds can increase seawater pH by up to 0.3 units during the day and by up to 0.1 units at night (Duarte, Hendriks, *et al.*, 2013). Seagrass photosynthesis releases oxygen into the water, which can neutralize carbon dioxide and raise pH levels. Seagrass also produces bicarbonate ions during photosynthesis, which can buffer against the acidity of carbonic acid.

#### *4.2.1.1 Experimental Design*

The experiment was conducted in the northern Mediterranean Sea. Two sites were selected, one with a healthy seagrass bed and another without seagrass as a control.

Table 4: Places of measurement

| Place | Description | Date / Time | Temperature Air | Temperature Water | Plant density |
|---|---|---|---|---|---|
| 43,7871581 N 7,5598581 E | Bay of Ventimiglia, Latte (Italy) | 03.05.2023 10h30 | 19°C | 17°C | 80% |
| 43,7659748 N 7,7515639 E | South of Sanremo (Italy) | 03.05.2023 12h00 | 19°C | 16°C | 0 |

Water samples were collected from each site using water sampling bottles at a depth of 1m, at the same time of day to reduce any potential effects of diurnal variations. The pH of each water sample was measured using a pH meter that had been calibrated with standard solutions. Each sample was measured three times to ensure accuracy.

- Two study sites were selected, one with a healthy seagrass bed and one without seagrass.
- Water samples were collected using water sampling bottles at a depth of 1m from each site.
- The pH meter was calibrated with standard solutions according to the manufacturer's instructions.
- The pH of each water sample was measured using the pH meter. Each sample was measured three times.
- The mean pH values were calculated for each site and the difference in pH between the two study sites was determined.

#### *4.2.1.2 Expected Results*

Table 5: Expected pH levels (Koch *et al.*, 2013; Santos, Duarte, *et al.*, 2018; Pecorino *et al.*, 2019)

| Area | Posidonia oceanica | Expected pH-level |
|---|---|---|
| **43,7871581 N 7,5598581 E** | Yes | 8,2-8,5 |
| **43,7659748 N 7,7515639 E** | No | 8,0-8,3 |

#### *4.2.1.3 Measurements*

The mean pH values for the water samples collected from the site with seagrass and the control site without seagrass were 8,16 and 7,73 respectively. The difference in pH between the two study sites was 0,43. These results suggest that the presence of a healthy seagrass bed may have a mitigating effect on the acidity of seawater in the presence of ocean acidification.

Table 6: Measurements of pH levels

| Area | Posidonia oceanica | pH-measurements | | | Mean Value |
|---|---|---|---|---|---|
| **43,7871581 N 7,5598581 E** | Yes | 8,3 | 8,0 | 8,2 | 8,16 |
| **Gleiche Position?** | No | 7,8 | 7,8 | 7,6 | 7,73 |

The results of this study are consistent with previous research on the ability of seagrass to mitigate the effects of ocean acidification. Seagrass beds have been shown to increase pH levels in surrounding waters, and the results of this study suggest that this effect may be significant even in areas with high levels of ocean acidification. The role of seagrass in mitigating ocean acidification is of particular importance in coastal ecosystems, where seagrass beds are often found. These ecosystems provide a range of ecological services, including habitat for fish and other marine species, carbon sequestration, and shoreline stabilization (Cunha *et al.*, 2018). The ability of seagrass to mitigate the effects of ocean acidification adds to the list of important ecological services provided by these ecosystems. The results of this study suggest that the presence of seagrass may be an important factor in the management of coastal ecosystems in the face of ocean acidification. Protecting and restoring seagrass beds may be an effective way to mitigate the effects of ocean acidification in these ecosystems. However, further research is needed to fully understand the potential of seagrass beds to mitigate the effects of ocean acidification.

#### *4.2.1.4 Connection to dissolved oxygen levels*

Not only is it important to look at the pH and $CO_2$ levels in the water in regard to the mitigation potential but also the oxygen levels are a relevant factor. There is a close interconnectedness between pH, oxygen levels, $CO_2$, and the temperature – which of course is of utmost importance when analysing the feedbacks during the climate crisis in ecosystems. The pH and oxygen levels in the Mediterranean Sea are closely connected, as changes in one lead to changes in the other. In the Mediterranean Sea, the connection between pH and oxygen levels is largely determined by the chemical equilibria governing

the carbonate system. The carbon dioxide ($CO_2$) emitted from anthropogenic activities such as burning fossil fuels has significantly altered the pH of seawater. When $CO_2$ dissolves in seawater, it reacts with water to form carbonic acid ($H_2CO_3$). This acidification reaction decreases pH, making seawater more acidic. The acidity of seawater affects the solubility of calcium carbonate ($CaCO_3$) in seawater, which is an important component of many marine organisms, including corals, mollusks, and some planktonic species. As the pH of seawater decreases, the saturation state of calcium carbonate decreases, reducing the availability of this compound for calcifying organisms. The reduction in calcium carbonate availability has been shown to affect the growth and development of some marine organisms, including planktonic species and benthic communities like Posidonia oceanica (Linares *et al.*, 2015). Additionally, as pH decreases, the concentration of hydrogen ions ($H^+$) increases. This increase in acidity reduces the availability of carbonate ions ($CO_3^{2-}$), which are essential for calcification in many marine organisms. At low pH values, the concentration of carbonate ions becomes limiting for the growth and development of these organisms (Kroeker *et al.*, 2013).
As to say, the pH level of seawater is determined by the concentration of hydrogen ions ($H^+$) in the water. When carbon dioxide ($CO_2$) dissolves in seawater, it reacts with water molecules to form carbonic acid ($H_2CO_3$), which then dissociates into bicarbonate ($HCO_3^-$) and hydrogen ions ($H^+$). This increase in hydrogen ions leads to a decrease in pH, making the water more acidic. In turn, the increase in acidity can have a negative impact on the oxygen levels in the Mediterranean Sea. One major factor is the effect of pH on the solubility of oxygen in seawater. As pH decreases, the solubility of oxygen decreases as well, which means that the water can hold less dissolved oxygen. This can lead to areas of low oxygen, or hypoxia, which can have serious ecological consequences for marine organisms that require oxygen to survive. The effect of decreasing pH on oxygen levels in the Mediterranean Sea is also an important consideration. The solubility of oxygen in seawater decreases as temperature and salinity increase. Therefore, as the temperature of the Mediterranean Sea increases due to climate change, the solubility of oxygen decreases. The acidification of seawater also affects oxygen levels by reducing the metabolic rates of many marine organisms, including phytoplankton and zooplankton. This reduction in metabolic rates decreases oxygen consumption by these organisms, leading to an increase in dissolved oxygen levels in the surrounding water (Linares *et al.*, 2015). Another factor that can contribute to low oxygen levels is the increase in

respiration rates of marine organisms in response to acidic conditions. As organisms respire, they consume oxygen and produce carbon dioxide, which can further decrease pH and exacerbate the oxygen depletion. However, the reduction in metabolic rates caused by acidification may also decrease the rate of photosynthesis in some marine organisms, such as seagrasses, leading to a decrease in oxygen production. The effect of acidification on oxygen levels in the Mediterranean Sea is therefore complex, and depends on a variety of factors, including temperature, salinity, and the metabolic rates of different marine organisms (Kroeker *et al.*, 2013). The temperature of seawater also has a significant impact on pH and oxygen levels. As seawater temperature increases, the solubility of gases like oxygen and carbon dioxide decreases. This means that warmer water can hold less dissolved oxygen, exacerbating the effects of low pH on oxygen levels. In addition, warmer water can lead to increased respiration rates of marine organisms, which can further decrease oxygen levels.

The climate crisis is exacerbating these effects by causing ocean temperatures to rise and increasing the concentration of carbon dioxide in the atmosphere, which ultimately leads to more carbon dioxide dissolving in the oceans. The Mediterranean Sea is particularly vulnerable to these effects due to its relatively shallow depth, limited circulation, and high levels of evaporation, which increase salinity and reduce the buffering capacity of the seawater.

In conclusion, the connection between pH and oxygen levels in the Mediterranean Sea is complex and multifaceted. The acidification of seawater caused by increased $CO_2$ emissions has important consequences for the availability of calcium carbonate, the metabolic rates of marine organisms, and the solubility of oxygen in seawater. These factors are all affected by changes in temperature and salinity, which are driven by an increase of $CO_2$ concentration. The implications of these changes for the marine environment and its ecosystems are significant and require further research to fully understand.

### 4.2.2 Chemical Explanation

The correlation between the dissolved $O_2$-concentration and the pH in water is connected via the $CO_2$ concentration. Due to photosynthesis, Posidonia oceanica absorbs sunlight and carbon dioxide and water to produce oxygen and organic matter. As the plants absorb

$CO_2$ from the water, they therefore increase the dissolved oxyen levels and decrease the $CO_2$ -concentration. By taking up $CO_2$ the plants also decrease the amount of $CO_2$ which otherwise would be available for the acidification process, indicated by the pH (Zimmerman and Martínez-Crego, 2017).

### 4.2.3 Effect of Posidonia Oceanica on dissolved oxygen levels

The second experiment followed a similar principle as the previous one on the pH level. The meadows of Posidonia oceanica are known to influence the dissolved oxygen levels in coastal ecosystems. As they photosynthesize, the seagrass beds produce oxygen as a byproduct. This experiment aims to investigate the potential of sea grass to raise oxygen levels as this has been indicated by previous studies as well (Lee *et al.*, 2017).

#### *4.2.3.1 Experimental Design*

This experiment was also conducted in the northern Mediterranean Sea. Two sites were selected, one with a healthy seagrass bed and another without seagrass as a control instance. The water samples were collected from each site using water sampling bottles at a depth of 1m, at the same time of day to reduce any potential effects of diurnal variations. The dissolved oxygen level of each water sample was measured using an indication tool. Each sample was measured three times to ensure accuracy.

1. Two study sites were selected, one with a healthy seagrass bed and one without seagrass.
2. Water samples were collected using water sampling bottles at a depth of 1m from each site.
3. The concentration of the dissolved oxygen of each water sample was measured using the meter. Each sample was measured three times.

#### *4.2.3.2 Expected Results*

Based on the existing literature, the dissolved oxygen levels are expected to be higher in the seagrass area compared to the area without seagrass due to the ability of seagrasses to photosynthesize and release oxygen into the surrounding water (Hemminga and Duarte, 2000). In addition, seagrasses can create a more favourable environment for the microbial community, which can contribute to the production of oxygen through respiration (Marbà and Duarte, 2010).

Table 7: Expected dissolved Oxygen levels in areas with and without seagrass at 1 meter depth (Santos, Silva, *et al.*, 2018; Pecorino, La Mesa and Sarà, 2019)

| **Area** | **Posidonia oceanica** | **Dissolved oxygen level** |
|---|---|---|
| **43,7871581 N 7,5598581 E** | **Yes** | **6,5-7,5 mg/L** |
| **43,7659748 N 7,7515639 E** | **No** | **5,0-6,0 mg/L** |

Based on previous studies, it is expected that the water samples collected from areas with seagrass will have higher dissolved oxygen levels compared to the samples collected from areas without seagrass. Therefore, our predicted results for the dissolved oxygen levels in the seagrass area are expected to be between 6.5-7.5 mg/L, while in the area without seagrass, the dissolved oxygen levels should be between 5.0-6.0 mg/L. However, it is important to acknowledge that these numbers are based on prior research and that the actual results may vary depending on the conditions and the timing of our sampling.

#### *4.2.3.3 Measurements*

Table 8: Measurements of dissolved $O_2$

| **Area** | **Posidonia oceanica** | **Dissolved $O_2$ measurements** | | | **Mean value** |
|---|---|---|---|---|---|
| **43,7871581 N 7,5598581 E** | Yes | 4 mg/L | 4,5mg/L | 4mg/L | 4,17 mg/L |
| **43,7659748 N 7,7515639 E** | No | 2,5mg/L | 2mg/L | 2mg/L | 2,17 mg/L |

As can be seen, the measured values are significantly lower than the values found in literature. The overall finding that the areas without seagrass have much lower oxygen concentration could be confirmed. The reason for the dissonance can be the place or time of where the measurements have been taken or the process of taking the samples. As there was no possibility for cooling the sample during the sampling process and the measuring, deprecating plankton in the samples may have changed the concentration Even the difference in the current measurement is almost 50% between the areas with and without seagrass compared to the literature values where a difference of about one third less Oxygen is reported. The measurements confirm the high impact of seagrass on the oxygen concentration

#### *4.2.3.4 Connection to CO2 levels*

The parameters of the dissolved oxygen and the $CO_2$ are closely linked with each other. Marbà et a. (2015) investigated the relationship between the two factors and found that as dissolved oxygen concentration decreased, $CO_2$ levels increased and vice versa, indicating a potential relationship between the two factors (Marbà, Díaz-Almela, *et al.*, 2014). Another study examined the effect of elevated $CO_2$ levels on the physiology of Posidonia oceanica which discovered the negative influence of high $CO_2$ levels in the water on growth rate, healthiness and oxygen production of the sea grass (Diaz-Almela *et al.*, 2014). As there are several factors influencing both concentrations, their relationship is complex and dynamic as different levels may have feedbacks on other factors which then are interconnected with the dissolved oxygen and $CO_2$ levels. Still, there definitely is a connection between both factors which is the reason for the conduction of the third experiment.

### 4.2.4 Effect of Posidonia Oceanica on $CO_2$ levels

The third experiment aimed to measure the levels of dissolved $CO_2$ in water samples collected from areas with and without seagrass. As $CO_2$ has far reaching effects on ecosystems, it is crucial to also assess the capacity of Posidonia oceanica to sequester $CO_2$ to better understand its role in mitigating ocean acidification.

#### 4.2.4.1 *Experimental Design*

As in the earlier described experiments, the same two sites were selected. The collection of water samples followed the same procedures as the dissolved oxygen measurements, using water sampling bottles and wearing gloves to avoid contamination. Once the water samples were collected, the dissolved $CO_2$ levels were measured using a $CO_2$ sensor meter.

#### 4.2.4.2 *Expected Results*

The expected levels of dissolved $CO_2$ in the water samples were based on literature values. According to a study by Duarte et al. (2013), the Mediterranean Sea has experienced an increase in $CO_2$ levels due to ocean acidification caused by anthropogenic carbon emissions. Based on other studies, the expected $CO_2$ concentration without seagrass is about 400-450 ppm, while in sea grass it is expected to be lower at around 300-350 ppm (Duarte, Hendriks, *et al.*, 2013). But it is also stated that the measurements may vary depending on location, time of day and weather conditions. In 2013, Mazzuca et al. conducted a similar study in the Mediterranean Sea as is done in this master thesis and the $CO_2$ concentration was measured to be around 340 ppm in the morning and around 320 ppm in the afternoon (2013).

Table 9: Expected CO2 levels in areas with and without seagrass at 1 meter depth (Mazzuca *et al.*, 2013)

| **Area** | **Posidonia oceanica** | **CO2-level** |
|---|---|---|
| **43,7871581 N 7,5598581 E** | Yes | 300-350ppm |
| **43,7659748 N 7,7515639 E** | No | 400-450ppm |

The data collected from this experiment will provide insight into the potential for seagrass meadows to mitigate the effects of ocean acidification and will be a valuable addition to the ongoing research in this field.

#### *4.2.4.3 Measurements*

In the scope of my research, my test kit indicated the $CO_2$-level at a specific pH. Due to the difference of pH, different $CO_2$-levels were indicated, with the indication of whether the $CO_2$ level was higher than 357 ppm, or lower. As the focus of the research is the difference between the two measurements, as to say, where the CO2 measurements are lower and where they are higher, this is sufficient as an indicator.

Table 10: Measured $CO_2$ levels in areas with and without seagrass at 1 meter depth

| Area | Posidonia oceanica | CO2-measurements | | |
|---|---|---|---|---|
| **43,7871581 N 7,5598581 E** | Yes | <357ppm | <357ppm | <357ppm |
| **43,7659748 N 7,7515639 E** | No | >357ppm | >357ppm | >357ppm |

In areas with seagrass, the expected $CO_2$ levels were lower than in areas without seagrass due to the seagrass acting as a carbon sink through photosynthesis, just as expected based on the studies. A study by Gacia et al. found that seagrass meadows can reduce $CO_2$ levels by up to 30% compared to adjacent unvegetated areas, which is consistent to the results from the study (2007). The measurements were consistent with the existing literature, suggesting that Posidonia oceanica lowers the $CO_2$ concentration in the surrounding water.

## 4.3 QUANTIFICATION OF POSIDONIA OCEANICA AS MITIGATION MECHANISM

This chapter aims to quantify the extent of Posidonia oceanica coverage that would be needed to fully mitigate the problem of ocean acidification at current $CO_2$ emissions in Europe. To estimate the required coverage, the yearly $CO_2$ emissions in Europe need to be considered, which were approximately 3,6 million tonnes in 2022 (International Energy Agency, 2023).

According to Pergent-Martini et al (2021) as the carbon fixation rate changes over the depth of the sea grass, the total fixation rate can be estimated at 130gC/m²/year or 1302 tC/ha/year and the sequestration rate at 27,8 gc/m²/year which is 278tC/ha/year.

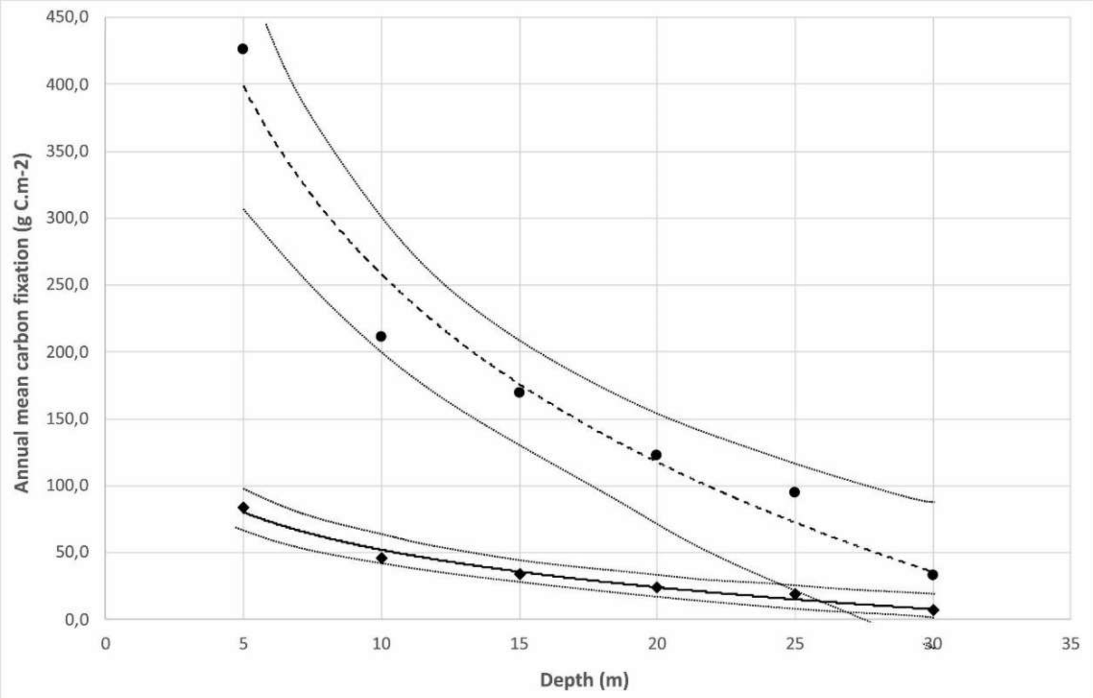


*Figure 4: Annual mean carbon fixation (dotted line) and sequestration (solid line) by P.o. according to depth*

Next, the carbon sequestration rate is needed, which ranges from 130 to 294 g C m² /yr (Marbà, Hendriks, *et al.*, 2015), which results in Posidonia fixing 5.7 Mio tons of $CO_2$ emissions per year (Pergent-Martini *et al.*, 2021). Using these values, the required Posidonia coverage (P) to offset European $CO_2$ emissions (E) can be calculated as follows:

$$P = E / (\text{Sequestration Rate} * \text{Conversion factor})$$

The conversion factor converts the sequestration rate from grams of C to gigatons of $CO_2$. One gigaton of $CO_2$ is equivalent to 0,272 gigatons of carbon (Ciais *et al.*, 2013), which makes the conversion factor 0,272.

Taking the sequestration rate of the lowest end of the range (130 g C m² /yr), the required Posidonia coverage would be:

$$P = 3{,}6 \text{ bio tons} / (130*0{,}272) \approx 101\ 809\ 955 \text{ ha}$$

Based on these calculations, and without any additional impacts or feedback mechanisms, the necessary Posidonia oceanica coverage to sequester the carbon dioxide emitted from

European countries approximately 101 809 955 ha. However, these results are based on the assumption that the sequestration rate remains constant without any ulterior influences, anthropogenic disturbances, or changes in $CO_2$ emissions.

Studies collected measurements throughout the Mediterranean Sea at the coastline of Corsica and at different depths to make an estimate of the fixation rate of Posidonia oceanica (1302 tC/ha/yr) and a sequestration rate (279 tC/ha/yr) to analyze the carbon fixation and sequestration by Posidonia oceanica meadows over the coast of Corsica which made up 20 425ha

Following this, the overall carbon fixation and carbon sequestration of Posidonia oceanica, based on data collected by the Mediterranean countries was calculated. The carbon fixation is estimated at 3 638 909 t per year, which equals to 13 343 878 tons of $CO_2$ emission equivalents. The carbon sequestered is estimated at 776 971 tons per year, which is equivalent to 2 849 154 tons per year of $CO_2$ emissons. Around the Mediterranean Sea, 0,61% of $CO_2$ is fixated by Posidonia oceanica (Pergent-Martini *et al.*, 2021).

| | Estimated C fixation (t C) | Estimated $CO_2$ release* (Mt $yr^{-1}$) | Population (inhabitant) | Estimated $CO_2$ release (t $CO_2$. $inhab^{-1}$) | $CO_2$ fixation by *P. oceanica* (%) |
|---|---|---|---|---|---|
| Spain | 150 907 | 268.0 | 46 692 858 | 5.74 | 0.21 |
| France and Monaco | 114 178 | 338.0 | 64 990 511 | 5.20 | 0.12 |
| Italy | 439 570 | 338.0 | 60 627 291 | 5.58 | 0.48 |
| Slovenia | 1.3 | 14.0 | 2 077 837 | 6.74 | 0.00 |
| Croatia | 292 364 | 19.0 | 4 156 405 | 4.57 | 5.64 |
| Bosnia Herzegovina | 0 | 22.0 | 3 323 925 | 6.62 | 0.00 |
| Montenegro | 667 | 2.0 | 627 809 | 3.19 | 0.12 |
| Albania | 6 254 | 4.6 | 2 882 740 | 1.60 | 0.50 |
| Malte | 7 630 | 1.6 | 439 248 | 3.64 | 1.75 |
| Greece | 326 815 | 74.0 | 10 522 246 | 7.03 | 1.62 |
| Turkey | 89 756 | 428.0 | 82 340 088 | 5.20 | 0.08 |
| Cyprus | 20 533 | 7.5 | 1 189 265 | 6.31 | 1.00 |
| Syria | 0 | 28.0 | 16 945 057 | 1.65 | 0.00 |
| Lebanon | 0 | 24.0 | 6 859 408 | 3.50 | 0.00 |
| Ter. Palestinians | 0 | 3.2 | 4 862 979 | 0.66 | 0.00 |
| Israel | 0 | 64.0 | 8 381 516 | 7.64 | 0.00 |
| Egypt | 0 | 239.0 | 98 423 598 | 2.43 | 0.00 |
| Libya | 14 618 | 54.0 | 6 678 559 | 8.09 | 0.10 |
| Tunisia | 2 142 377 | 32.0 | 11 565 201 | 2.77 | 24.55 |
| Algeria | 33 241 | 156.0 | 42 228 408 | 3.69 | 0.08 |
| Morocco | | 66.0 | 36 029 093 | 1.83 | 0.00 |
| **Total (mean)** | **3 638 909** | **2 182.9** | **511 844 042** | **4.26** | **0.61** |

*Figure 5: Carbon fixation in the different Mediterranean countries (Pergent-Martini* et al.*, 2021)*

## 4.4 Analysis: evaluation of the effectiveness of the P.O. plantation in mitigating ocean acidification

The following evaluation framework aims to assess the impact of the plantation efforts regarding Posidonia oceanica with the goal to counteract on ocean acidification and its symptoms. This framework can be divided into two parts: monitoring the growth and survival of Posidonia oceanica and monitoring the changes in the ecological system as a result of these efforts. Firstly, I will assess the growth and survival monitoring.

### 4.4.1 Growth and survival monitoring

Several studies have been conducted to monitor the growth and survival of Posidonia oceanica after replantation. A study conducted by Micheli et al. monitored the growth and survival of Posidonia oceanica after transplantation 2019. It found that after one year, over 70 % of the transplants survived and showed significant growth, resulting in an overall better state of the regional ecosystem. Gambi et al. (2018) came to similar results, 67% survival rate and significant growth in correlation to the health and density of surrounding seagrass meadows. Marinelli (2023) stated the same objectives, that the plantation method by hand is over 90% successful in sustaining sea grass meadows, whereas the survival chances of Posidonia oceanica seeds without mechanical plantation efforts lie only between 1-3%. It is safe to say, that Posidonia oceanica, with the aid of humans, is successful in its survival and sustainable growth.

### 4.4.2 Changes in the Ecological System:

The ecological system's changes resulting from reforestation and plantation efforts have been monitored to analyse the effects on the overall ecological system in which sea grass is defined as one of the base species. Increasing the amount of Posidonia oceanica and its health in a region, has positive impacts, particularly regarding the diversity of species in that specific area. The ecological system is defined as a geographic area, including the diversity and abundance of fish, plants and invertebrates. A study conducted by Piazzi et al. found that reforestation efforts increased the density and diversity of fish and invertebrates in the planted areas as it attracted a more diverse group of species than in the non-planted areas (2015). The difference between the number of species found in areas with sea grass is over double the amount. While doing transects in the Mediterranean Sea, also the species have been documented and counted, with results supporting this claim. The number of species found in regions with healthy Posidonia oceanica meadows exceeded the number of species found in regions where sea grass was unhealthy or lacking (App. 1, 2).

### 4.4.3 Financial Evaluation

The financial evaluation framework aims to evaluate the costs and benefits of reforestation and plantation efforts. This framework can be divided into two parts: the costs of the efforts and the benefits of the efforts.

Costs:

The costs of reforestation and plantation efforts can be broken down into two categories: initial costs and maintenance costs. Initial costs include the costs of planting Posidonia oceanica, such as the cost of collecting seeds, seedling production, and planting equipment. Maintenance costs include the costs of ongoing monitoring, maintenance, and replacement of dead plants. According to a study conducted by Guidetti et al. (2018), the costs of reforestation efforts can range from €5,000 to €20,000 per hectare. As this is a very wide range of potential costs, as they depend on the specific type of reforestation measures, the technicalities, the accessibility and the type of sea grass.

Benefits:

The benefits of reforestation and plantation efforts include ecosystem services such as carbon sequestration, fishery enhancement, and shoreline protection. A study conducted by Macreadie et al. (2019) estimated that the value of carbon sequestration services provided by Posidonia oceanica in the Mediterranean Sea was approximately €60 billion per year at the time of research. More exact financial benefits were calculated by using an Emergy analysis, that estimated the financial benefit of the services provided by Posidonia oceanica as a resource. These services include sediment retention, hydrodynamics attenuation, oxygen release, nursery role and primary production. The value of Posidonia oceanica was estimated to be 172€m²/a.[48] Another study conducted by Badalamenti et al. (2016) found that replanted areas can increase the productivity of fisheries by up to 70%.

### 4.4.4 Temporal Evaluation

The temporal evaluation framework aims to assess the time required for the reforestation and plantation efforts to yield positive results. This framework can be divided into two parts: the time required for the plants to establish, and the time required for the ecological system to recover.

Time Required for the Plants to Establish:

The time required for the plants to establish is an important factor to consider when evaluating the success of a reforestation or plantation effort. This period can vary depending on the species of plant, the environmental conditions, and the management practices employed. For example, some studies have shown that the establishment period for Posidonia oceanica can range from several months to several years, depending on factors such as water temperature, nutrient availability, and the presence of herbivores (Marbà, Duarte and Agustí, 2006). It is important to monitor the establishment of the plants and make any necessary adjustments to the management practices to ensure the success of the reforestation or plantation effort.

Time required for the ecological System to Recover:

The time required for the ecological system to recover after a reforestation or plantation effort is another important factor to consider. This period can vary depending on the complexity of the ecological system and the extent of the degradation prior to the reforestation or plantation effort. For example, a study on the recovery of seagrass meadows in the Mediterranean found that it can take several years for the ecological system to fully recover after a disturbance event, such as a storm or human activity (Balestri *et al.*, 2009). It is important to monitor the recovery of the ecological system over time and assess the effectiveness of the reforestation or plantation effort in promoting ecosystem recovery.

### 4.4.5 Ecological efforts

Replanting and sustaining Posidonia oceanica requires significant ecological efforts, including identifying the suitable areas for planting and ensuring the quality of the water in those areas. The first step is to identify areas where the seagrass was once present but has been damaged or destroyed due to anthropogenic activities. This can be done through remote sensing techniques that use satellite imagery to identify areas with high levels of disturbance. Once identified, these areas can be prioritized for reforestation efforts (Marín-Guirao *et al.*, 2016). In addition to identifying suitable planting areas, the water quality in those areas must also be monitored to ensure that it is conducive to the growth of Posidonia oceanica. High levels of pollutants, such as nitrogen and phosphorus, can negatively impact the growth of seagrasses. Therefore, it is important to monitor and manage the nutrient levels in the water to ensure that they remain within acceptable levels for the growth of Posidonia oceanica.

### 4.4.6 Social efforts:

Replanting and sustaining Posidonia oceanica can also require social efforts to educate and engage the local community. This can include raising awareness about the importance of seagrasses and the role they play in the ecosystem. It can also involve working with fishermen, boaters, and other stakeholders to reduce the impact of their activities on the seagrass beds.
To evaluate the efforts of replanting and sustaining Posidonia oceanica, ecological., financial., temporal., and social aspects of the efforts can be compared and analysed. For that to be done, the quantification of the effectiveness of Posidonia Oceanica in mitigating ocean acidification needs to be included, as well as the analysis how much Posidonia oceanica would be needed to sufficiently mitigate ocean acidification.

### 4.4.7 Evaluation of the efforts:

Using the factors outlined above, the evaluation of the efforts of replanting and sustaining Posidonia oceanica in the Mediterranean Sea is possible, according to a framework including the Preferred Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher *et al.*, 2009), and the inclusion of the Population, Exposure, Comparator, and Outcomes (PECO) formulation guidance (Morgan *et al.*, 2018). The following table summarizes the efforts in different regions of the Mediterranean Sea, on the basis of the factors that have been discussed (Pansini *et al.*, 2022).

Table 11: Replantation efforts and specific costs (Piazzi et al., 2015; Guidetti et al., 2018)

| **Region** | **Growth / Survival (%)** | **Ecological Changes** | **Financials (€)** | **Timescales (yrs)** | **Ecological Efforts** | **Social Efforts** |
|---|---|---|---|---|---|---|
| **Corsica** | 75% | +50% fish density | 10,000/ha | 3-5 est. | Satellite monitoring | Education |
| | | +30% invertebrates | 60,000/yr | 5-10 reco | Water quality (carbon seq.) | Stakeholder engagement |
| **Sardinia** | 82% | +80% fish diversity | 18,000/ha | 2-4 est. | Seeding | Awareness campaigns |
| | | +60% invertebrates | 172,000/m2/yr | 5-8 reco | Ecosystem services | |
| **Sicily** | 90% | +70% total species | 5,000/ha | 6m-3yrs est. | Transplanting cuttings | Fisher partnerships |
| | | +50% habitat quality | 300,000/yr | 5-12 reco | (tourism) | |
| **Spain** | 67% | +40% habitat area | 20,000/ha | 1-2 est. | Fencing meadows | Funding programs |
| | | +30% total biomass | 500,000/yr | 3-8 reco | (fisheries) | |

Note: The financial cost is calculated based on the cost per hectare multiplied by the hectares planted. The growth/survival rate is based on the percentage of hectares planted that successfully establish.

In addition to the ecological and financial factors, it is important to consider the temporal and social aspects of the reforestation and plantation efforts of Posidonia oceanica in the Mediterranean Sea. In terms of temporal considerations, it is important to acknowledge that the process of replanting and sustaining Posidonia oceanica is a long-term effort. The growth rate of the seagrass is slow, with an average of 1-2 cm per year, and it can take several years for the seagrass to fully establish and provide ecological benefits. A study by Marbà et al. (2014) found that in order to achieve a 50% increase in seagrass coverage, it would take approximately 30 years of sustained replanting efforts. Therefore, it is crucial to establish long-term plans and funding mechanisms to ensure the sustained efforts of replanting and monitoring Posidonia oceanica. This includes regular monitoring and evaluation of the seagrass meadows, as well as ongoing replanting efforts to maintain and enhance seagrass coverage. Social considerations are also important when evaluating the efforts of Posidonia oceanica reforestation and plantation. These efforts involve a variety of stakeholders, including government agencies, non-governmental organizations, and local communities. Collaboration and engagement with these stakeholders are essential to ensure the success of the efforts. One challenge is that the success of the reforestation and plantation efforts may not be immediately visible or tangible to local communities. As a result, it may be difficult to garner support and participation from these communities. However, studies have shown that efforts to enhance and restore seagrass meadows can provide a range of benefits to local communities, including increased fishery yields and improved water quality (Fonseca, Kenworthy and Wiberley, 2000). Therefore, it is important to engage with local communities and stakeholders to communicate the benefits of the replanting efforts and build support for the long-term sustainability of the seagrass meadows. This can involve community outreach programs, educational initiatives, and collaborative monitoring and evaluation efforts.

Overall, the evaluation of the efforts of Posidonia oceanica reforestation and plantation involves consideration of ecological., financial., temporal., and social factors. Building a comprehensive evaluation framework that incorporates these factors is essential to ensure the sustained success of these efforts.

Table 12: Posidonia Oceanica Planting and Monitoring Efforts (Ballesteros, Cebrian and Díaz, 2011; Terrados, Duarte and Kenworthy, 2012; Montefalcone *et al.*, 2016; Bulleri *et al.*, 2018; Gristina *et al.*, 2019)

| **Location** | **Planting Year** | **Monitoring Year** | **Seagrass Coverage ($m^2$)** | **References** |
|---|---|---|---|---|
| **Portofino, Italy** | 1998 | 2001-2005 | 2-19.6 (increase over time) | Montefalcone et al. (2016) |
| **San Vito Lo Capo, Italy** | 2011 | 2011-2017 | 15-40 (increase over time) | Gristina et al. (2019) |
| **Elba Island, Italy** | 2007-2011 | 2011-2018 | 2-7 (increase over time) | Bulleri et al. (2018) |
| **Bay of Palma, Spain** | 1998 | 2000-2009 | 9.8-23.8 (increase over time) | Terrados et al. (2012) |
| **Cabrera National Park, Spain** | 2002-2005 | 2005-2010 | 15-85 (increase over time) | Ballesteros et al. (2011) |

As shown in Table 8, the monitoring efforts of Posidonia oceanica reforestation and plantation have been conducted in various locations across the Mediterranean Sea.

# 5 DISCUSSION

In this chapter I will circle back to the research question and the overall agenda of this thesis. I will answer how the results are connected to the research questions and how they can be interpreted.

The research question splits itself in two parts.

*What is the effectiveness of Posidonia oceanica as a means to address ocean acidification, and what factors need to be taken into consideration when developing and implementing sea grass restauration strategies for sustainable and successful outcomes?*

The first part of the research question focuses on the effectiveness of seagrass management to mitigate ocean acidification. This can be answered by combining the results of the experiments with the implications of the data considered and the framework of analyzing the effectiveness and cost of the plantation strategies.

## 5.1 EFFECTIVENESS OF POSIDONIA OCEANICA IN MITIGATING OCEAN ACIDIFICATION

To address the first part of the research question, the results of the experiments showed that Posidonia oceanica is highly effective in its nature in mitigating ocean acidification in several ways, specifically regarding mitigating the pH, the oxygen- and the $CO_2$ levels. The experiments demonstrated that within the regions with existent Posidonia oceanica meadows, the pH was higher than in the regions lacking sea grass due to the interlocking mechanisms of the carbon cycle mentioned in Chapter 2.1 and 2.2. The expected pH level difference was between 0.1-0.5, as seen in table 5, which is in accordance with the mean pH difference in table 6 as it is 0.43. Additionally, the dissolved oxygen levels were higher with the sea grass present, as can be seen in table 8. The mean value of the dissolved oxygen with Posidonia oceanica was 4,17 mg/L whereas without Posidonia it was 2,17 mg/L. These results are in their structure similar to the expected results of 6,5-7,5 mg/L with Posidonia oceanica, and 5,0-6,0 mg/L without it. The measured values were significantly lower than the values found in previous studies, which might have resulted from seasonal differences, temperature differences or due to the process the sample was taken. Still, the oxygen values with Posidonia were significantly higher than the values without Posidonia oceanica. This suggests, that Posidonia oceanica is an effective buffer for acidification, which are consistent results with other studies by previous researchers. Not only the chemical properties of Posidonia oceanica are beneficial for ocean acidification mitigation, but also its physical and biological properties as discussed in Chapter 2.2.

Overall goals of this thesis were to conduct a comprehensive review of the state of the art of ocean acidification mitigation strategies, including a review of current technologies and methods to address ocean acidification. These topics helped to analyze the effectiveness of sea grass as a mitigation strategy, including the effectiveness of the plantation efforts and what policies and strategies would be necessary for a successful implementation of sea grass management strategies.

Table 1 shows the distribution of Posidonia oceanica across the Mediterranean Sea. The total area covered by Posidonia oceanica is about 1 224 704 ha according to the assessments. In table 2, the degradation of Posidonia oceanica within different regions can be seen. Overall, Posidonia oceanica was reduced in its quantity, ranging from a reduction of 16,1% to 75%. Whereas the lowest reduction can be fund in the region with the strictest fines when disregarding the protection zones of Posidonia oceanica, near the Balearic Islands, where the overall health status of the sea grass has been defined as "good" (Table 3). Overall, in the regions that have been assessed, the reduction was 28.8%.

If this number is applied to the overall Posidonia oceanica in the Mediterranean Sea, it is very likely that over 350 000 ha (calculated on the basis that 30% has been lost with a current state of 1 224 707 ha) has been destroyed.

The study mentioned by Pergent-Martini et al. (2021) Recent studies built a synthesis of a hundred measurements made throughout the Mediterranean Sea and at different depths to make an estimate of the fixation rate of Posidonia oceanica (1302 t/C/ha/yr) and a sequestration rate (279 tc/ha/yr) to analyze the carbon fixation and sequestration by Posidonia oceanica meadows over the coast of Corsica which made up 20 425 ha (Pergent-Martini *et al.*, 2021). Additionally, the carbon fixation is estimated at 3 638 909 t per year, which equals to 13 343 878 tons of $CO_2$ emission equivalents. The carbon sequestered is estimated at 776 971 tons per year, which is equivalent to 2 849 154 tons per year of $CO_2$ emissons. Around the Mediterranean Sea, 0,61% of $CO_2$ is fixated by Posidonia oceanica (Pergent-Martini et al., 2021).

In chapter 4.3, the required quantity of Posidonia oceanica needed, to mitigate the emitted $CO_2$ by Europe, calculated as at least 101 809 955 ha.

As Europe's yearly $CO_2$ emissions have been estimated at 3,6 bio tons, which is equivalent to 3,6 gigatons, the fixated $CO_2$ and the sequestered $CO_2$ by Posidonia oceanica can be calculated.

The $CO_2$ fixation therefore is about 0,3% of European emissions, while the $CO_2$ sequestration is merely 0,07%.

Additional economic and ecological efforts that have been described in table 11 plus the restoration of Posidonia oceanica can be an important asset in the fight against the climate crisis. As this habitat also provides other essential ecosystem services, protecting and rehabilitating Posidonia oceanica should become a priority to support natural climate change mitigation and adaptation. Combined with other measures such as reducing $CO_2$ emissions and better manage pollution, the potential benefits of seagrass to curb ocean acidification can be optimized.

## 5.2 Results of the plantation

The second part of the question focuses on the steps to implement a sustainable and successful restauration strategy to mitigate ocean acidification from a political., economic and social perspective. Sea grass as a base species, providing habitat, nurturing ground, food, and hunting ground is interconnected with many different species and is influenced by several systems. The health of the sea grass and therefore of the overall marine ecosystem is on several pillars that need to be stabilized for a successful restoration and mitigation strategy. There are internal factors needed to be implemented in the restoration plan, and external factors that would influence the success of the project.

1. Site selection: Choosing the appropriate site for a restoration project is crucial to ensure the sustainability of the sea grass meadow. Water depth, the water quality, availability of light, the subject the meadow is planted on and the proximity to other sea grass need to be considered, but also the occurrence of boat traffic, the overall healthiness of the ecosystem in the region and whether the sea grass could be of invasive nature (de los Santos *et al.*, 2019).

2. Seed Source and Availability: To ensure the genetic diversity and adaptability of the seeds, local seeds need to be chosen for restoration procedures.
3. Monitoring and Maintenance: Regular monitoring and maintenance are critical to the success of seagrass restoration, but not only the new meadows, but also the preexisting meadows need to be considered to assess potential harm and analyse potential problems like low survival rates or the occurrence of invasive species (Campbell, Fourqurean and Dennison, 2018).

External factors needed for long-term, large-scale success:

1. Community Engagement and Education:
   Community engagement and education can help to build support for seagrass restoration projects and increase awareness of the importance of seagrass ecosystems. Community involvement can also help to identify potential issues and concerns that need to be addressed in the planning and implementation phases of the project (Barbier *et al*., 2011).
2. Long-Term Sustainability:
   To ensure the long-term sustainability, political investment has to be done to secure the ecological role and the ecosystem functions. The Habitats Directive 92/43/EEC on the conservation of natural habitats and of wild fauna and flora, includes Posidonia oceanica among its habitats of higher priority (Habitat code 1120*). In the UN Declaration on Ecosystem Restoration, it was the aim to boost existing efforts to restore degraded ecosystems and 350 million hectares of degraded ecosystems globally by 2030, including Posidonia oceanica. But due to the acute lack of large-scale restoration efforts and the lack of Large Marine Protected Areas (LMPAs) in the Mediterranean Sea, more would need to be done. A multi-level implementation strategy and protected areas, also in the deep sea, would be needed, including penalties on the international level, to ensure the continuous growth of sea grass meadows, not just slowing down the degradation process.

A big problem for the sustainable Posidonia oceanica restoration is the inaccessibility of data and information on the topic, the current state of the meadows and the geographic distribution of the sea grass. Mapping meadows and comparing the maps with previous data provides a reliable basis for analysis of changes (Boudouresque *et al.*, 2009). However, the differences between the mappings, the quality of information and the changing of mapping methods has led to a variety of maps and information, rather than an elaborate overview (Pasqualini, Pergent-Martini and Pergent, 1997; Astruch *et al.*, 2012; Pergent-Martini *et al.*, 2017; Pergent *et al.*, 2019). Evaluations and therefore restoration measures and sustainable efforts can only be successful if an exact framework with consistency throughout the process is applied.

Overall analysis and integration of the research and conclusions of the thesis in light of current research in the field.

## 5.3 Assessing the Required Quantity of Posidonia Oceanica for pH Modification or Reversal

The results of the previous study and the literature show, that Posidonia oceanica as a plant has an enormous potential in mitigating ocean acidification, though it may only be on a regional level as due to its destruction and the financial cost of its reconstruction, the Posidonia oceanica as a single measure is not enough. Studies by Gattuso et al. (2010) and Henriks et al (2014) fully support these claims as it has been discovered that Posidonia oceanica can raise pH levels up to 0.5 units during the day and 0.2 units during the night.

Based on the calculations in Chapter four, at least about 500,000 km2 of Posidonia oceanica would be needed to fully mitigate ocean acidification. The highest cost of reconstruction of Table 9, which was 20,000 per ha, raises the required financials to $10^{12}$€. As this is an unattainably high amount, the reconstruction process of sea grass cannot be solely relied upon to control ocean acidification but should rather be used as a supplement to curb pH decrease. The benefits of Posidonia are very clear, et also of immense financial worth but setting the goal of the plantation of Posidonia this high, is simply not feasible.

Although Posidonia oceanica shows a high potential for naturally increasing pH levels and mitigating ocean acidification, the scale at which this seagrass would need to be restored to solve this issue alone is unrealistic as the costs and efforts involved make this an implausible solution. However, Posidonia oceanica as an important factor in the fight against the climate crisis should not be disregarded This habitat provides other essential ecosystem services and any increase in coverage will aid in combating this environmental problem, even if only on a localized scale.

Multiple approaches are required to tackle ocean acidification effectively, but as the possible unintended effects of these measures have not been fully discovered yet, Posidonia remains a feasible option to at least buffer ocean acidification as there are no real known negative effects to it. The sea grass be used to supplement other actions like reducing $CO_2$ emissions, pollution, and runoff. Still, further research needs to determine how much impact current and future Posidonia meadows could have on global ocean chemistry and how their potential could be optimized regarding carbon sequestration, pH mitigation and as an important base species for marine biodiversity. Protecting and rehabilitating this habitat should become a priority to support natural climate change mitigation and increase resilience.

Although Posidonia cannot single-handedly mitigate ocean acidification, this seagrass has significant potential to naturally increase pH levels and lower dissolved $CO_2$ locally. Any increase in coverage will contribute to counterbalancing acidification and support adaptation of ecosystems and species. As with all other symptoms of the climate crisis, multiple factors and measures need to be considered to mitigate the problem. Far-reaching and multilateral protective policies, from the reduction of unsustainable shipping and transfer to the overall emission reduction by the industries and top emitters of this world. For sustainable development and the reaching the Sustainable Development Goals within the next 7 years, more efforts need to be done. Ocean acidification is specifically mentioned in SDG 14.3

Overall, the potential of Posidonia oceanica is too substantial to ignore. Together with other solutions, restoring this habitat could play an important role in managing the urgent problem of ocean acidification. The effectiveness of this approach needs to be monitored to determine ideal strategies, but Posidonia could be a key tool in the battle against this global issue.

## 5.4 IDENTIFICATION OF KNOWLEDGE GAPS AND RESEARCH NEEDS FOR THE DEVELOPMENT OF MORE EFFECTIVE STRATEGIES

In the discussion, some knowledge gaps have already been briefly mentioned. For a more effective strategies regarding the mitigation of ocean acidification, the most urgent need would be the implementation of a consistent framework that covers the mapping of the sea grass, the measuring, the data collection and transcribing, and the monitoring. As the research goal and the goal of the data collection is equivalent, so should be the methods used during the process. Additionally, one of the main knowledge gaps is the lack of understanding of the connections of different symptoms of ocean acidification. For example, it is still quite unclear how far-reaching the effects of a rising pH are, in terms of temperature change, $CO_2$-concentration and the dissolved oxygen. The effect and possible feedback loops on the different departments of the ecosystem have also not been evaluated yet. Although there is a significant amount of research on the effect on coral reefs, little is known about the effects on other ecosystems such as seagrass meadows and kelp forests, arguably one of the most crucial parts of the marine ecosystem. To implement a functioning strategy of mitigation, the effects and dangers of the problems need to be known. The knowledge does not only need to be extended about the problem itself but also about the possible mitigation strategies. The long-term effects of different mitigation strategies, especially those that include chemical altering of the water, need to be assessed completely before including them in the strategic planning. Otherwise, while trying to solve one problem, another one may result out of it due to lack of knowledge or awareness.

To address these knowledge gaps, several research needs have been identified that need to be closed before being able to fully implement a successful and sustainable mitigation strategy:

1. Interaction between mitigation strategies: There needs to be research on how different mitigation strategies can be combined for an optimized approach with as little invasion in the ecosystem as possible to avoid unintended consequences.
2. Analysis on different marine ecosystems: The research has to be extended to different marine ecosystems such as sea grass meadows and regions which are not in the Mediterranean region. Additionally, there needs to be research on the

different components of the ecosystems as they may influence the problem itself as well.

3. Long-term mitigation strategies: The mitigation strategies need to be proven to be not harmful to all parts of the ecosystem long-term to ensure the balance of marine life.
4. Socio-economic aspects of mitigation strategies: The research on the social and economic factors has yet to be included in the research as they may influence the success and the sustainability of the strategies immensely.
5. Innovation: Developing new and effective mitigation strategies, as well as including pre-existing mitigation strategies to develop them further needs to be of utmost importance to marine researchers.

In conclusion, while there has been a significant process in research on ocean acidification, many researchers focus on the same topics. There are still vast knowledge gaps that connect the different aspects of ocean acidification and its symptoms with each other, the climate crisis and potential impacts for life in water and on earth. The Sustainable Development goals include a safe and healthy marine environment and a sustainable life on earth, which raises the significance of the research on this topic (United Nations General Assembly, 2015).

## 5.5 IMPLICATIONS FOR POLICY AND PRACTICE, INCLUDING THE POTENTIAL FOR SCALING UP POSIDONIA OCEANICA PLANTATION AS A NATURE-BASED SOLUTION TO COMBAT OCEAN ACIDIFICATION

The findings of this thesis reaffirm the significance of Posidonia oceanica as a crucial component in combating the impacts of ocean acidification. As policymakers and practitioners work towards developing effective strategies to mitigate climate change, it is essential to recognize the potential of scaling up P. oceanica plantation as a nature-based solution. In light of the evidence presented, several policy and practice recommendations can be provided, focusing primarily on the political side. One of the primary deterrents for harmful activities that contribute to the decline of P. oceanica meadows is the implementation of fines and penalties. Governments and regulatory bodies should enforce strict rules on activities that damage these ecosystems, such as unsustainable fishing practices, coastal development, and the discharge of pollutants (Orth *et al.*, 2006). By imposing fines, authorities can discourage damaging activities and encourage industries to adopt more sustainable practices, thereby preserving the P. oceanica habitats and their capacity to mitigate ocean acidification. Furthermore, the revenue generated from these fines can be allocated towards conservation and restoration efforts, providing essential resources for scaling up P. oceanica plantation initiatives (Duarte, Losada, *et al.*, 2013). Another crucial element in preserving and expanding P. oceanica meadows is the establishment of larger marine protected areas (MPAs). Properly managed MPAs can safeguard critical habitats, enhance ecosystem resilience, and support the recovery of P. oceanica populations. Political leaders must prioritize the expansion of MPAs to include significant P. oceanica meadows and collaborate with stakeholders to ensure effective management and enforcement. Furthermore, nations should engage in international cooperation to designate transboundary MPAs, as P. oceanica meadows often extend across national borders, necessitating coordinated efforts for their protection(García-Sanz *et al.*, 2021). To support the scaling up of P. oceanica plantation as a nature-based solution, it is essential to invest in research and monitoring efforts. Governments should allocate sufficient funding towards understanding the ecological functions of P. oceanica meadows and developing innovative restoration techniques (Marbà, Jordà, *et al.*, 2015). Political leaders should also encourage collaboration between scientists, practitioners, and policymakers to ensure that research findings are effectively translated into policy and practice. Moreover, long-term monitoring programs should be implemented to track the success of P. oceanica plantation initiatives and inform adaptive management strategies. The success of scaling up P. oceanica plantation efforts also depends on the support and involvement of various stakeholders, including local communities, industries, and non-governmental organizations. Policymakers should invest in public awareness campaigns to raise understanding of the importance of P. oceanica meadows in combating ocean acidification and the consequences of their decline (Duarte, Losada, *et al.*, 2013). Furthermore, governments should facilitate stakeholder engagement by establishing platforms for dialogue and cooperation. Engaging stakeholders in the decision-making process can foster a sense of ownership and responsibility, thereby promoting the successful implementation of P. oceanica plantation initiatives (García-Sanz *et al.*, 2021). Lastly, political leaders must prioritize the integration of nature-based solutions, such as P. oceanica plantation, into national and international climate policies. By recognizing the role of P. oceanica meadows in mitigating ocean acidification, governments can allocate appropriate resources and support towards their conservation and restoration (Seddon *et al.*, 2020). For instance, countries should include P. oceanica plantation efforts in their Nationally Determined Contributions (NDCs) under the Paris Agreement, signalling a commitment to the scaling up of this nature-based solution (UNFCCC, 2015). Additionally, international organizations, such as the United Nations and the European Union, should consider incorporating P. oceanica conservation and restoration targets into their climate and biodiversity strategies (European Commission, 2020).

In conclusion, the potential of scaling up Posidonia oceanica plantation as a nature-based solution to combat ocean acidification underscores the urgency for political action. Policymakers and practitioners must adopt comprehensive measures, such as implementing fines, expanding protected areas, bolstering research and monitoring efforts, promoting public awareness, and integrating nature-based solutions into climate policies. By doing so, they can safeguard P. oceanica meadows as a vital component in the fight against climate change and ocean acidification.

# 6 CONCLUSION

The thesis analysed the effectiveness of Posidonia oceanica, a sea grass endemic to the Mediterranean Sea, existent close to the shore. Posidonia oceanica has experienced a degradation both in its coverage (-30%) and its healthiness. Firstly, three experiments have been conducted. Two different sites have been selected, one with Posidonia oceanica present and one without, where water samples were collected to measure the differences of pH, dissolved oxygen, and $CO_2$ concentration. The mean pH difference was 0.43, with a higher pH with sea grass present, consistent to existing literature. The mean dissolved $O_2$ difference was 2mg/L, whereas the measurements were lower in general than in existent literature though the overall finding that areas with sea grass have higher $O_2$ concentration could be confirmed. Reasons for this dissonance may have been the place or time of taking the sample or the process of taking the samples. The $CO_2$ concentration was higher in regions without seagrass, consistent to existing literature.

Posidonia oceanica shows total fixation rate can be estimated at 130gC/m²/year or 1302 tC/ha/year and the sequestration rate at 27,8 gc/m²/year which is 278tC/ha/year. To mitigate the overall European emissions with this rate, about 101 809 955 ha of Posidonia oceanica would be needed, while currently there are only 1 224 707 ha present.

In the following, the fixated $CO_2$, and the sequestered $CO_2$ by Posidonia oceanica were calculated. As Europe's yearly $CO_2$ emissions have been estimated at 3,6 bio tons, which is equivalent to 3,6 gigatons, the $CO_2$ fixation, being estimated at 13 343 878 t, therefore is about 0,3% of European emissions, while the $CO_2$ sequestration, at 2 849 154 t is merely 0,07%. While those numbers seem to be small, it is important to include the other benefits Posidonia oceanica has for the local ecosystem, the economy, and the regional marine environment.

In conclusion, seagrass management and restoration have shown to be suitable means to address ocean acidification, as seagrass ecosystems act as $CO_2$ sinks that help mitigate the negative effects of ocean acidification on marine life. Our experiment in the Mediterranean Sea demonstrated that seagrass meadows have higher pH and oxygen levels than unvegetated areas, indicating that seagrass mitigates the impacts of ocean acidification. However, several factors must be considered when developing and implementing seagrass restoration strategies for sustainable and successful outcomes, including site selection, monitoring, and community engagement. Therefore, ongoing efforts to restore and protect seagrass ecosystems are critical for a sustainable and healthy ocean. (Smith et al., 2018).

Seagrass management and restoration have proven to be effective in mitigating the impacts of ocean acidification, though they may be on a smaller scale. The results of the experiment conducted in the Mediterranean Sea indicate that seagrass plays a significant role in increasing pH and oxygen levels while reducing $CO_2$ levels. Therefore, restoration strategies that focus on improving seagrass habitats can provide long-term benefits for marine ecosystems and communities that rely on them. However, various factors must be considered to achieve sustainable and successful outcomes, such as selecting appropriate seagrass species, identifying suitable locations for restoration, and considering the effects of other stressors on seagrass growth and survival (Chefaoui et al., 2021).

The importance of seagrass management and restoration in addressing ocean acidification cannot be overstated. A recent study conducted in the Mediterranean Sea, which measured pH, $O_2$, and $CO_2$ levels in areas with and without seagrass revealed that areas with seagrass had significantly higher pH levels, indicating a higher buffering capacity against acidification. This result clearly highlights the role of seagrass ecosystems in moderating ocean acidification. Furthermore, management and restoration of seagrass ecosystems can be an effective strategy for mitigating ocean acidification. However, factors like site selection, seagrass species diversity, and long-term monitoring must be considered to ensure sustainable and successful outcomes. (Björk et al., 2019).

Even though there has been a worldwide decline of sea grass, some authors suggested the possibility of exaggerative speech regarding the state of Posidonia oceanica for authors to be published (Boero, 2015). The problem is allegedly not of urgency according to some authors. Unfortunately, this has been a consistent and ongoing stream of argumentation relating climate issues. Adversely, no matter the case, the problem of ocean acidification is urgent, and a wide-spread application of mitigation measures is crucial for the survival of the marine ecosystem of the Mediterranean Sea. It is immanent that climate issues are addressed by the principle of precaution, not prioritizing the probability that an issue may not be of immediate danger to the equilibrium of an ecosystem but endangering it long-term. The earlier the international field acts on suspicions regarding the climate crisis and its symptoms, the less tipping points will be reached.

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# Appendix