Master's Thesis – Master Sustainable Development

The Distribution of Seagrass Meadows in the Mediterranean Sea: Its Changes and Implications for Climate Change


Seagrass meadow on a sandy substrate (Jones, 2021).

Heather Huijting
h.huijting@uu.nl
6186017

Supervisor
Assist. Prof. Dr. Kees Klein Goldewijk
c.g.m.kleingoldewijk@uu.nl

Second Reader
Dr. Ralph Temmink
r.j.m.temmink@uu.nl

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Utrecht University | Faculty of Geosciences
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Abstract

Seagrass meadows in the Mediterranean Sea are critical to coastal ecosystems, offering important ecosystem services such as climate change mitigation, habitat provision for marine life, and coastline protection. Since the 20th century, the Mediterranean seagrasses have been in decline due to increasing human activities along the coastline. Despite their significance, comprehensive and accurate mapping of these meadows remains limited, creating an important knowledge gap. This research aims to address this gap by providing an updated, detailed understanding of seagrass distribution, status, composition, and their associated blue carbon potential in the Mediterranean.

To achieve this, integrated data from various sources that employed different mapping or observation methods were collected, including both ex-situ (e.g., LiDAR and remote sensing) and in-situ observations. These reports were synthesised to create an interactive QGIS map, presenting a comprehensive view of the current extent and status of seagrass meadows across the Mediterranean. This research further highlights various seagrass conservation priority areas. Additionally, an estimation of the blue carbon stock and annual carbon fixation and sequestration rates associated with Mediterranean seagrasses is presented, focusing primarily on the dominant species, *Posidonia Oceanica*. Indeed, the current estimated CO_2 stock from the seagrass meadows in the Mediterranean covers 1 to nearly 3 times the amount of their combined annual emissions.

The results highlight the role of seagrasses in the carbon cycle and highlight the urgent need for continuous monitoring and more accurate mapping techniques. This research provides valuable insights for policymakers and conservationists, offering a framework for targeted conservation efforts. The interactive map developed in this study serves as a tool for monitoring changes in seagrass meadows, planning conservation strategies, and assessing their impacts over time.

In conclusion, this research addresses the knowledge gap in Mediterranean seagrass distribution, status, and composition, emphasising the importance of seagrass meadows in carbon sequestration. It provides a foundational baseline for future research and conservation measures, advocating for targeted efforts to protect and restore these critical habitats.

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1. Introduction

1.1 Background and Knowledge Gap

Seagrass meadows are ecosystems dominated by seagrasses which are submerged flowering plants found in shallow coastal waters and can be found along the coastlines of every continent on Earth, apart from Antarctica (Unsworth, 2014). They represent crucial and diverse ecosystems, their services include fostering marine biodiversity, supporting fisheries, contributing to coastal stability, and sequestering carbon (Tang & Hadibarata, 2022). However, these important habitats face an increasingly urgent threat, their gradual degradation on a global scale. In the last 50 years, an estimated 34 per cent of seagrass meadows has disappeared (Telesca et al., 2015). The loss of these underwater habitats not only endangers the livelihoods of the local communities reliant on fisheries but also undermines their important role in combating climate change.

Although seagrass meadows can be found along many regions, the seagrass meadow population along the Mediterranean coast holds significant interest due to the region its unique ecological and socioeconomical characteristics (Aurelle et al., 2022). The Mediterranean Sea stands as a biodiversity hotspot home to various marine life within its relatively enclosed basin. Seagrass meadows in this region play a crucial role in supporting the rich marine ecosystem by providing habitats for a wide range of species, including fish, invertebrates, and endangered species such as seahorses and monk seals (Boudouresque, 2004). Moreover, the Mediterranean coastline sustains numerous communities whose livelihoods are intricately linked to coastal resources and fisheries. However, these seagrass habitats face increasing threats from human activities, including urbanisation, tourism, pollution, and climate change impacts, placing pressure on the marine environment (Unsworth et al., 2019). The Mediterranean Sea as the research area will be further discussed in *section 1.3 The Research Area.*

Furthermore, these meadows play an important role in mitigating climate change by sequestering carbon from the atmosphere, contributing to the regulation of global climate patterns. The loss of seagrass meadows disrupts this carbon sink capacity, potentially intensifying the impacts of climate change. Noticeably, the organic carbon stock of seagrass meadows (blue carbon) is higher than that of terrestrial forests (green carbon) (Temmink et al., 2022). Although the importance of seagrass meadows as a large carbon sink went unnoticed behind the extensive forest conservation efforts for a long time, the United Nations have highlighted the significance of this ecosystem as they proclaimed March 1st to be World Seagrass Day where they underline that they are in danger and emphasise the need for further research and increased awareness globally (United Nations, 2023). Understanding where seagrass meadows are being lost can help make informed targeted conservation efforts or emphasise close monitoring or call for further research where needed.

The identified gap in the literature regarding seagrass meadow mapping lies in the lack of a comprehensive map of the current distribution and state of various seagrass species along the Mediterranean coastline. While existing research has focused on mapping seagrass meadows in specific areas using collected data or remote sensing, these maps often rely on dated data, i.e., over a decade ago, or focus on one species only (Telesca et al., 2015; Traganos et al., 2022). Furthermore, these maps do not mention the (health) status of the seagrass meadows. This makes it difficult to evaluate where conservation and management actions are required.

It is essential for future research to bridge this gap by creating an overview of the location and status of all the different seagrass meadows to showcase how their distribution has been changing, and where targeted conservation efforts need to be prioritised. Further research could build upon such a visualisation through continuous monitoring of seagrass meadows, especially meadows that are in regression.

1.2 Research Aim and Questions

Therefore, to contribute to closing the knowledge gap, this study aimed to create a visualisation of the distribution and status of seagrass meadows and define conservation priorities accordingly along the Mediterranean coast. To do so, the following research question was answered:

"How can the visualisation of seagrass meadow distribution and status in the Mediterranean identify high seagrass conservation value areas and assess changes in carbon storage potential?"

The overarching research question was divided into four sub-questions:

1. What is the current distribution and status of seagrass meadows along the Mediterranean coast?
2. How can a visualised distribution and status map be used to identify areas of high seagrass conservation value along the Mediterranean Coast?
3. How are different seagrass species distributed throughout the Mediterranean Sea?
4. What are the implications of the change in seagrass meadow distribution on their past, current, and future total potential for carbon storage, fixation, and sequestration?

By answering the sub-question, an answer was given to the overarching research question of this paper. A short elaboration to the purpose of each sub-question will be given below, however, a more detailed explanation of the methods used to answer each research question can be found in the Methodology Section.

The aim of the first question was to provide a comprehensive and up-to-date assessment of the current distribution and status of seagrass meadows along the Mediterranean coast. This involved mapping the extent and health of these meadows, which is important for identifying conservation needs and establishing a baseline for monitoring future changes.

The aim of the second question was to utilise the visualised distribution and status maps to pinpoint areas of high seagrass conservation value. These areas are crucial for prioritizing conservation efforts, as they represent regions where seagrass meadows are currently considered to be most vulnerable.

The aim of the third question was to analyse the distribution patterns of different seagrass species throughout the Mediterranean Sea. Understanding these patterns could help in identifying species-specific conservation needs and in assessing the overall health and biodiversity of seagrass ecosystems in the region. Specifically, the expansion of invasive species can be further monitored this way.

The aim of the fourth question was to evaluate how changes in seagrass meadow distribution have affected their capacity for carbon storage, sequestration, and fixation over time. This includes assessing historical, current, and projected future changes in carbon storage and fixation and sequestration potential.

1.3 Research Area: The Mediterranean Sea

The Mediterranean basin is the largest European sea with a coastal length of 46.000 km and an estimated surface of 2.5 million km^2 (Onea et al., 2016). The sea encompasses a diverse region with 23 countries and territories bordering its coastline. Below in figure 1, a map presenting the countries surrounding the Mediterranean Sea is shown. Approximately $1/3^{rd}$ of the 480 million Mediterranean population live along the coastal region (EEA, 2015). The Mediterranean is the world's most popular tourist destination, in fact, their tourism has grown by nearly 75% since 1995 and over 640 million tourists are expected to visit the region in 2025 (Mejjad et al., 2022).

***Figure 1**. Mediterranean Sea and the surrounding countries (Google Maps, n.d.)*

The Mediterranean Sea contains many habitats and species including seaweeds, seagrasses, reefs, seamounts, and underwater canyons (Tsirintanis et al., 2022). Seagrasses are one of the most productive ecosystems on marine level. They inhabit up to 40 meters below the surface (open sea and lagoons) (Panayotidis et al., 2022). Generally, five main different species of seagrass can be found throughout the Mediterranean Sea (Chefaoui et al., 2018). The distribution varies, however, *Posidonia Oceanica* is often considered to be the most important and extensive meadow as it can be found along most Mediterranean coastlines (UNEP-MAP RAC/SPA, 2010). The seagrass species are further discussed in the *Theory* section.

In 2015, Telesca et al. (2015) presented multiple maps which indicated the *Posidonia Oceanica* distribution and spatial decline in the Mediterranean thus far (figure 2). The green line shows where the species had been found up until 2011, no line indicates either insufficient data or no *Posidonia Oceanica* found. The time ranges from the data used in this meta-analysis differed rather noticeably. Telesca et al. (2015) further found that there were many coastlines that had a low percentage of currently surveyed coastline (i.e., Greece, Croatia, Libya, and Algeria) whereas others had been surveyed completely such as Spain, France, and Malta. Finally, it became evident that the percentage of historically surveyed coastlines was close to zero for most countries apart from Spain, France, and Italy. Which were 70, 60 and 42 percent respectively. Within this same figure below, the red line in the bottom map shows *Posidonia Oceanica* meadows in regression, progressing or stable meadows are not reported. No line indicates no health status data on those meadows.

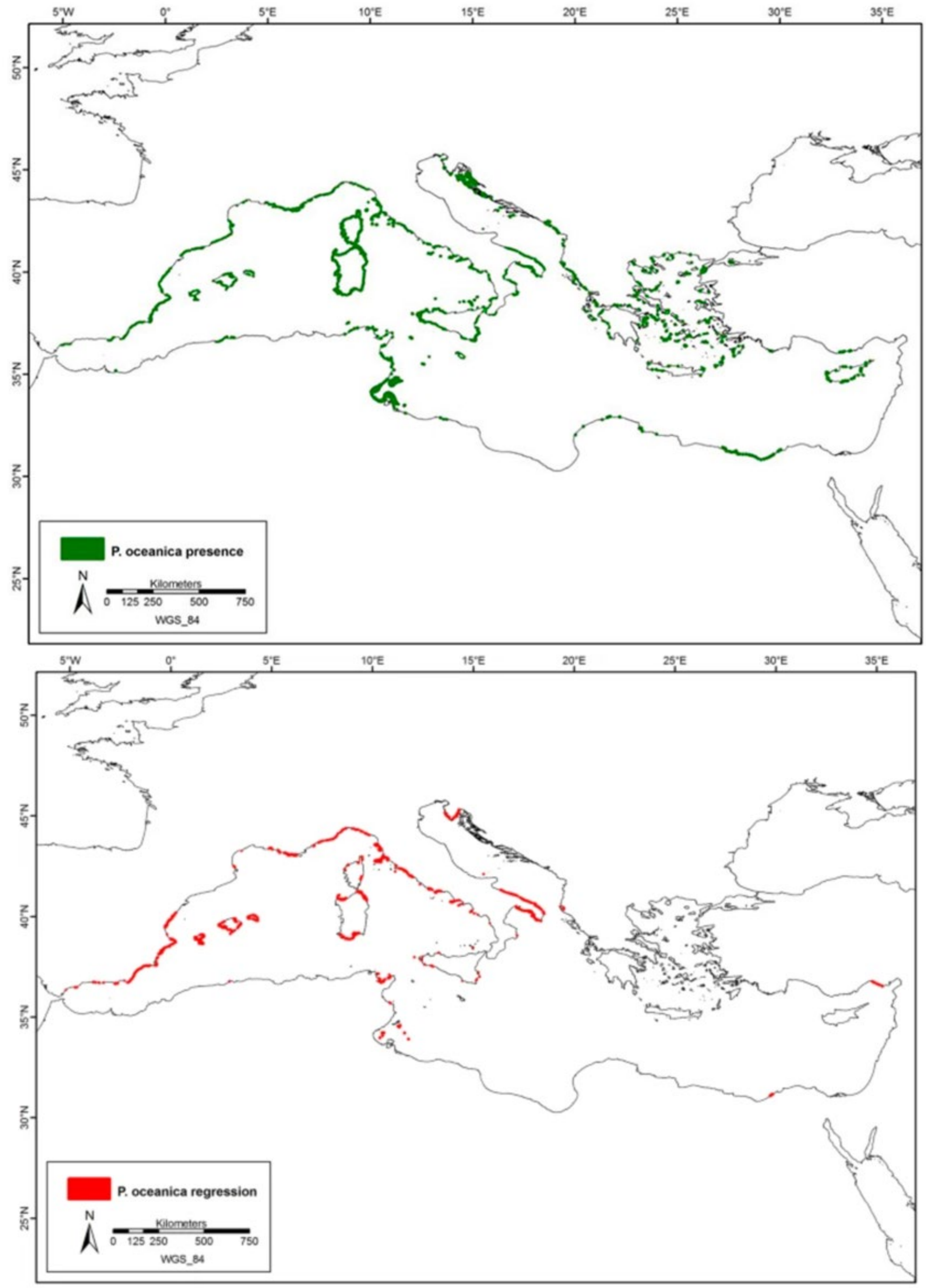

Figure 2. *Found Posidonia Oceanica presence and regression along the Mediterranean Coastlines in 2015 (Telesca et al., 2015). Top: green indicates presence, no additional coloured line indicates no found presence or insufficient data. Bottom: red indicates regression of the seagrass, no line indicates no change or insufficient data.*

1.4 Societal and Scientific Relevance

Mapping and understanding seagrass meadows along the Mediterranean coast hold substantial societal relevance. These ecosystems are vital to the livelihoods of local communities, particularly those reliant on fisheries and coastal tourism. Seagrass meadows provide crucial habitats and breeding grounds for many marine species that are economically significant and essential for sustaining fisheries. As these habitats degrade, the food security and economic stability of these communities are directly threatened. Additionally, seagrass meadows help protect coastlines by trapping sediments and reducing wave impacts, which mitigates erosion and protects coastal infrastructure. Identifying and prioritising areas for conservation through this research can guide effective policy and management strategies, ensuring the protection of these ecosystem services and aiding to the resilience of coastal communities.

Scientifically, this research addresses important gaps in our knowledge of seagrass meadow distribution and their health status, in the Mediterranean region. Creating a comprehensive and up-to-date maps that include both the distribution and health of seagrass meadows is important for understanding their presence and historical and future changes. This research aims to create a baseline for urgent and targeted conservation and management efforts by providing detailed assessments of the meadows along the Mediterranean coastlines. Moreover, by evaluating the carbon storage and fixation/sequestration potential of seagrass meadows, the study contributes to the broader field of blue carbon research, which is increasingly recognised for its role in climate change mitigation. Given that seagrass meadows are highly efficient carbon sinks, often more so than terrestrial forests, this research not only informs regional conservation strategies but also supports global efforts to combat climate change.

2. Theory

Throughout this research various concepts are used. This section functions to state, explain, and connect these concepts. Below, in figure 3, the concepts related to Seagrass Meadows are further explored, defined, and related to each other.

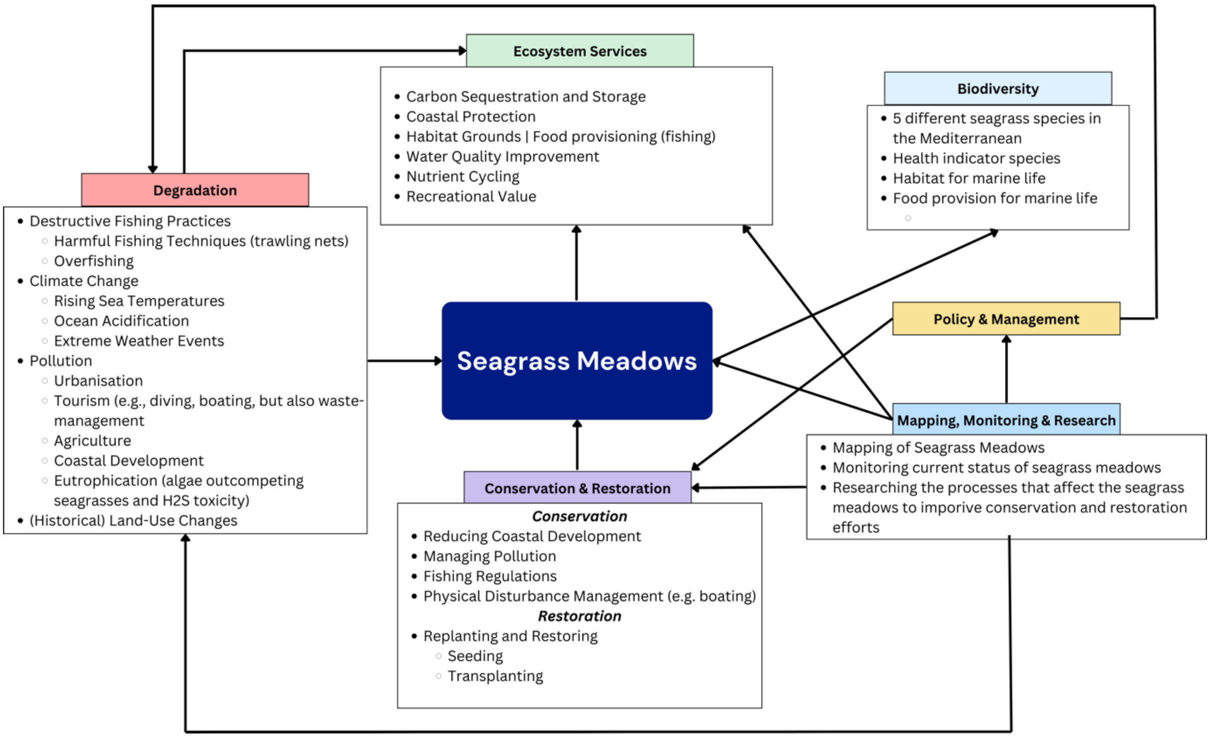

Figure 3. *Theoretical Framework: An overview of the intricate relationship between the concepts of ecosystem services, biodiversity (seagrass species), degradation, conservation & restoration, policy & management, and mapping, monitoring & research related to the seagrass meadows as described in the sections below.*

2.1 Seagrass Species in the Mediterranean

Commonly five different seagrass species are mentioned within marine habitat research in the Mediterranean Sea (Chefaoui et al., 2018). Within this section each of these five species are introduced. First a closer look is taken at the native species, and then the invasive species is discussed.

2.1.1 Native Species

Posidonia Oceanica (P.O.) | Endemic

Common Name: Neptune grass or Mediterranean tapeweed.

P.O. is an endemic species to the Mediterranean Sea. Its preferred habitat is clear, relatively shallow waters ranging from the shoreline to 25 to 30 meters in depth, although it can occasionally be found up to 40 meters depth in insular areas (Panayotidis et al., 2022). P.O is considered one of the world's oldest and largest organisms (~ 100,000 years old) (Guierrero-Meseguer et al., 2018). The species is known for this very long lifespan, with meadows regularly being thousands of years old, however, the species also grows very slowly (Pansini et al., 2022). This makes the species increasingly vulnerable to disturbances as recovery can take up to decades if not centuries.

The species can withstand certain seasonal variability when it comes to temperature, optimally between 10 °C and 25 °C, however, it can at times adapt for a short time to slightly lower or higher temperatures (Stipcich et al., 2022). Prolonged exposure to temperatures outside these ranges can cause stress to the species and ultimately lead to a decrease in their growth, reproductive, and photosynthesis rates (Stipcich et al., 2022).

Cymodocea Nodosa (C.N.)
Common name: little Neptune grass.

Its distribution falls within the Mediterranean Sea, the eastern Atlantic Ocean, from the Iberian Peninsula down to Senegal where it thrives best in shallow coastal waters, estuaries, and lagoons (Cunha & Araújo, 2009). These suitable habitats are preferably muddy or sandy substrates at depth ranging from shallow waters up to 35 meters depth, they need ample light and can tolerate up to moderate water movement (Schäfer et al., 2022; Ivajnšič et al., 2022). The species its optimum temperature range is between 10 °C and 32 °C, which causes for less concern when it comes to future continued warming comparatively to P.O. (Egea et al., 2018).

Zostera Marina (Z.M.)
Common Name: Eelgrass

Z.M. is one of the most widely distributed seagrass species of the Northern hemisphere, it can be found in subtropical coastal regions, however, also can be found in the Arctic Circle (Boutahar et al., 2020). It thrives best in a depth range of 1 to 10 meters, and a temperature range between 10 °C and 25 °C, higher temperature during seasonal variation has caused plant mortality within meadows (Plaisted et al., 2022).

Zostera Noltei (Z.N.)
Common Name: Dwarf Eelgrass or Nolte's Seagrass

Z.N. is predominantly found along the Atlantic coastlines of Europe and Africa, ranging from Northern Norway all the way into the Mediterranean Sea, where it occurs in very shallow coastal waters around intertidal depth (Azevedo et al., 2016). An estimates sub-lethal temperature of the seagrass species is about 38 °C, which is necessary with the intertidal habitat where temperatures reach higher numbers than in deeper waters (Massa et al., 2008).

2.1.2 Invasive Species

Halophila Stipulacea (H.S.)
Common Name: Broadleaf Seagrass

This seagrass species is native to the Red Sea and the Indian Ocean. Since the opening of the Suez Canal in 1869, a way was open for the species to spread towards the Mediterranean where it was first reported in Rhodes only 25 years later (Fritsch, 1895). It has also spread to the Caribbean Sea, it is assumed this happened through maritime traffic from the Mediterranean to the Caribbean, unlike the spread towards the Mediterranean, this invasion is recent, around 2 decades ago, and much more rapid (Winters et al., 2020).

Like most seagrasses the species prefers sand, rubble, and dead seagrass mats substrates in shallow waters (and lagoons and estuaries). It can be found at depth ranging between 0 to 27 meters and within a large temperature range of 10 °C and 30 °C (Winters et al., 2020; Georgiou et al., 2016). This makes temperature a non-limiting factor within the Mediterranean for this species, and therefore, it is expected to spread throughout the entire Mediterranean Sea in the next 100 years (Georgiou et al., 2016).

As H.S. is an invasive species within the Mediterranean it poses a threat to native seagrass species and the natural habitats. H.S. could outcompete native seagrass species such as C.N. and P.O. and alter entire local marine ecosystems. Therefore, it is important to monitor the expansion of this species and study consequent effects and potentially implement measures.

2.2 Ecosystem Services and the (Potential) Role of Seagrass in Climate Change

Seagrass meadows offer numerous ecosystem services that hold substantial societal and scientific value. These meadows serve as a shield against coastal erosion, provide habitat to various marine life, provide food resources (i.e., fishing), enhance water quality by trapping sediments, and offer recreational opportunities such as diving (de los Santos et al., 2022). Beyond these direct benefits, seagrass ecosystems contribute significantly to fundamental processes like nutrient cycling and carbon storage and sequestration. Of particular significance is their role in carbon sequestration, especially in the context of combating climate change. The carbon sequestered by water-based ecosystems like seagrass meadows, salt marshes, and mangroves is often termed 'Blue Carbon,' distinguishing it from the 'Green Carbon' stored in terrestrial vegetation and soil (e.g., tropical, and boreal forests). Seagrasses have a higher potential CO_2 stock—approximately 522 Mg to 711 Mg per hectare—compared to both tropical (242 Mg/ha) and boreal forests (239 Mg/ha) combined (Pergent-Martini et al., 2022; Pendleton et al., 2012; Pan et al., 2011). This underscores the crucial role of seagrass meadows as essential carbon sinks, comparable to the function of forests in mitigating climate change. Therefore, their disappearance not only endanger their invaluable direct services but also eliminates significant carbon sinks, exacerbating the challenges associated with climate change. Protecting and preserving seagrass meadows is therefore of great importance, not only for their inherent ecological value but also for their important role in mitigating the impacts of climate change.

While seagrasses are home to various species, these species also influence the seagrass meadows they live in. On the one hand, species such as turtles eat the grass which can be problematic in already regressed meadows and further cause degradation (Christianen et al., 2014). On the other hand, species such as sea otters aid seagrass recovery in two different ways, namely (1) they dig in the sand promoting increased reproduction rate in seagrasses and (2) they eat crab species that tend to hunt algae-eating slugs, leaving the slugs free to combat eutrophication that has been degrading seagrass meadows in some areas (Foster et al., 2021; Levy, 2015).

2.3 Degradation

Degradation of seagrass meadows can happen due to numerous drivers, in 2010, the European Environmental Agency asked the European Mediterranean countries what activities caused what percentage of P.O. degradation. The results of this inquiry can be seen in the pie chart below (figure 4). It must be noted that this is Mediterranean specific (high levels of tourism has increased construction of coastal infrastructure (22%)) and does not include the sea temperature rise as this was not considered as a driver for the degradation of these habitats yet at the time. This rapid increase in tourism and coastal infrastructure, and invasive species have already been discussed as degradational drivers. Water pollution, fishing, and shipping will be further discussed in this subsection.

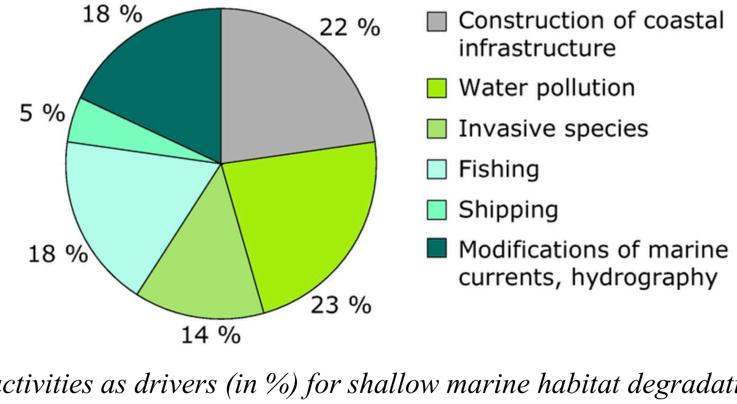

Figure 4. *Human activities as drivers (in %) for shallow marine habitat degradation (EEA, 2010).*

Firstly, pollution, specifically from nutrient and organic matter accumulation, emerges as a concerning factor leading to eutrophication and subsequent algal blooms. These algal blooms outcompete seagrasses for light, inhibiting growth and survival of seagrasses. Then once the algae die and decompose hydrogen sulphide is produced, which is a toxic substance that can further harm the marine life and disrupt the ecosystem (Rai et al., 2000). Urbanisation, tourism, and agricultural activities are identified as potential pollution sources in the Mediterranean region (Çulha et al., 2022). Furthermore, Çulha et al. (2022) discovered that sedimentation from coastal development and inadequate waste management practices can suffocate and harm seagrass. Research has found paleontological evidence within seagrass meadows, indicating degradation spanning thousands of years, extending beyond recent human activities (López-Merino et al., 2017). These findings underscore the significant impact of land use and land cover (LULC) changes in seagrass decline. López-Merino et al. do, however, further stress that the decline in seagrasses did not seem to be as extreme then as it has been in recent decades.

Secondly, perhaps more directly destructive drivers of seagrass ecosystem degradation are overfishing, harmful fishing practices and maritime traffic. Trawling nets, notorious for scraping and uprooting seagrass, pose a significant threat (Ramesh et al., 2018). Additionally, anchoring boats in shallow seagrass areas can inflict considerable damage, as highlighted by Ramesh et al (2018).

Thirdly, although not mentioned in the EEA pie chart above, climate change may also cause seagrass degradation. Elevated sea temperatures, ocean acidification, and shifts in weather patterns are disrupting the distribution and productivity of the meadows. Studies indicate their sensitivity to temperature changes, forecasting a further decline if warming trends persist (Tang & Hadibarata, 2022). Moreover, the ability of seagrass to withstand climate shifts is also based on sediment type and varying levels of exposure to wind, the latter of which faces potential changes with increased extreme weather events due to climate change (de Smit et al., 2021).

2.4 Conservation and Restoration

Efforts to conserve and restore seagrass meadows have seen some progress in select regions. Successful conservation endeavours have prioritised decreasing pollution, reducing fishing pressure, and promoting sustainable tourism practices (Losciale et al., 2022). Additionally, restoration initiatives have been undertaken, employing methods like transplanting seedlings and fragments of seagrasses into degraded areas (Ventura et al., 2022).

However, it is crucial to note that restoration techniques are not as effective as conservation strategies for seagrass meadows, making them a less preferable option over conservation if possible (Pansini et al., 2022). Pansini et al. (2022) explain that this is primarily due to the slow growth rate of seagrass and the lack of consensus on successful restoration approaches, stemming from limited available data. Consequently, ongoing monitoring and further research are imperative to comprehend the current status, conservation, and restoration potential of seagrass meadows. This research will play a pivotal role in informing policymakers about the most urgent and target-specific conservation areas within the Mediterranean Sea

2.5 Seagrass Mapping Strategies and the Frontiers

The mapping of seagrasses can be done through different methods, mainly via on-site data collection (In-situ) and via remote or indirect data collection (Ex-situ). In this section some relevant methods are discussed for each type of data collection and mapping method. Lastly, the most prominent Mediterranean seagrass maps are discussed and compared.

2.5.1 In-Situ

Diving and Snorkelling Data Collection

This method uses direct observations and mapping by divers or snorkelers with a sufficient knowledge of identifying seagrass. The advantages are that there is high accuracy, detailed ground-truthing, and species can be identified and their health assessed. Limitations include the labour intensity, highly time intensive for a limited spatial coverage and finally the weather and depth constraints related to diving and snorkelling limit this type of collection also.

Underwater Video and Photographic Surveys

Underwater cameras can capture videos and imaging of seagrass meadows. This can be done by the divers and snorkelers, however, can also be done by boats. Advantages include visual confirmation, and here too identification of species and health statuses can be attained. Limitations are similar to diver and snorkelling, however, can be less labour intensive if boats are used to retrieve the imaging. The process still remains relatively time intensive.

Citizen and Participatory Mapping

Local communities could be involved to collect data using simple tools and techniques (such as during snorkelling). Advantages would include high cost-effectiveness, retrieving large datasets, while simultaneously raising awareness. Limitations include that it requires training and coordination and more importantly for accuracy-sake, the data quality may vary greatly depending on the individual and their background experience.

2.5.2 Ex-situ

Aerial Photography (manned) and Drone (unmanned) Surveys

One method captures images from aircrafts and the other employs drones to capture high-resolution imaging and videos (E.g., Yang et al., 2020 is currently developing a drone training program for researchers who wish to monitor and research seagrasses). Both have the advantage of produce high spatial resolution imagery, they are relatively cost-effective for small to medium areas (drone) and large areas (aircraft). Downsides include that it is limited by weather conditions for both flying and water clarity, aerial photography may be more labour intensive to interpretate, but drones are limited to the battery life of the device.

Satellite Remote Sensing

Here satellite imagery is used to detect seagrasses (An example would be the earlier discussed Traganos et al., 2022). The advantages are that it can cover large areas, it can be done repeatedly over time for monitoring purposes, it can be very useful for more remote locations, and with AI algorithms it can be very cost and time efficient. Limitations here are the lower spatial resolution compared to aerial photography which can lead to lower accuracies (around 70%), and it is very limited by water depth and turbidity, finally, it cannot differentiate between all seagrass species (Panayotidis et al., 2022).

Acoustic Mapping (Sonar)

Sonar equipment can be used to map the seafloor and detect seagrass meadows (Moniruzzaman et al., 2019). Advantages to this technique is that it is effective in turbid waters, it can cover large areas and it also provides detailed bathymetric data in general. Disadvantages are that is requires specialised equipment and expertise, therefore, the procedure is more costly, and the interpretation of the data can be complex.

Light Detection and Ranging (LiDAR) and Multi/hyperspectral Imaging

Laser light can be used to measure the distances between and map underwater features. Spectral imaging can capture images in various wavelengths to identify different types of vegetation. Pan et al., published a comparison paper on hyperspectral imagery and bathymetric lidar in shallow waters (Pan et al., 2016). LIDAR has high spatial resolution, it can penetrate clear waters and provide a full 3D mapping.

Recently, a study in the Bahamas showed that accuracies for mapping seagrass through LiDAR can range between 92 to 98% (Ekelund et al., 2024). However, it its very cost intense, not as effective when turbidity is high, and it requires an aircraft or advanced drone platforms. Spectral imaging has the same advantages and limitations; however, it does not need an aircraft, but instead specialised sensors and data processing. However, its advantage is that it can differentiate between different seagrass species.

2.5.3 Combination of In-Situ and Ex-Situ

Any combination of the techniques above can be combined and entered into a GIS platform. This could lead to a comprehensive analysis; it would be easy to update and manage and can support different data types. Limits here is that it requires technical expertise, there could be some data integration challenges and it is resource-intensives as multiple mapping techniques are used.

2.5.4 Current Published Distribution Map

In the literature currently, there are two prominent and often referenced seagrass distribution maps. Namely (1) Telesca et al. (2015) and Traganos et al. (2022). The difference between these maps can be seen in the figure below (figure 5).

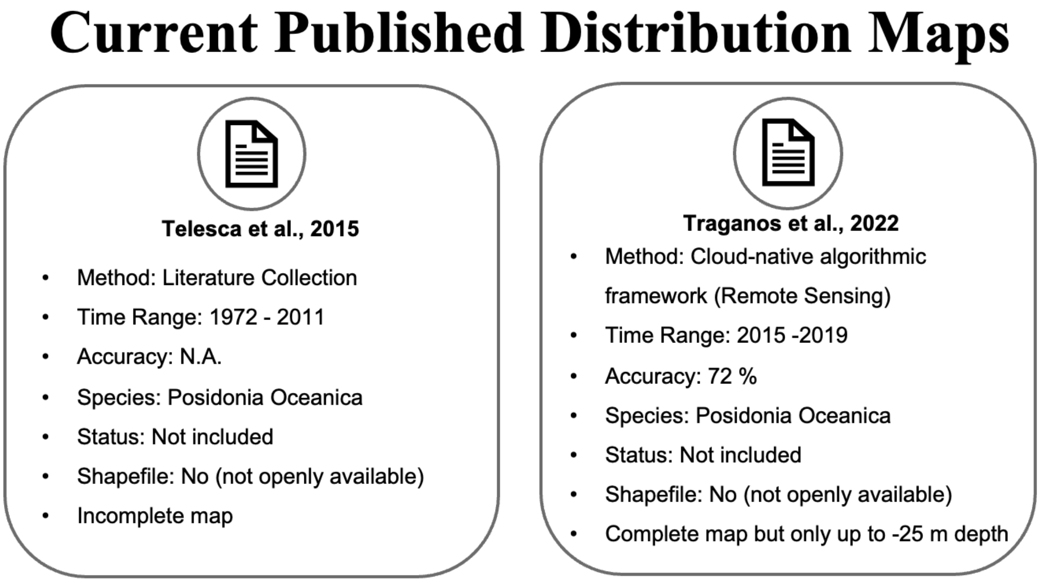

Figure 5. *A characteristics comparison between the two prominent seagrass distribution maps of the Mediterranean.*

Their methodology differs as do their time ranges. The main differences here are that Telesca et al (2015) is older and is not a complete map as not all coastlines had been reported upon during their literature collection. Traganos et al. (2022), was able to use remote sensing to map all the coastlines of the Mediterranean, however, only up to -25 m depth as the current satellite imaging can only be analysed up to that point within marine habitats. They have some similarities, which can be considered limitations, such as: both maps only consider one species (P.O.), do not include the status of the mapped meadows (regressing, progressing, etc.), and do not have a publicly available shapefile accessible.

This research aims to build upon those limitations, and has included all Mediterranean seagrass species, the health status of the meadows, and has made the map publicly available for others to use in further research.

2.6 Policy and Management

Within and along the Mediterranean Sea several policy and management implementations are to be highlighted. Most notably, the marine protected areas and both international agreements and national policies that apply to the habitats within the sea or even seagrasses specifically.

2.6.1 Marine Protected Areas (MPAs)

Marine protected areas are legally designated to conserve biodiversity, in some cases including seagrass meadows, and often restrict or manage human activities such as fishing, anchoring, and coastal development. Examples are marine reserves, wildlife sanctuaries, or national parks. MPAs can differ in levels of protection (from no access to various levels of limited access). Additionally, they can also differ throughout the year, for instance activities such as fishing may not be allowed at all during an important breeding season of a fish species (van Overzee & Rijnsdorp, 2015). A large and notable MPA network is the Marine Natura 2000 Network in Europe, which was coined based on the habitat and birds directive (see section 2.6.2) to protect threatened species in European waters (Kriegl et al., 2021). Due to the large presence of this network, the European Mediterranean coastline is covered by significantly more MPAs than the Asian and African Mediterranean coastlines (MAPAMED, 2022). A map containing MPAs can be seen below in figure 6.

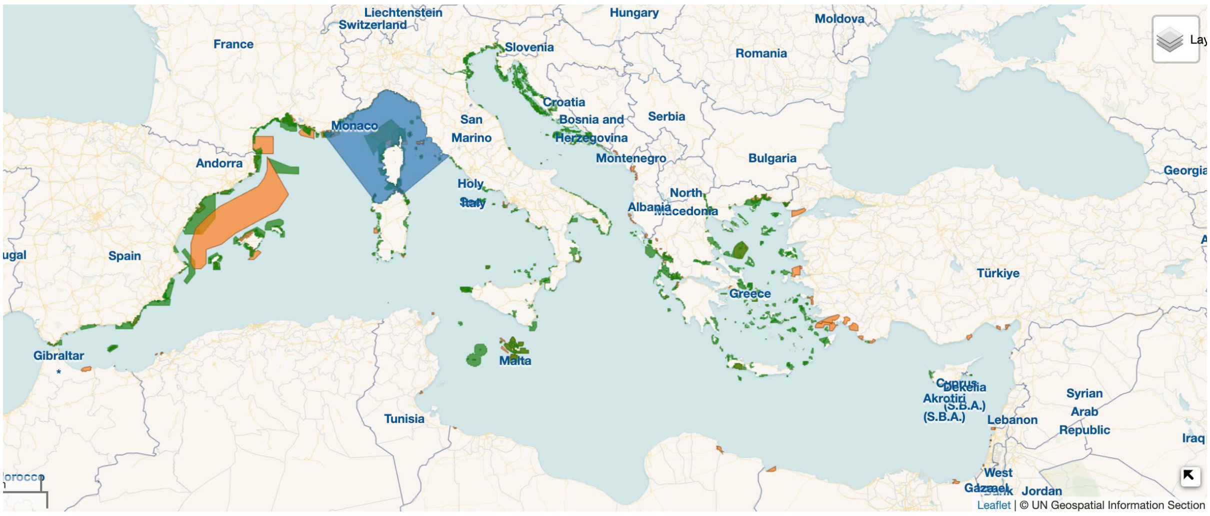

Figure 6. *The MPAs of the Mediterranean. Green indicate Natura 2000 areas, blue indicates the Pelagos Sanctuary areas, and orange represents national MPAs. (MAPAMED, 2022)*

2.6.2 International Agreements and National Policies

The Barcelona Convention (UNEP-MAP, 2024)

The Convention for the Protection of the Marine Environment and the Coastal Region of the Mediterranean, commonly known as the Barcelona Convention, is a regional agreement adopted in 1976 to combat pollution and protect the Mediterranean Sea from various sources of contamination. It originally focused on preventing pollution from ships, aircraft, and land-based activities such as dumping and discharges, the Convention has, since 1995, evolved to address broader environmental concerns and promote sustainable development in the Mediterranean region. One such addition is the conservation of biological diversity, which includes marine flora and fauna that are rare, endangered or threatened. The Convention considers one seagrass species among the threatened category, namely *Posidonia Oceanica*. All Mediterranean countries are members of this Convention.

The Bern Convention (The Council of Europe, 2024)

The Bern Convention, formally known *as the Convention on the Conservation of European Wildlife and Natural Habitats*, was initially signed in 1979 and revised in 1996 to include marine species like *Posidonia Oceanica*, *Zostera Marina*, and *Cymodocea Nodosa*, emphasising their need for protection.

It states that contracting parties must uphold suitable legislative and administrative measures to conserve these habitats, striving to prevent or minimise any regression, and to coordinate efforts especially in border regions. It must be noted that as this is a European Convention, not all Mediterranean countries are part of this. Although Morocco and Tunisia have also signed to the convention. This leaves Algeria, Egypt, Israel, Lebanon, Libya, and Syria as non-part of the Convention.

EU Directives: Habitats Directive, Water Framework Directive, and Marine Strategy Framework Directive (Mediterranean Posidonia Network, 2023)

These directives state that *Posidonia Oceanica* is considered a priority habitat for conservation and the evaluation of *Posidonia Oceanica* health can be used as an indicator to assess the "Good Environmental Status" of marine waters within the European Union.

National Policies and Legislation

On a national level, different policies and legislations may apply. To avoid redundancy, any policies and legislation specific to Mediterranean seagrasses on a national level are discussed and considered under the country specific section within the results of this thesis.

3. Methodology

3.1 Research Strategy

This research strategy encompassed four key components: (1) data collection, (2) mapping within a Geographic Information System (GIS), (3) defining conservation areas, and (4) analysis of carbon fixation, sequestration, and stock potential.

Figure 7 below provides a concise overview of the methodology approach. The following subsections will elaborate on each component in greater detail.

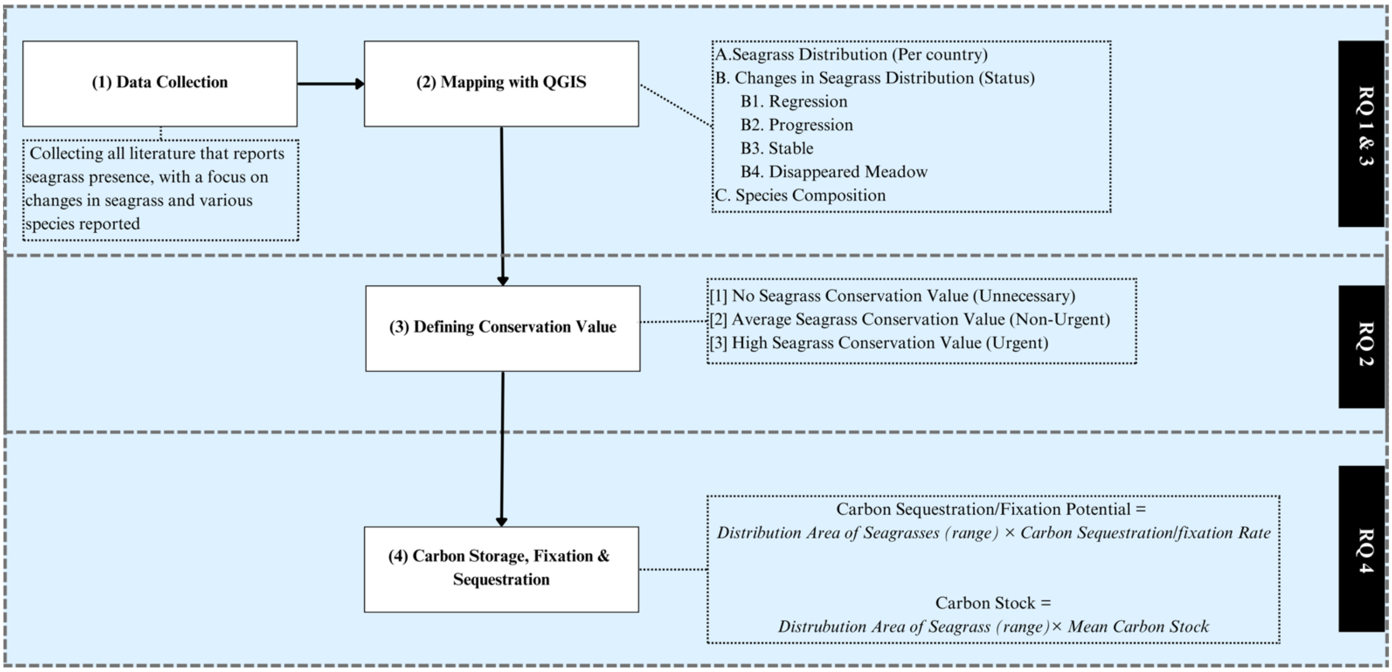

***Figure** 7. Flow Diagram of Methodology steps, including a specification of which section belong to which sub research question (RQ).*

3.1.1 Data Collection

First, a collection of existing literature concerning seagrass species within the Mediterranean Sea took place. The collection was done with peer-reviewed literature sourced both online (e.g., published articles, e-books) and offline (e.g., books), accessible within Dutch University libraries. Online searches were done through various search engines including Google Scholar, Wolfram Alpha, Science.gov, and JSTOR. The search criteria encompassed keywords such as "seagrass," "meadow," "distribution," and "Mediterranean coast," among others.

All reports of seagrass presence, and their status (progression, regression, stable or disappearance) were collected. An excel document with an overview of all reports collected can be found in the Supplementary Information (Section 9.1). Within this document a complete overview of all the papers can be found within the *Meta Data* sheet, which for each report includes: (1) country, (2) region, (3) area of seagrass reported in km_2 (if available), (4) the start and end year of the data collection, (5) the kind of information: Shapefile, PNG, descriptions or coordinates, (6) source information including in-text reference, APA reference, and a direct link, finally (7) notes containing important conclusions or findings (if applicable to this research).

Moreover, a tab was created for each country which contains the according PNG files, with their references. This information was used during the next section of the research.

3.1.2 Mapping within QGIS

Next, to gain a more precise and visual grasp of the literature collected, QGIS was used to construct an interactive map presenting three main aspects: (1) seagrass distribution (per country), (2) status of seagrass: progression, regression, stable or disappeared, and finally (3) the species along the Mediterranean coastline.

The presence is divided into groups, each group representing a country. This allows for country specific information to be consulted. This interactive map can be found in the Supplementary Information (Section 9.1).

3.1.3 Defining Conservation Value

Third, to highlight the high seagrass priority conservation areas, a definition specific to this research needs to be established. Therefore, the national coastlines will be divided into three categories according to three Seagrass Conservation Priority (SCP) values. To assure consistent allocation of these SCP values, four criteria are considered, namely (1) seagrass presence, (2) seagrass status, (3) reported degrading factors (tourism, urbanisation, maritime activity, etc.) and (4) legislation, regulations and MPAs.

The SCP values range from 0 to 2, each category in connection to the mentioned criteria is described below:

0 – No seagrass conservation priority value (unnecessary)
Category 0 represents areas of low to no conservation value, indicating there are no seagrass meadows (left) to conserve. These regions lack seagrass, no longer possess it, or have as good as disappeared, labelling them of least interest for conservation efforts.

1 – Average seagrass conservation priority value (non-urgent)
Category 1 signifies an average conservation value, representing stable seagrass areas without extreme regression or direct threats and they may have some regulations in place. While these regions warrant protection from potential future degradation, they are not deemed a primary priority for conservation efforts at this very moment.

2 – High seagrass conservation priority value (urgent)
Regions categorised as 2 in the conservation scale are under direct threats, requiring urgent conservation measures. Immediate action is essential to prevent these meadows from reaching a critical point where they might vanish. Areas experiencing coastal expansion, growing tourism, or other degrading impact changes identified through the literature review and mapping may be flagged as areas of concern as well. These categories may not have policies in place to protect the seagrass meadows, or they may have policies which appear not to be effective in protecting the meadows. If these areas are in proximity to seagrass meadows, they warrant classification as having a high conservation value (2).

Each national coastline was allocated a SCP value, and further descriptions of the motivation for each value were briefly described for each country.

3.1.4 Carbon Fixation Rate and Stock

To calculate the fixation and sequestration rate and stock of the seagrass within the Mediterranean, several values were used. As there is no current knowledge on the exact area of each individual seagrass species, the fixation rate and stock of most common Mediterranean seagrass species *P.O.* was used and extrapolated.

A lower and upper limit of seagrass area was used to calculate and extrapolate the carbon fixation rate and stock because there is no precise data on the extent of seagrasses in the Mediterranean and estimates vary. By using a range for the seagrass area, variability and uncertainty can be partially accounted for. Note that this therefore means that no range of either rates or stock was taken as the range in seagrass extent is much higher.

Fixation rate
The mean carbon fixation corresponds to the integrative depth of -15 m and was calculated to be 138,5 g C m/yr (or 138,5 Mg C/km^2/yr) (Monnier et al., 2020).

Here,

Carbon fixation rate = Area of Seagrass (upper and lower limit) × Mean Carbon Fixation Rate

Sequestration rate
Where fixation has initially captured the carbon out of the surroundings, sequestration presents the amount of Carbon that is then consequently fixed and added to the Carbon storage. According to the same research, 27 to 30 % of the fixation rate is sequestered into the Carbon storage (Monnier et al., 2020).

Carbon Stock
The mean matte thickness of P.O. within the Mediterranean Sea is 210 cm, the trapped organic carbon within a matte a thickness of 210 cm is 711 Mg C/ha (or 71.100 Mg C/km^2) and is referred to as the carbon stock (Monnier et al., 2020).

Here,

Carbon Stock = Area of Seagrass (upper and lower limit) × Mean Carbon Stock

Conversion factor of C to CO_2
As a comparison to national annual CO_2 emissions is made within the results, below the according conversion factor of C to CO_2 is presented.

- The weight ratio of CO_2 to C is:

$$\frac{44\ (CO2)}{12\ (C)} = \frac{44}{12} \approx 3{,}67$$

Therefore, each Mg C corresponds to the release of 3,67 Mg CO_2.

3.2 Data Management and Archiving

Over the course of the last 30+ week, a substantial volume of data was gathered, refined, and analysed. While the conclusive results of this analysis are detailed in this paper, it is essential not to overlook the importance of archiving all the data into a database accessible to the Sustainable Development department. Therefore, a Sustainable Development server was set up by Assist. Prof. Dr. Kees Klein Goldewijk. This Sustainable Development server allows others within the academic community to benefit from, learn from, or expand upon the dataset. By making this data available on the server, it serves as a resource for inspiration and potential further research, fostering opportunities for further research and development within the field of Sustainable Development.

For interested individuals not affiliated with the Sustainable Development Master, all the data gathered as mentioned above can be found in the Supplementary Materials (*Section 9.1*).

4. Results

Within this section the results are presented in detail based on the order of the research questions posed in this thesis. First, a visualisation of the distribution and status, i.e., progression, regression, stable and disappeared, of seagrass meadows is presented. Second, the seagrass conservation priority values are assigned to the different coastlines based on the conditions presented in the methodological framework. Third, the composition of seagrass species around the Mediterranean Sea is discussed, including two other species that were found during the research process that were not mentioned in the theory section. Finally, the carbon stock potential change and projections are discussed.

Note that an interactive QGIS file with the data discussed in the first three sub-sections is available and can be found in the Supplementary Material.

4.1 Seagrass Distribution and Status

This subsection provides an overview of the current distribution and status of seagrass meadows, accompanied by illustrative maps. Figure 8 offers a visual representation of where seagrass is present (green line) or absent (white dots) and highlight regions where research is still needed (yellow line, specifically highlighting Palestine).

Figure 8. *Seagrass Distribution along the Mediterranean Coastlines, where green indicates seagrass presence, white dots indicate reported seagrass absence, and the yellow line (Palestine specific) indicates that the national coastline has no published research on seagrass presence.*

Additionally, the second map, figure 9, indicates the status of seagrass meadows, showing areas of regression (red), progression (green), stability (blue), and disappearance (black). Although some progression is reported (8 papers), regression was reported in higher numbers (47 papers), another 12 papers found stable meadows in various locations and another 7 papers reported disappeared meadows.

For a more detailed and country-specific analysis of seagrass distribution and status, please refer to the following section, 4.2. The composition of which seagrass species was reported to be in different states is discussed in section 4.3. To see the number of reports for each country, see the Appendix (section 9.2.1)

Figure 9. *Seagrass status along the Mediterranean Coastlines. Green indicates progressing meadows, blue indicates stable meadows, red indicates meadows in regression and black highlights areas where seagrass meadows have entirely disappeared.*

4.2 Country Summaries and Seagrass Conservation Priority Value

Within this section, each Mediterranean country/state is discussed in more depth and assigned a SCP value based on the conditions described in the methodology: (1) seagrass presence, (2) seagrass status, (3) known degrading factors (tourism, urbanisation, maritime etc.), and (4) legislation, MPAs, and regulations. This value ranges from 0 to 2, a more in-depth explanation for each value was discussed in the Methodology:

0 – No seagrass conservation priority value (Unnecessary)
1 – Average seagrass conservation priority value (Non-Urgent)
2 – High seagrass conservation priority value (Urgent)

For an overview of the SCP values assigned to each country and state, see table 1 below.

Country	Seagrass Conservation Priority Value
Albania	1
Algeria	1
Bosnia & Herzegovina	0
Croatia	1
Cyprus	1
Egypt	1 (leaning towards 2)
France	**2**
Greece	1
Israel	0
Italy	**2**
Lebanon	0
Libya	1

Country	Seagrass Conservation Priority Value
Malta	1
Monaco	1
Montenegro	1
Morocco	1
Palestine	0
Slovenia	1
Spain	**2**
Syria	1
Tunisia	**2**
Turkey	1 (leaning towards 2)
Gibraltar	1

Table 1. *Seagrass Conservation Priority (SCP) Value per Country. Countries in bold have a SCP value of 2; High Seagrass Conservation Priority (Urgent)*

4.2.1 Albania

Three species were found along the Albanian coastline, C.N., P.O., and Z.N. Most of the distribution is on the southern coast, close to the Greek coast. A large concentration can be found within the Narta Lagoon, which borders a nature reserve (Vjosë-Nartë Delta Protected Area), limiting direct human influences near the coastline. A bit more south right off the coast of the city Vlorë, the third largest city in the country, the present seagrass meadows are in regression. Here you can also find various hotels, beaches, and harbours. According to Pergent-Martini & Le Revallec (2007), seagrasses are protected in the national legal framework, however, they are not of specific concern in EIA Albanian regulation.

Albania has no Marine Natura 2000 sites; however, they do have A MPA with National statute. Such as the Karaburun Sazan National Marine Park, which was set up in 2016 (MAPAMED, 2022). Other protected areas are three nature parks on coastal lands which may limit direct anthropogenic effects from coastal acitvities, however, do not technically consider marine habitat (MAPAMED, 2022).

Due to the presence of seagrass, the limited regression to the urban areas, and somewhat lacking protection within legislation and marine protected areas, a SCP value of 1 is allocated to the Albanian coastline.

4.2.2 Algeria

There have been two species found in Algeria, namely, P.O and Z.N (previously also Z.M.). Most P.O. can be found from the central coast eastwards. In the central coast area, several P.O. and Z.N. meadows are found to be in regression; however, one P.O. meadow seems to be stable as well. Previously found Z.M. is no longer detected on the seafloor in this location (Pergent et al., 2014). This location is just off the coast of Algiers, the capital and largest city of Algeria. Algeria is, as of now, not a large tourist destination mainly due to difficult visa requirements and a general lack of tourism accessibility and demand (Ministry of Foreign Affairs Algeria, 2022). This lack of coastal tourism and resulting need for no coastal development could be a reason for no regression outside of the coastal area of the capital city being reported.

Although Algeria has had strong regulations concerning EIA studies for the protection of wild flora and fauna, marine ecosystems were not directly considered in these regulations (Pergent-Martini & Le Revallec, 2007). Furthermore, they have little to no MPAs. The four marine reserves they do have, span from a total of 6 km^2 (since 2005) to 42,83 km^2 (since 2019), which is extremely small compared to their total coastline of 2.148 km (MAPAMED, 2022; Yahia Meddah et al., 2023). Only recently it was discovered the coastline was much longer than previously thought. Prior to 2023 and the use of remote sensing, it was believed the coastline was 1.622 km (Kaddour et al., 2022; Yahia Meddah et al., 2023).

As, apart from the capital city, there is no direct concern about human impacts on the seagrass meadows along the coast, the absence of large regressing meadows, however, still a lack of marine protected areas covering the meadows, the Algerian coastline is considered to have a SCP value of 1.

4.2.3 Bosnia & Herzegovina

There used to be little known about the seagrass presence in Bosnia & Herzegovina (Telesca et al., 2015). Until Celebicic et al. (2018), found a complete absence of seagrasses up to 10M depth. The study assumed the degradation of artificial beaches are the cause of this. They stumbled on this discovery during research on the endemic Bivalvia fan shell in the coastal area in 2018, where they compared their findings to a survey 38 years prior.

After Monaco, Bosnia & Herzegovina have the shortest coastline in the world which only stretches over 24,4 km long (Gekić et al., 2022). There could be seagrasses at >10M depth, however, this has not yet been researched. Partially as this short coastline is mostly sheltered from open sea by the Croatian islands and coastlines, which could make it unlikely that any seagrass species have been introduced in this area or could be able to thrive here. Milanovic et al. (2015) found there to be no Natura 2000 marine areas in Bosnia & Herzegovina, however, they did mention that the Natura 2000 marine areas bordering in Croatia, did have some P.O.

Therefore, further research could answer the question if here too seagrasses can be found in depths over 10M. However, as there is no current seagrass presence known and the potential seagrass cover is rather small compared to other larger coastlines with already established cover, Bosnia & Herzegovina falls under the SCP value of 0.

4.2.4 Croatia

P.O., Z.N., and C.N. can be found along the Croatian coast. Significant P.O. regression can be seen since 1938, however, areas where P.O. has disappeared, C.N. has extended. A further drastic decrease in the already small presence of Z.N. can also be seen, Zavodnik & Jaklin (1990) go as far to call it 'largely extinct'. They assume the reason for the alterations in distribution and presence is on a local scale due to direct pollution effects and on a broader scale an increased siltation and altered light conditions due to an increase in water turbidity.

The largest amount of regression can be seen near Rijeka, a large port city that is seen as the "gateway port" to the Croatian islands which has no specific regulations as to protect marine life. Whereas the P.O. and C.N. progression areas are found near the city of Pula, which is a Marine Natura 2000 site (MAPAMED, 2022). On paper, seagrasses have officially been protected since 2006 according to Pergent-Martini & Le Revallec (2007). The authors emphasise that although they may be considered protected, there is no official legislation or rules connected to the protection of these marine plants.

These factors considered; the Croatian coastlines are given a SCP value of 1.

4.2.5 Cyprus

Cyprus has three different species of seagrass in their coastal waters, namely, H.S., P.O., and C.N. Not the entirety of the coastline has been investigated, however, some in depth research on specific regions has been conducted. For instance, the Saphos district was mapped with remote sensing and pixel-based classification and has resulted in a highly detailed distribution map (Makri et al., 2023). The downside with the method of remote sensing is that it mostly focusses on shallow waters and no differentiation between species is made.

In Southern Cyprus a regression of P.O. has been found, these meadows are being replaced by the Lessepsian migrant *Caulerpa Racemosa* (C.R.), a type of seaweed that is quickly migrating and expanding in the Mediterranean (Argyrou et al., 1999). Although seaweed can provide similar ecosystem services as seagrass such as serving as a carbon stock, the carbon stock of C.R. is only 0,012 kg/m^2, whereas Posidonia Oceanica has a carbon stock ranging between 14,4 kg/m^2 (lower limit) and 44.3 kg/m^2 (upper limit) (Raza'I et al., 2023; Monnier et al., 2022). Therefore, in the face of climate change mitigation this replacement of species does not close the carbon stock gap that remains after the disappearance of P.O.

Some areas used to experience regression, however, are now showing recovery or progression. Further off the coast in southern Cyprus, fish farming has moved away to deeper sea areas to mitigate seagrass degradation due to fish farms (Kletou et al., 2018). Although this has aided recovery, it also became clear that areas that also experience other anthropogenic influences did not recover after the fish farms moved towards deeper areas (Kletou et al., 2020).

Cyprus is part of three different international conventions and directives. P.O. beds are part of the Bern Convention and Barcelona convention as mentioned in the Theory section of this paper, and they are listed as natural habitat in the habitat directive, but no other marine vegetation habitat or species is specifically mentioned (such as C.N.) (UNEP/MAP-SPA/RAC, 2019.). Cyprus has several Marine

Nature 2000 areas, among which a large area on the Western coast where an extensive network of P.O. meadows can be found (MAPAMED, 2022). However, most of the smaller meadows do not fall under any MPAs and are therefore not offered any protection against future coastal developments and other anthropogenic pressures. Therefore, the coastline of Cyprus is assigned a SCP value of 1.

4.2.6 Egypt

On the Mediterranean coastline of Egypt three different seagrass species can be found: P.O., C.N., and H.S. A sighting of Z.M. can no longer be found in the preciously spotted area and is considered to have disappeared or potentially could have been mislabelled as the wrong seagrass species. P.O. is present along the western coast, whereas it is absent in the eastern part. Telesca et al. (2015) mentions how a possible cause could be the freshwater input from the Nile decreasing the salinity and water transparency. There have been a few sightings of the invasive seagrass H.S. along the coastline, also further to the east. As discussed within the Theory section of this paper, the spread rate of H.S. is extremely slow (12 km/yr) and therefore is not expected to cover the eastern coast within the next few decades (Georgiou et al., 2016). Also due to the fact that the Mediterranean climate can vary through seasons much more extremely than the Red Sea and Indian Ocean, therefore making it less likely to strongly settle and grow within the Mediterranean opposed to the Caribbean, which it has also started invading (Winters et al., 2020).

The area experiencing the regression of P.O. and the potential disappearance of Z.M. is off the coast of the city Alexandria is a large mediterranean port city, with much maritime traffic. This in combination with no MPAs in the vicinity of large cities, may be cause for the regression of seagrasses (MAPAMED, 2022). It appears that there is only one MPA along the coastline of Egypt, adopted in 2010, at the very Western end of the coast near the border with Libya, with a marine area of 362,91 km^2 and a coastal area of 53,09 km^2 (MAPAMED, 2022). A very small portion of the country their seagrass meadow lies within this MPA. To protect further degradation of seagrasses, additional MPAs could prove an effective conversation effort. These factors combined lead to a SCP value of 1 (leaning towards 2).

Overall, there is much more information available on the Red Sea coastline of Egypt than on the Mediterranean Sea coastline.

4.2.7 France

There is a large amount of research on marine habitats in France, however, less on the mediterranean coastline. The two seagrass species of C.N. and P.O. can be found along the French coastline. No progression of either species has been reported. Most of the central and eastern coast is experiencing regression, and previously recorded Z.M. has entirely disappeared from a large coastal lagoon. The latter happened due to urban and industrial pollution (i.e. powerplant) and the diversion of a river close by, these disturbances led the species to become extinct within the lagoon between 1994 and 2004 (Bernard et al., 2007). Despite efforts to limit pollution and freshwater input from the river since the late 70s and early 80s, the species distribution in the lagoon continued to shrink until it disappeared entirely.

Research in France was some of the first research to specifically differentiate between the lower and upper limit of seagrass while assessing their health status individually. Earlier research focussed on shallow seagrass, potentially since this was degrading at a rather quick pace due to the poor waste management near the coast, boat trawling, and coastal development due to the growing tourist sector (Holon et al., 2015; Alami et al., 2015). Holon et al. (2015) found a total decrease of 13.4% of P.O. spatial extent between 1922-2012 along the southeastern coastline, which comes down to 332 m^2 per day over those 85 years. They further noticed that there was one area, about 1% of the southeastern coastline that saw a small form of progression. They found this one area to be the historically least man-made within the study area. Another study investigating various meadows in France, Greece, Italy, and Spain, saw regression rates between 17,7% and 98,9 %, the highest regression was found in Spain and

France, which they emphasised was in accordance with the high level of coastal pressures (Montefalcone et al., 2019).

However, as researchers started to investigate the health-status of the lower limit they quickly found that this was regressing as well (Boudouresque et al., 2000; Mayot et al., 2006). Neither of these papers were able to find a cause for this regression within their study. Around the same time, a new observation was reported with regards to the disappearance of seagrass by Mayor et al. (2005), who found evidence that the increasing temperatures could have a negative effect on P.O. near its cold limit. This was the first time that regression was seen due to temperature and a changing climate or extreme weather events opposed to the often-attributed cause being direct human influences such as coastal development or pollution. Another study showed that a lagoon in Corsica lost an estimated 49% of its C.N. cover between 1973 and 1994, to regain almost 42% of its C.N. cover between 1994 and 2011(Garrido et al., 2013). Indeed, this area experienced high levels of turbidity due to rainfall events and eutrophication and was relatively untouched by human impacts, the authors emphasise how climate events altering turbidity, salinity and temperature levels may drastically alter seagrass presence (Garrido et al., 2013)

In the 80s and 90s, France increased their waste management by up to 85%, partially slowing regression rates, however still an overall negative trend is found specifically for P.O. (Boudouresque et al., 2000). More recently, they have started various large restoration pilots along the coast to find suitable and efficient approaches to apply on larger scale along the coastline (Pergent-Martini et al., 2022). Since 2020, France has adopted anchoring regulations to minimise maritime activities harming specifically *P.O.* (MYS, 2023*)*. In the last 15 years an increasing number of MPAs have been established (MAPAMED, 2022). Furthermore, between 2016 and 2022, strict anchoring regulations have been set in place that do not allow anchoring in seagrass meadows, if these regulations are violated captains may risk imprisonment or can be fined up to 150,000 EUR and may be banned from French Mediterranean waters (Rankine, 2024).

Due to the continued regressing trend of seagrasses and the difficult nature of restoration especially for P.O., the remaining seagrass meadows are considered to be of a high conservation priority with an SCP value of 2. The prior mentioned disappearance of Z.M. in a lagoon, where after much degradation the pollution was lessened and this consequently leading to extinction nonetheless stresses the importance of continued assessment and timely measures (Bernard et al., 2007).

4.2.8 Greece

The Greek coastline is covered by seagrasses along 70% of its length (Topouzelis et al., 2018). Greece has several 'firsts' on the topic of Mediterranean seagrasses. Greece is the first Mediterranean country with a full country specific spatial mapping through both optical (satellite) and acoustic (sidescan sonar) remote sensing (Topouzelis et al. 2018; Panayotidis et al., 2022). Remote sensing for the entire Mediterranean had been done prior, however, these large-scale mapping techniques tend to be less accurate than more localised mapping especially because addition in-situ research can be combined on a national level research (Traganos et al., 2022). It must be emphasised once more that not only is it difficult to distinguish between species through remote sensing techniques, other species than C.N and P.O. cannot be mapped with remote sensing techniques and instead need to be mapped through in-situ approaches (Panayotidis et al., 2022). Through both these remote and in-situ approaches it can be seen that there are various different seagrasses present along the Greek coastline, namely P.O. (present almost everywhere along the coast), C.N., Z.N., and H.S. - Z.N. has been mentioned to be present in very small quantities by a remote sensing mapping study, however, there was no mention of coordinates nor were they able to map the species remotely (Panayotidis et al., 2022). Therefore, this species is not mapped along the Greek coastline within this study.

A second 'first', is the discovery of the tropical seagrass species Halophila Decipiens (H.D.), also known as Caribbean or Paddle seagrass, which was reported for the first time in the Mediterranean in 2018 within Greek coastal waters about 1000 km away from its geographic limit (Gerakeris et al., 2018). It has not yet been found elsewhere in the Mediterranean since, however, with the warming climate and sea it could be plausible that this tropical seagrass might further extent their distributional range. After H.S., H.D is the second invasive seagrass species in the Mediterranean Sea.

In 2007, the coastline of Greece was only mapped for 8% (Telesca et al., 2015), therefore, the newer mapping techniques using remote sensing was very useful to map 100% of the coastline. However, there is one downside to the large remote sensing mapping techniques as these studies have not focussed on the changes in the health status of the mapped meadows. Although the authors, or others, may revisit the research and compare the changes in distribution, this still has yet to be done. Furthermore, as most remote sensing techniques use satellite data over a range that can be various years as to make sure the imaging is clear and usable, it might not fully reflect the actual trends that are occurring. Especially as species other than C.N. and P.O. cannot be mapped through this method (Panayotidis et al., 2022). Therefore, in-situ observations of the health of the meadows are necessary to monitor how the meadows are doing and when and where conservation efforts are needed.

In the Saronikis Gulf multiple meadows of both C.N. and P.O have been monitored and have shown various levels between regression and stable statuses (Brodersen et al., 2018). This research showed that the meadows closest to the most urbanised coastal areas were most negatively affected, most of these meadows where P.O. Brodersen et al. (2018), further emphasises that the largest pressures are land pollution and direct physical damaging from the maritime sector.

Greece has multiple MPAs covering a lot of mainland coastal area and island coastal area, however, the area in which seagrass regression has been reported is not protected (MEDAMAP, 2022). As for coastal development, EIAs are mandatory and also focus on measures to reduce the harmful effects expected (Pergent-Martini & Le Revallec, 2007).

Due to the extensive seagrass meadows present along the Greek coastline, the coast being a popular tourist destination and the current knowledge gap of the health status of most of the seagrass meadows a seagrass conservation level of 2 is assigned. The extensive MPAs and regulations are the reasoning for assessing it with a SCP value of 1 instead of the most urgent priority value of 2.

4.2.9 Israel

There is little literature on the seagrasses in Israel. There is consensus that there is no P.O. along the coastline, most likely since water temperature can regularly reach 30 degrees Celsius (Telesca et al., 2015; Kletou et al., 2020). However, it appears that there are small meadows of C.N. along the coast that are so small that when seasonal fluctuations happen, they may disappear entirely until they regrow again from the seed stocks in the sediment (Lipkin et al., 2003). Back in 2003, Lipkin et al. estimated that the C.N. meadows did not exceed a few hundred m^2. Remote sensing mappings also concluded that there was very little seagrass presence to be found (Traganos et al., 2022).

Israel has no specific regulations when it comes to seagrasses, however, they have a Territorial Water Committee (TWC) which must approve any development on maritime territory and the coastline (Pergent-Martini & Le Revallec, 2007). The committee makes decisions based on the national plans for coastal development, it is not outlined if the protection of seagrasses is part of the national plans and therefore may not hold much value for seagrass conservation. Israel does have a few very small MPAs, however, the C.N. meadows seem to not be located within these areas (MAPAMED, 2022).

Due to the very small C.N. presence, lack of regulations, but also the current political situation, Israel is assigned a SCP value of 0.

4.2.10 Italy

P.O., C.N., Z.M., Z.N, R.C., and H.S can all be found along the Italian coastline. Where C.N. seems to mostly dominate Sicily, P.O. still seems to dominate the northern coast of Italy and the island of

Sardinia. A lot of seagrass meadows are in regression in Italy, especially P.O. meadows. It seems that various anthropogenic pressures have driven many meadows into regression, such as oil spills, trawling, coastal development and eutrophication (Calvo et al., 2010; Montefalcone et al., 2007; Peirano et al., 2005; Cossu et al., 2006). These anthropogenic activities have caused major losses of seagrass meadows, for example, extensive coastal development in Liguria in the 60s caused a total decrease in seagrass meadow extent of 30% by the 90s (Pergent et al., 2014). The mass tourism in the coastal areas of Italy, may contribute further to a decline due to coastal development. Some meadows have entirely disappeared, such as a Z.M. meadow in Sicily (Calvo et al., 2010). It seems that direct human disturbances are causing regression along major parts of the Italian coast. However, research has also reported that one-time disturbances can occur without major seagrass loss occurring and recovery may even occur (Flagella et al., 2006.)

A new consideration came to be when a study investigated the effects of a large severe weather event on P.O. meadows. Here the conclusion was made that due to one extreme storm, the lost seagrass cover was equal to the findings of a research analysing the difference in seagrass presence over a 160-year period in the same area due to anthropogenic pressures, namely a 50% decrease in seagrass cover (Oprandi et al., 2020). Although these are not direct human created pressure, severe weather events are expected to increase due to human-caused climate change in the future (Clarke et al., 2022). Conservation efforts could be considered to limit the damage done by extreme waves uprooting grass and the sediment burial. Further concerns that the largest pressures may shift from anthropogenic activities to climate related events have been expressed in recent years (Danovaro et al., 2020).

Italy has several MPAs along the coastline, not all covering the seagrass meadows and specifically the regressing meadows (MAPAMED, 2022). Since the 90s, all sea development needs accompanying EIAs, these are similar to the EIAs within the European Directive, however, also contain a monitoring period after development (Pergent-Martini & Le Revallec, 2007). Protected vegetation must be considered in these assessments and monitoring events. P.O., Z.M., and Z.N. are nationally protected (MAPAMED, 2022).

The large number of regressing meadows are cause for worry, however, new and more recent evaluations of these meadows are necessary, and measures should be taken to limit the loss of seagrasses along the coastline in Italy. Furthermore, concern for climate related losses should be investigated further and potential conservation measures may have to be implemented. Therefore, the Italian coastline is assigned a SCP value of 2.

4.2.11 Lebanon

There is no P.O. present anymore, in 1976 two small P.O. meadows were still present, but newer surveys have been unable to locate them (Kletou et al., 2020; Telesca et al., 2015; Mayhoub, 1976). In the 60s Dr. J.H. Powell photographed and collected H.S. in southern Lebanon (Lipkin, 1975). The presence of H.S. has not been reviewed since, and therefore is assumed to still be present. This was the first time H.S. was reported on the eastern coast of the Mediterranean. Almost four decades later, H.S. was reported once more in a northward direction (Sghaier et al., 2011).

Little research on native seagrasses has been done along the Libyan coast, and recent research contradicts each other. An AI remote sensing mapping method resulted in a small presence of seagrass (species unidentified) along the Lebanon coast, whereas other research was unable to find a native seagrass presence (Traganos et al., 2022; Kletou et al., 2020). As mentioned within the Theory section of this paper, mapping with AI and remote sensing methods is not as reliable as in-situ research and is unable to identify the species and the health status of a meadow. Although it is a cost and time efficient method of mapping, it is less accurate than confirming presence on location. Generally, the remote sensing found very little seagrass presence and therefore does not spark a major need for immediate further research in the area (Traganos et al., 2022).

Ultimately, the conservation level of seagrasses along the coast of Lebanon assessed in this work is a SCP value of 0. Mainly due to the assumption that the high temperature, salinity and turbidity make it difficult for native seagrasses to thrive here and the resulting lack of native seagrasses. There is no information available on the current status of the H.S. meadows, and although they are an invasive seagrass they are of no threat to native seagrass in the immediate area as there are none.

4.2.12 Libya

Libya has one of the longest coastlines in North Africa with approximately 1,770 km, along this coast the capital city Tripoli is located (Emrage & Nikolaus, 2023). Three different species can be found here, namely, P.O., C.N., and H.S. There is no information on the health status of these meadows. The last distribution research done in situ was back in 2015 where the authors emphasised that repetitive monitoring needs to occur to discover trends within the distribution, no monitoring of these study sites have been reported (Ezziany et al., 2015). this could be due to the civil conflict and unrest that remains, also after the UN-backed ceasefire in 2020, within the country today (Chapman et al., 2022)

A small MPA can be found on the east side of the coastline, somewhat near the Egyptian border, for the Ain Al-Ghazalah Lagoon and Elba Island, this area was designated as a MPA in 2011 (MAPAMED, 2022). This MPA covers the seagrass meadow distribution that can be found within the gulf of Bomba, where all three seagrass species can be found. However, all other seagrass meadows are not protected by MPA legislation. Other specific legislation regarding seagrass species is not present.

Due to the civil unrest, the resulting lack of mass tourism, not knowing the health status of the meadows, and the final sightings being almost a decade ago, the seagrass conservation status is low with a SCP value of 1.

4.2.13 Malta

Malta is surrounded by MPAs, all along the coast apart from near the capital city Valletta and its harbour (MAPAMED, 2022). Within the bay, artificial beach has buried and consequently killed the P.O. previously present (Borg & Schembri, 1995). This dead matte seems to have been grounds for the establishment of the invasive H.S. seagrass (Sghaier et al., 2011), which meadows have settled around the bay and near the capital city. No other seagrass species than P.O. and H.S. have been reported along the coastline of Malta. The same artificial beach extension caused for the disappearance of P.O. in the Maraxlokk bay area (Borg & Schembri, 1995). Some further P.O. regression can be found in another bay (Xemxija Bay), it is assumed due to offshore fishing and boat anchoring (Borg & Schembri, 1995).

More recent research focussed mostly on the mapping of the seagrass meadows along the coastline through AI-driven remote sensing and acoustic textures mapping, which provided a complete overview of the distribution (both with corresponding specified certainty), however, these research papers do not make an indication on the health of the reported meadows (Traganos et al., 2022; Chowdhury et al., 2023; Chowdhury et al., 2024). The most recent study researching the health status of these meadows was published in 2007, in which most seagrass meadows seem to be stable, but no specific locations or coordinates were provided (Mifsud et al., 2007).

Considering the large P.O. extent, little competition from invasive species and overall positive health status especially for the meadows outside of the main bay and port areas, Malta has an average SCP value of 1. No immediate action is needed to keep further areas from regressing completely, however, proper regulation especially within the boating areas could prove beneficial in halting any further regression in these areas.

4.2.14 Monaco

Little is known about the seagrass of Monaco, there has been no research done on the coastline of Monaco specifically, however, due to the small size of the coast it is often considered as a part of France and at times mentioned in papers researching seagrasses along the French coastline (Traganos et al., 2022; Telesca et al., 2015). This has led to two very small meadows of P.O. being reported along the Monaco coastline on the far west coastline and on the far east coastline. Both these meadows are experiencing regression (Telesca et al., 2015).

Monaco has the shortest coastline in the world with only 3.83 km of coastline (Gekić et al., 2022). The small coastal strip is mostly composed of seaports and bays. One bay is partially covered by a MPA, since 1978, as an underwater reserve (MAPAMED, 2022). However, no specific mention is made of seagrasses. There are no Natura 2000 areas, but the entire coastline is part of the Pelagos Sanctuary for Marine Animals (MAPAMED, 2022). Furthermore, the strict anchoring regulations in France, mentioned priorly, do not apply in Monaco and there are no clear laws set in place for any specific seagrasses.

Due to the lack of large seagrass meadows, the regression of the small present seagrasses, the short coastline and lack of regulations, Monaco is assigned a SCP value of 1.

4.2.15 Montenegro

Montenegro only has reports of P.O. presence; however, the presence is along most of its coastline. One research set out to evaluate three different areas along the coast to find its status, all these three locations turned out to be in stable conditions (Mačić, 2014). Not too long ago, the entire coastline was mapped (Petović & Mačić, 2021).

On the one hand, within national legislation P.O. is seen as a rare or endangered species (red list) and the country protects P.O. meadows from trawling as is it is illegal up until 50 m depth and within two nautical miles, which is around 3.7 km, from the coastline (Pergent-Martini & Le Revallec, 2007). On the other hand, there are currently no specified MPAs along the coast of Montenegro (MAPAMED, 2022). Regardless of the latter, the seagrass meadow population appears to be stable. Montenegro has several regulations, laws, and international commitments, e.g., the law on nature protection since 2016 and the earlier mentioned Barcelona Convention (UNEP, 2024).

Overall, Montenegro is a valuable location for existing seagrass meadows. However, due to the stable status of these meadows, the explicit protection of these species and no current known pressures driving the meadows into regression, Montenegro is classed under a SCP value of 1. Naturally, continuous monitoring is important even in these cases.

4.2.16 Morocco

C.N. and Z.M. have been reported along the Moroccan coastline, whereas P.O. is entirely absent. However, many of the Z.M. meadows have disappeared over the last few decades (Boutahar et al., 2020). Another study showed that the C.N. meadows are also in regression, trawling marks were found within the meadows even though prohibited (Boutahar et al., 2022). Ultimately, a lot of the coastline remains unstudied regarding seagrass presence.

There is one MPA, which is part of a land and marine national park which was designated in 2024, the MPA is near the city of Al-Hoceima which is a popular tourist destination (MAPAMED, 2022). There is a lack of reinforcement to ensure compliance of good environmental practices, which is problematic for the conservation of the known and still remaining meadows (Boutahar et al., 2022).

Further research is needed to map the entire coast of Morocco and simultaneous monitoring and conservation should be implemented to avoid the disappearance of seagrasses completely. Therefore, a SCP value of 1 is assigned.

4.2.17 Palestine

There is little research done on the coastal zone of Gaza strip, which is only 42 km long, the last publicly available research mentioning seagrasses states that there are likely none in the shallow waters due to the unsheltered nature of the seabed, however, the authors state that otherwise the seabed has favouring characteristics for seagrass growth (Ali, 2002). However, a paper published more recently found that the Gaza fishing harbour falls among the most polluted areas in the Mediterranean Sea (Zaqoot et al., 2018). There are no MPAs along the coastline, and no national regulations present concerning marine flora (MAPAMED, 2022).

Considering the political situation during the submission of this thesis (June 2024), no conservation status is allocated. The potential presence of a small area of seagrass meadows, and in the case, they are present; any conservation efforts, are not a priority as of this moment.

4.2.18 Slovenia

The Slovenian coast, although being only 46 km long and the marine basin rather shallow (max. 20-25 m), is home to many different seagrass species, namely P.O., C.N., Z.M., and Z.N. (Vahtar, 2002). P.O. has the smallest presence, followed by Z.N. and Z.M., along the coastline C.N. holds the largest presence by far. Although there is some regression in a few meadows, about an equal number of meadows are in progression and even more are considered stable. The regressing meadows lost around 91 hectares of seagrass between 2014 and 2020, whereas 284 ha of meadows were seen to be stable (Ivajnšič et al., 2022). This research made no comment on why different areas saw different trends.

One theory why the regressing areas experienced regression could be related to the fact that all regressing meadows were off the coast of a resort town populated with tourists and yachts, Portorož, and a port city, Koper. Koper sees 10 million tons of freight each year, this development although beneficial to the local economy caused large coastal development putting strain on the marine environment (Vahtar, 2002). It appears that agriculture is a very small sector within Slovenia, however, fishing and mariculture is a large sector, which can cause degradation due to trawling and other harmful activities (Vahtar 2002),

Slovenia has multiple MPAs already, however, they do not cover the current meadows in regression (MAPAMED, 2020). However, they do have specific laws on EIAs for coastal development, where a description of the original condition, projected development and the expected impacts including measures to combat these impacts are required, the Ministry of the Environment will then judge the cases (Pergent-Martini & Le Revallec, 2007). It must be noted that there is no mention on seagrass meadows within these EIA laws. However, P.O. is protected by a governmental decree since 2004 (Pergent-Martini & Le Revallec, 2007). There is no mention on C.N. which can be problematic as this seagrass species occupies much more of their coastal area than P.O.

Ultimately, the Slovenian coast is classified as a SCP value of 1, as the seagrass meadows are relatively small and stable, however, with the expected growth in tourism in the Mediterranean and regression in these resort and port cities, active monitoring and potential conservation measures should be implemented.

4.2.19 Spain

Along the Spanish coastline, three seagrass species can be found; P.O., R.C., and C.N. Previously reported Z.M. has disappeared along the coat (Pergent et al., 2014). Regression of seagrass can be seen mostly along the central to southern Mediterranean coastline, where many port and resort cities can be found (e.g., Cartagena, Alicante, and Marbella) and along the Balearic Islands which are popular tourist destinations (e.g., Mallorca, Menorca, and Ibiza). There are currently no stable or progressing meadows known within Spain.

Spain follows the European Directive regarding impact studies, additionally it includes an overview of the waste or energy as a result from the proposed development, the ability of the environment to recover and a consequent environment-monitoring programme (Pergent-Martini & Le Revallec, 2007). Specifically for seagrasses this means that EIAs will be required in special areas of conservation, but not outside of these areas (Pergent-Martini & Le Revallec, 2007). However, it seems that large parts of the Spanish coastline are protected through MPAs (MAPAMED, 2022).

Although this leaves a large proportion of the country's seagrass meadows in protected areas, as mentioned before, regression can still be seen along parts of the coast. In fact, together with France, Spain sees some of the largest numbers of regression in meadows in the Mediterranean, with two monitored meadows, La Azohia and El Campello, even reaching 87,4% and 98,9% regression respectively (Montefalcone et al., 2019). Another study found that some of the regression dates to the 1960s where 27 seagrass meadows were monitor and 80% of these meadows were found to be in decline between the 60s and 90s (Marba, 2009). Most of the previous decline within Spain has been attributed to pollution, coastal development, aquaculture, and tourism (Montefalcone et al., 2019; Torres et al., 1990; Polifrone et al., 2014; Boudouresque et al., 2020). However, various authors have stressed rising concerns on how a changing climate may change the seagrass distribution along the Spanish coast (Azcárate-García et al., 2023; Diaz-Almela et al., 2009; González-García et al., 2022; Romero et al., 2007).

These large numbers of regression, especially being located near large maritime and tourism locations in combination with the concerns about the changing climate further degrading the seagrass presence has placed Spain within a SCP value of 2. Although some regulations are in place, and the coast seems to be relatively protected through EIAs and MPAs it seems that this has not (yet) stabilised the seagrass meadows. Therefore, immediate conservation measures are required to halt further regression and potentially support restoration where possible.

4.2.20 Syria

The exact presence of seagrass species is rather ambiguous along the Syrian coast. Multiple sources indicate that there is no longer any P.O. to be found along the coastline (Mayhoub, 1976; Telesca et al., 2015; Kletou et al., 2020). However, the UNEP-WCMC (2022) has marked some unidentified seagrass presence along the coastline. It is possible this could be H.S. seagrass, as this species has already been identified along the coast (Sghaier et al., 2011). However, earlier identified seagrasses of C.N. and Z.M. in the 50s were already showing signs of severe regression and two decades later they were already considered to have been regressed beyond saving (Thiebault, 1953; Mayhoub, 1976). It is emphasised that seagrasses are uncommon along the Syrian coastline, also due to the high salinity, warm temperatures and turbid water (Lipkin et al., 2003; Kletou et al., 2020). Ultimately this high turbidity is also the reason why recent remote sensing mapping techniques have failed to map the seagrass presence along the Syrian coast due to the lack of usable satellite imaging (Traganos et al., 2022).

Syria has two very small MPAs, namely (1) a coastal forest environmental reserve in Om al Toyour (1999), and (2) nature reserve for marine wildlife (2000) in Fanar Ibn Hani near the principal port city Latakia (MAPAMED, 2022). Within the latter marine area, P.O. has disappeared before the designation of an MPA, and since the introduction of the MPA, H.S. has been reported. There is no current legislation specifically for seagrass meadows along the Syrian coast. The lack of legislation and research into marine flora could very well be the result of the ongoing civil war (Kešeljević & Spruk, 2024).

Considering the lack of knowledge of certain distribution and presence and the ongoing civil war, a SCP value of 1 was assigned.

4.2.21 Tunisia

According to estimates from research on P.O. and remote sensing mapping, Tunisia has the largest seagrass cover throughout the entire Mediterranean (Telesca et al., 2015; Traganos et al., 2022). P.O., C.N., and H.S. can be found along the coastline. An earlier reported Z.M. meadow has been confirmed to have disappeared near the capital city Tunis (Pergent et al., 2014). Regression of meadows can be found within the Gulf of Gabes, near the Kerkennah Islands, Monastir, Sousse, and in the Gulf of Tunis near the capital Tunis. All of these locations are either ports or tourism resorts and have seen rapid urban and coastal development over the last few decades as Tunisia has quickly grown into a large tourist destination (Widz & Brzezińska-Wójcik, 2020). In fact, in 2020 the cities of Monastir, Sousse, Tunis were reported to have a problem of overtourism in a call for sustainable development along the coastline (Widz & Brzezińska-Wójcik, 2020). Furthermore, wastewater pollution has been a reported problem along the coast contributing to the deterioration of the meadows (Mabrouk et al., 2013).

To visualise the locations of cities, ports, and tourism resorts in relation to the regressed and disappeared meadows a preliminary figure was created which can be seen below (figure 10). Note that this figure cannot be used to imply causation, however, due to the many human drivers of seagrass regression a spatial relationship can be theorised. Within this figure, the red lines imply regressed meadows, the purple line serves to indicate the disappeared Z.M. meadows near the capital city, where two harbours are present.

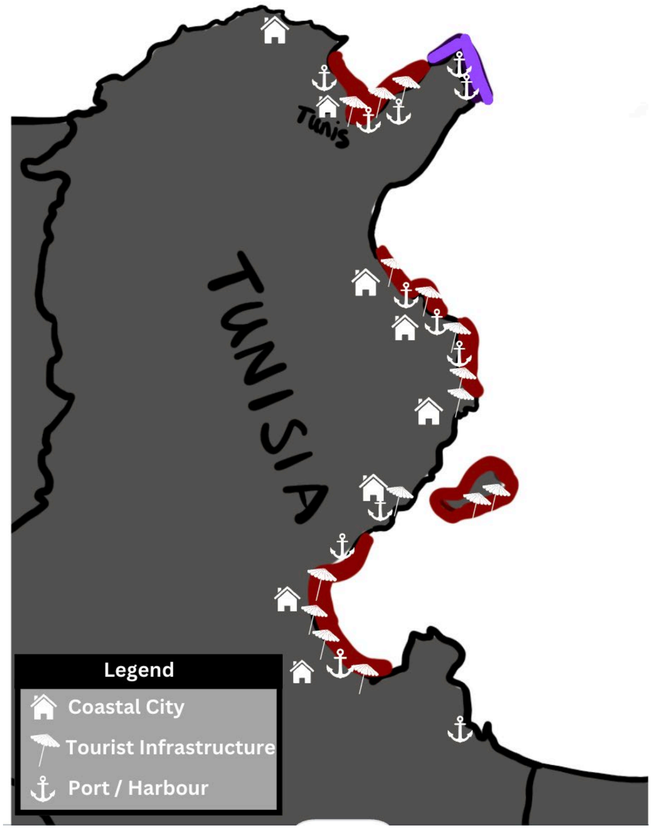

***Figure 10**. A preliminary figure visualising the locations of coastal cities, tourist infrastructures and port/harbours in relation to regressing (red) and disappeared (purple) meadows. Note that this does not imply full causation, however, a relationship can be theorised based on the figure.*

Another topic of concern is the presence of the invasive seagrass species H.S., which was first found near Sfax in 2003, however, reports have slowly been made of H.S. presence more northwards to Tunis as well (Ben Mustapha et al., 2023). It has been slowly outcompeting and replacing C.N. meadows ever since. Due to the invasive nature of H.S., the distribution and migration of the species should be monitored closely.

Tunisia requires EIAs for large development projects, however, no mention is made on seagrass meadows within these assessments or any other regulations (Pergent-Martini & Le Revallec, 2007).

Moreover, Tunisia only has one small MPA, a nature reserve, of less than 60 km^2, dating back to 1993 (MAPAMED, 2022). While restrictions on trawling are in place, the activity was still responsible for an 80% loss of seagrass surface are, concluding that the legislation is not enforced nor respected (Brahim et al., 2010).

Due to the rapidly growing tourism, lack of enforced legislation and MPAs, introduction of the invasive H.S. species and the regressing native meadows, Tunisia is classified with an SCP value of 2. Rapid measures should be undertaken to ensure a limited loss of seagrass in the most densely seagrass populated coastline of the Mediterranean Sea.

4.2.22 Turkey

Turkey has a shoreline of 8,333 km, of which approximately 1,577 km spans along the Mediterranean Sea (Kucuksezgin et al., 2019; Öztürk & Başeren, 2008). Along this Turkish Mediterranean coastline two species of seagrass can be found: P.O. and H.S. Although P.O. seems to be absent along the Eastern coast, potentially due to the high turbidity (due to coastal development), salinity, and temperature; the same characteristics of the coastal waters of the Eastern Mediterranean, including Syria, Lebanon, Israel, Palestine, and Eastern Egypt (Kletou et al., 2020).

A large study used acoustic ground discrimination systems to create a habitat map along the Aegean Sea coastal areas of Turkey, where the authors concluded that seagrass meadows were under threat, especially in areas with intense human activities (Duman et al., 2019). This study also found that these areas that were abandoned by P.O., have been invaded by invasive species H.S. According to the researchers the largest invaded areas were found in places where tourism and coastal development are highest (Duman et al., 2019). Further research on the status of specific meadows along the coast are sparse. With Turkey seeing a large yearly growth in tourism, it is important more research is done to assess the status of the seagrass meadows in Turkey (UNWTO, 2022.)

EIAs are required for large new development projects, however, there is no mention of P.O. in their regulations, but it does fall under the protection of a national legal framework (Pergent-Martini & Le Revallec, 2007). Although there are no marine natura 2000 sites, there are several smaller MPAs with a national statute (MAPAMED, 2022). Regardless, regression is still taking place in meadows within these MPAs.

Overall, due to the lack of information on the status of the meadows, the growing tourism and the lack of regulations and MPAs, Turkey is classified as a SCP value of 1, leaning towards 2.

4.2.23 Gibraltar (United Kingdom)

Gibraltar is an overseas territory of the United Kingdom. Gibraltar is a case of somewhat contradicting reports. Back in 1993, small seagrass meadows were found, which later in 1998 were gone, in 2010 it was once again confirmed all seagrasses were gone which is still what UNEP-WCMC reports as well (Sánchez Moyano et al., 1998; Bull et al., 2010; UNEP-WCMC, 2022.). This is contradicting with research that references older sources as if the meadows are still there, although the paper did not set out to confirm or disprove the existence (McWilliams, 2009). Satellite remote sensing, however, does show there is a small seagrass area of 4,20 km^2 along the coastline of Gibraltar (Traganos et al., 2022). However, this research observed an overall accuracy of 72% and therefore seagrass presence would have to be confirmed in-situ considering the contradicting literature.

Gibraltar does not have MPAs of its own, however, some MPAs instigated by Spain overlap somewhat with Gibraltar (MAPAMED, 2022). It is unclear if the United Kingdom has specific regulations in place for seagrasses within their Mediterranean territory.

Due to the small length of coastline, contradicting news of seagrass presence and no known regulations Gibraltar is given a SCP value of 1. More research remains necessary.

4.3 Seagrass Species in the Mediterranean

In this research, seven different seagrass species were found within the Mediterranean Sea. These findings contradict the common assumption that only the five earlier mentioned species can be found within the Mediterranean Sea (Chefaoui et al., 2018). The distribution of these various species can be seen in figure 11 below. Although most of the endemic, common, and invasive species within the Mediterranean have already been introduced within the Theory section of this paper, this section here dives into the distribution and status of all species while also introducing the newly reported and mentioned seagrass species, (1) Ruppia Cirrhosa (R.C.) and (2) Halophila Decipiens (H.D.)

Figure 11. *Map of Composition of Seagrass Species along the Mediterranean Coastline.*

4.3.1 Seagrass Species Reports and Status in Numbers

Most reports assessed within this thesis mentioned which seagrass species was found within the individual study, namely 161 of the total 186 reports considered. This led to a total of 161 reports of seagrass species presence, of which 102 reported P.O., 31 reported C.N., 5 reported Z.M., 7 reported Z.N., 11 reported H.S., 4 reported R.C., and finally, 1 reported H.D.

In addition, a total of 74 literature sources reported the status of various seagrass meadows. Either these meadows were in progression, stable, in regression, or they disappeared entirely.
8 papers reported progression, 12 reported stable meadows, 47 reported regression, and another 7 reported meadows that have disappeared. For a visual overview of these numbers and additionally which species fell under these status categories, see table 2.

	Progression	Stable	Regression	Disappeared
P.O.	4	9	36	2
C.N.	3	1	3	1
Z.M.		1	2	2
Z.N.			4	1
H.S.			1	
R.C.				
H.D.				
Unspecified	1	1	1	1
Total	8	12	47	7

Table 2*. reported meadow status and associated seagrass species. Where on the left side, the type of seagrass is indicated for the row, and the columns indicate how many reports per status were published.*

4.3.2 Native Species

Posidonia Oceanica (P.O.) | Endemic

Common Name: Neptune grass or Mediterranean tapeweed.

This research found that both direct human impacts and a changing climate were the drivers behind P.O. meadow regression. Direct human impacts were mostly related to coastal development in port or resort cities and trawling practices, however, climate change being an important factor in P.O. regression is becoming increasingly more mentioned and researched (Beca-Carretero et al., 2024; Stipcich et al., 2022).

P.O. can still be found all throughout the Mediterranean Sea, although not reported in the Eastern basin along the coatlines of Israel, Palestine, Lebanon, Syria and Eastern Egypt. Historically P.O. meadows have been reported in Syria, but later research showed that these meadows were no longer there. The most extensive meadows can be found in Tunisia, Italy, France, Croatia and parts of Turkey. All these regions apart from Turkey are experiencing high rates of regression in these meadows. Especially near large cities or popular tourist cities. Some meadows in Croatia and Turkey are experiencing progression due to implemented legislation and restoration efforts.

Cymodocea Nodosa (C.N.)

Common name: little neptune grass.

Three reports mentioned regressing meadows, however, another 3 mentioned progressing meadows. In Tunisia C.N. is being displaced, coincidentally at the same time of arrival of the invasive H.S. species, where 50% of C.N. was displaced within four years (Sghaier et al., 2014). However, the regression of native seagrasses due to human activities also plays a large role in this displacement, moreover, leaving more space for invasive seagrasses to be invade.

C.N. is distributed throughout the entire Mediterranean but has large consecutive meadows along the coastline of Sicily, Italy, Northern Croatia and Slovenia, and finally some smaller more fragmented presence in parts of Tunisia, Libya, Egypt, Spain, Morocco, Lebanon, Cyprus, Albania, and Greece. Especially in Greece, Egypt and Morocco C.N. regression can be seen, these regressing meadows are all off the coast of large cities or ports.

Zostera Marina (Z.M.)
Common Name: Eelgrass

Within this thesis, small Z.M. meadows were found along the coastline of Morocca, Italy, and Slovenia. Regression was reported in Italy and Morocco; however, one stable meadow was also reported in Northern Italy. Multiple meadows have disappeared within the Mediterranean Sea along the coastlines of Italy, France, Spain, Morocco, Algeria, Tunisia, and Egypt. These reports mention a combination of both direct human impacts and temperatures that exceed the species tolerable range. The latter especially so along the African coast, whereas the Italian regression is due to human coastal activities.

Zostera Noltei (Z.N.)
Common Name: Dwarf Eelgrass or Nolte's Seagrass

Z.N. was found along the Algerian, Italian, Slovenian and Albanian coastline, the latter where it has been in regression. Furthermore, an earlier reported Z.N. meadow in France, could no longer be found by new researchers.

Ruppia Cirrhosa (Cosmopolitan Species: few reports in the Mediterranean)
Common Name: Spiral Ditchgrass and Curly Pondweed

R. Cirrhosa is not an invasive species as it is naturally found in many regions amongst which is Europe, and it is not known to pose a threat to the other native grasses, therefore it could be referred to as a Cosmopolitan species. R. Cirrhosa was found along the coastline of Egypt, Sicily (Italy), and in three separate small meadows in Spain, the seagrass can tolerate a large range of water temperature, namely between 5 °C and 30 ◦C (Geneid et al., 2006; Mannino et al., 2015; Obrador & Pretus, 2010). Their high tolerance for salinity makes them a strong competitor in high salinity areas (Obrador & Pretus, 2010). According to (Mannino et al., 2015), they can be found in shallow waters and their most limiting growth factor is light availability. Mannino et al. (2015) further mentions that hybrid populations between R. Cirrhosa and R. Maritima have been found within the Mediterranean basin. The authors emphasise that the Ruppia family taxonomy is complex, and it has proven difficult to properly identify and map the presence within the Mediterranean. This confusion has led to prior misidentification of various Ruppia species (Triest & Sierens, 2014).

Research on Ruppia Cirrhosa within the Mediterranean Sea is sparse as for a long time the species was seen as a freshwater plant with some level of salinity tolerance but now is increasingly being researched as a species occupying coastal saline lagoons within the Mediterranean (Adams & Bate, 1994).

The relatively recent further migration towards the Mediterranean is likely due to natural dispersal mechanisms through water and by birds and by human activities such as the maritime industry (Martinez-Garrido et al., 2017). Perhaps this seagrass species is often not considered by studies to have a Mediterranean presence, due to the limited distribution throughout the basin. However, with their earlier mentioned high tolerance to varying temperature and salinity, they might become increasingly important within the Mediterranean basin in the face of climate change.

4.3.3 Invasive Species

Halophila Stipulacea (H.S.)
Common Name: Broadleaf Seagrass

The spread rate through the Mediterranean is only 12 km over those 120 years, although this is relatively low for an invasive species, it has still led to a displacement of 50% of C.N. within a study area in Tunisia within 4 years (Georgiou et al., 2016; Sghaier et al., 2014). It is important to consider that this could also been partially facilitated due to the human pressures degrading the native species and creating more space for H.S. to thrive in.

Furthermore H.S. was reported along the coastlines of Italy, Greece, Turkey, Cyprus, Syria, Lebanon, Algeria, Egypt, and Tunisia. H.S. is the only type of seagrass species to have been reported in both Syria and Lebanon.

Halophila Decipiens (H.D., newly reported)
Common Name: Paddleweed or Strapweed.

Originate from tropical regions such as the Indian Ocean and the western Pacific Ocean, where it is found in shallow coastal waters typically in tropical and subtropcial regions with sea water temperature ranging from 15 °C to 30 °C and a wide depth range from 0 to 85 m, although are not very common at intertidial level (Dawes et al., 1989; Kahn & Durako, 2009).

In 2018, it was reported in the Mediterranean Sea for the first time, the sighting being reported along the Greek coastline (Gerakeris et al., 2018). There have been no further reports on its presence in the Mediterranean since. Future monitoring is required to monitor the invasion, spread rate and consequent impacts for the local marine ecosystems it newly inhabits.

4.4 Carbon Stock Potential of Seagrasses: the Implications for Combatting Climate Change

Seagrasses play a critical role in coastal ecosystems and have significant potential for carbon fixation, sequestration and carbon storage, making them an important natural factor in combatting climate change. However, quantifying their exact contribution is challenging due to the uncertainties in their exact spatial distribution and composition. This section explores these uncertainties while also providing careful estimates and projections for the carbon stock potential of seagrass meadows in the Mediterranean Sea.

Estimates of Seagrass Coverage in the Mediterranean
Currently, the exact distribution and coverage of seagrass meadows in the Mediterranean is not fully known. Estimates have been made using various methods, including field data collection and remote sensing, each with its own limitations. Field data collection, such as the study by Telesca et al. (2015), focussed only on the seagrass species P.O. and collected data up until 2011. This method provides a more detailed but possibly outdated picture of the previously studied coastline, moreover, it is limited to areas previously studied therefore not including coastlines that have not been studied as of the time of data collection (prior to 2011). More recent studies, such as Traganos et al. (2022), utilised remote sensing techniques which led to broader coverage but lack the ability to differentiate between seagrass species and map existing coverage accurately due to the limitations of satellite imaging in capturing underwater habitats beyond certain depths and various weather conditions.

Therefore, historical and current estimates of seagrass coverage in the Mediterranean vary. The most recent and complete, although with a limited estimated accuracy of 72%, suggests that seagrass coverage within the Mediterranean Sea covers approximately 19.019,6 km^2 up until a depth of 25 meters (Traganos et al., 2022). Traganos et al. (2022) states that the largest seagrass presence was found in Tunisia, Italy, and Greece (6.369 km^2, 3.261 km^2, and 2.878 km^2 respectively), indeed, the first two were assigned a SCP value of 2 in this thesis. Remarkably, the same authors used similar techniques to map Greece two years earlier, when they found an area that was 13,7% smaller than the Mediterranean Sea wide mapping; no explanation was given by the authors why their findings were different (Traganos et al., 2018). Therefore, this total coverage number is an estimate. Slightly older research estimated that the total seagrass coverage within the Mediterranean ranges between 1.0 million ha and 1.5 million ha, or 10.000 km^2 and 15.000 km^2 respectively (Valette-Sansevin et al., 2019). This research makes no reference to where the most expansive seagrass meadows can be found, nor gives an indication of coverage per country in general.

Carbon Fixation and Stock Estimates

Due to the uncertain nature of the total coverage, in this section an estimated range, based on the two papers discussed in the previous section, of 10.000 km^2 (lower limit) and 19.019,6 km^2 (upper limit) range is used to calculate carbon fixation, sequestration, and stock estimates (Valette-Sansevin et al., 2019; Traganos et al., 2022).

Using this as a baseline, and the earlier introduced fixation, sequestration rates and existing stock within Section 3, a carbon fixation, sequestration and stock potential based on the P.O. characteristics can be estimated:

- **Carbon (dioxide) fixation (lower and upper limit):** Studies, introduced and discussed within the methodology section, indicate that P.O. fixate carbon at a mean rate of approximately 138,5 Mg C/km^2/year. This would translate to a carbon fixation of 1,39 million tonnes of carbon to 2,6 million tonnes of carbon per year for the entire Mediterranean. This converts to a range of 5,1 million tonnes CO_2 per year to 9,7 million tonnes CO_2 per year.
- **Carbon (dioxide) sequestration (lower and upper limit):**
  This makes the total annual sequestration between a range of 0,38 to 0,72 million Mg C, or 1,4 to 2,67 million tonnes CO_2 per year.
- **Carbon (dioxide) stock (lower and upper limit):** Within P.O. a mean carbon stock of 71.100 Mg C/km^2 was calculated. With the seagrass coverage estimates a calculated total potential carbon stock range of 711 million Mg C to 1.350 million Mg C. This converts to a range of 2.609 million Mg CO_2 to 4.955 million Mg CO_2.
- **Other Estimates:** The carbon stock potential of seagrasses can vary greatly depending on the species composition of the meadows. For instance, a large-scale replacement of P.O. by H.S. would lead to a lower overall carbon fixation and stock potential. However, if the H.S. meadows become more extensive than the initial P.O. coverage and mature over time, their carbon fixation capacity and stock could increase over time and potentially lead to entirely different estimates.

Future Projections and high SCP (2) countries

Future projections depend on conservation efforts and the impact of climate change on seagrass habitats. If current trends continue, the loss of seagrass meadows could result in significant reductions in their carbon sequestration capacity. On the other hand, successful conservation efforts could enhance this potential.

Conservation (and Restoration) Scenario

Enhanced protection and restoration efforts, especially when focussed on the coastlines with a SCP value of 2, could stablise or even potentially increase the total seagrass coverage. This would keep the stored carbon within the seagrass sink, and the seagrasses could continue to fix carbon from the atmosphere and play a part in combatting climate change. If restoration efforts continue, with an emphasise on proper site selection, the fixation and stock numbers could increase even further.

Degradation Scenario

Continued degradation and loss of suitable seagrass habitats could further reduce coverage, in fact some researchers have stated they expect P.O. to disappear from the Mediterranean if heatwaves continue to become more common within the Mediterranean (Chowdhury et al., 2024). As the habitat would no longer be suitable for P.O., and there would not be enough time for the seagrass species to recover due to its slow grow rate. Ultimately, seagrass plays a pivotal role in combatting climate change, however, too much climate change leading to frequent heatwaves will push the species over a tipping point where their loss will not only mean a loss of carbon fixation, but also a release of the large stores of carbon they have trapped.

SCP 2 Countries

Below in table 3, an overview of the SCP 2 countries can be seen. Here the seagrass area is indicated and used as a baseline to calculate the CO_2 fixation and sequestration rate per year and the existing CO_2 stock. This is compared to the annual national CO_2 emissions per country, in 2022, and the percentage of the fixation rate and stock compared to the emissions is presented.

The existing stock for Tunisia, for example, is 4.668,5% of their yearly national emissions in 2022. The fixation rate traps about 9% of their yearly emissions. It must be emphasised here that Tunisia has the most extensive seagrass area estimate, and has low emissions compared to the rest of the Mediterranean. Therefore, these percentage numbers are extremely high. However, this does show the importance of conserving the seagrass meadows in Tunisia. A full table including all Mediterranean countries can be found in Appendix 9.2

Country	Seagrass Area* (km^2)	CO_2 Stock (in million t)	CO_2 Fixation (in million t/year)	CO_2 Sequestration (in million t/year)	Annual CO_2 Emissions** (2022) (in million t/year)	Percentage Stock of Annual CO_2 Emissions	Percentage Fixation of Annual Emissions	Percentage Sequestration of Annual CO2 Emission
France	900,28	234,9	0,46	0,13	297,53	79,0%	0,2%	0,0%
Italy	3261,23	851,0	1,66	0,47	338,10	251,7%	0,5%	0,1%
Spain	1480,88	386,4	0,75	0,21	245,61	157,3%	0,3%	0,1%
Tunisia	6369,05	1661,9	3,24	0,92	35,58	4670,9%	9,1%	2,6%

*This estimate is based on the remote sensing study from Traganos et al. (2022), with an estimated accuracy of 72%. ** This data is based on Friedlingstein et al. (2023).

Table 3. *An overview of the countries given an SCP value of 2 and how their CO_2 stock, fixation and sequestration rates compare to their annual national emissions.*

Implications for Climate Change

The current CO_2 stock, calculated earlier to be within a range of 2.609 million Mg CO_2 to 4.955 million Mg CO_2, is substantial. In 2022, the entire Mediterranean emitted 2.146 million Mg CO_2 from fossil fuels and industry (Friedlingstein et al., 2023). Comparatively, the current estimated carbon dioxide stock from the seagrass meadows in the Mediterranean covers 1 to nearly 3 times the amount of these yearly emissions.

Since the 1960s, it is estimated that a total of seagrass coverage between 13 to 38% has already been lost (Marbà et al., 2014). Based on the estimated 10.000 km^2- 19.019,6 km^2 coverage range today, the coverage around the 1950s ranged between 11.300 km^2 to 26.545 km^2. This would mean an extrapolated estimate of 1,57 million Mg Carbon – 3,68 million Mg Carbon fixation a year (or 5,74 million tonnes CO_2 and 13,5 million tonnes CO_2 respectively). Which is a decrease of 0,64 – 3,8 million tonnes CO_2 fixed each year. This is comparable to a loss of 0,03 – 0,2 % of the annual CO_2 emissions of the entire Mediterranean (in 2022). A consequent annual sequestration of 0,18 to 1,06 million CO_2 has been lost. Which is a decrease of 0,04 to 0,22 times the annual Albanian CO_2 emissions.

Furthermore, this means there has been a decrease in carbon stock of 93 million Mg Carbon – 534 million Mg Carbon (or 341,31 and 1961 million tonnes CO_2 respectively). The former is the equavalent to Italy's CO_2 emissions in 2022 and the latter is approaching the equavalent to the annual CO_2 emissions of the entire Mediterranean combined in 2022 (i.e., 2.146 million tonnes CO_2).

The potential loss of seagrass meadows due to human activities and climate change represents a significant risk to the Mediterranean's ability to sequester carbon and its overall function as a carbon sink. Once lost or regressed these seagrass meadows no longer trap carbon, however, they will also slowly start releasing the stored carbon. Therefore, protecting and restoring these meadows could provide substantial climate benefits by maintaining and potentially increasing their carbon stock potential. Ultimately, failing to act could result in a significant loss of this natural carbon sink, exacerbating the impacts of climate change.

5. Conclusion

This researsch set out to answer the question of "**how can the visualisation of seagrass meadow distribution and status in the Mediterranean identify high priority conservation value areas and assess changes in carbon storage potential?**". To answer this question, a literature collection was done to create a dyanmic visualisation of the seagrass distribution and status in the shape of a QGIS map. Based on these findings and various criteria, the coastlines along the Mediterranean were assigned seagrass conservation priority calues to highlight high priority conservation areas. Finally, estimated and potential changes in the carbon stock and yearly fixation and sequestration were calculated.

Below the sub-questions are concisely answered one-by-one:

Q1. What is the current distribution and status of seagrass meadows along the Mediterranean coast?

The resulting interactive QGIS map was able to indicate the current known distribution of seagrasses and includes the status of various meadows along the Mediterranean coastline. Regression has been reported much more often (47 times), whereas progressing, stable, and disappeared meadows were reported less frequently (8, 12, and 7 times respectively).

Q2. How can a visualised distribution and status map be used to identify areas of high seagrass conservation value along the Mediterranean Coast?

Through using the four criteria (1) Presence, (2) Status, (3) Degradation drivers and (4) MPA/Legislation presence, each country was assigned an SCP value. Four countries were deemed to have the highest priority level, namely, Italy, Spain, France, and Tunisia. Along these coastlines urgent and targeted conservation efforts are needed to halt further degradation of the seagrass meadows.

Q3. How are different seagrass species distributed throughout the Mediterranean Sea?

The interactive map was able to visualise the distribution of all the seagrass species within the Mediterranean Sea. Two additional seagrass species were found to be reported within the Mediterranean Sea. One, R.C., a cosmopolitan species who is not often mentioned as a Mediterranean seagrass, however, is not considered new. The other, invasive, species H.D. was reported for the first time in 2018 and has not been studied or reported since.

Although P.O. remains the most widely distributed seagrass within the Mediterranean Sea, large meadows are in regression due to human activities in their preferred shallow habitats and the occurrence of extreme weather events. Meanwhile, the invasive species H.S. is spreading due to its broad tolerance of environmental conditions such as higher temperatures. It has already displaced large areas of C.N. seagrass meadows and is expected to have spread throughout the entire mediterranean in the next 100 years.

Q4. What are the implications of the change in seagrass meadow distribution on their past, current, and future total potential for carbon storage and fixation/sequestration?

Based on the characteristics of Posidonia Oceanica its mean fixation rates and mean stock estimates, the current estimated CO_2 stock ranges from 2.069 million Mg CO_2 to 4.955 million Mg CO_2, which is 1 to nearly 3 times the annual total CO_2 emissions of the entirety of the Mediterranean (based on 2022). The mean fixation rate is estimated to be 5,1 to 9,7 million Mg CO_2 per year, which is equal to 0,24 -

0,45% of the annual emissions of the Mediterranean. An estimated total of 341 to 1.961 million Mg CO_2 stock has already been lost since the 1960s. The lower limit is similar to Italy's annual CO_2 emissions and the latter is approaching the equivalent to the annual CO_2 emissions of the entire Mediterranean combined (in 2022).

A continued decline is expected to occur, due to both human activities and extreme weather events, especially without any urgent action for conservation and restoration measures. If seagrass coverage continues to decline, not only will less carbon be fixed from the atmosphere over time, but the stored carbon stock will also slowly be released and consequently add to the emissions aggravating climate change further.

General Conclusion

To conclude, this research set out to close the knowledge gap of the current seagrass distribution including status and composition in the Mediterranean Sea. A comprehensive and interactive map was created to be used as a baseline for future research and conservation and restoration measures. The visualisation of seagrass meadows, their status, and species composition has provided critical insights into the areas requiring immediate conservation measures. By identifying high priority conservation areas, this research highlights the urgent need for targeted conservation strategies to protect these seagrass meadows and the overall ecosystems.

The findings underscore the significant role of seagrass meadows in carbon storage and fixation/sequestration, emphasising their importance in mitigating climate change. The alarming rate of regression and the spread of invasive species pose a serious threat to these meadows, emphasising the need for prompt conservation measures. The potential decline in carbon storage capacity due to the loss of seagrass meadows could exacerbate climate change, making it increasingly more important to implement effective conservation and restoration measures.

6. Discussion

This section delves into the key aspects of the research findings and their broader implications. It begins by addressing the limitations of the study, acknowledging the constraints and potential inaccuracies in data collection and analysis. Following this, the theoretical implications are explored, highlighting the contributions made to existing knowledge and suggesting directions for future research. Lastly, the policy and management implications are discussed, offering practical recommendations for conservation efforts and policy development.

Limitations

While this thesis provides valuable insights into the distribution and status of seagrass meadows within the Mediterranean Sea, several limitations are to be acknowledged, particularly concerning the reliability and validity of the data. One notable limitation is the uncertainty associated with some mapping methods used in the literature collection. For instance, remote sensing accuracy can vary significantly, ranging from 70 to 98%, where satellite imaging generally offers lower accuracy compared to LiDAR techniques. Due to the limited available research for the entire research area, various different methods were included in this research, leading to potential discrepancies in accuracy between different reports. Nonetheless, despite these potential discrepancies, the map offers a significant step forward in completely mapping, understanding and conserving Mediterranean seagrass meadows.

Additionally, estimates of total seagrass presence are reported in a wide range and are likely underestimates due to the limitation of depth for many remote sensing mapping techniques. Moreover, calculation of blue carbon stock and fixation/sequestration related to seagrasses also faces limitations due to the mean factors used in these calculation. Variables such as matte thickness, depths, and plant age, which all influence carbon fication and present stock, differ between and among seagrass meadows. This research extrapolated mean fixation, sequestration, and stock numbers to the estimated total seagrass range, however ultimately still providing a useful indication of the estimated values and quantifying the importance of seagrasses within the carbon cycle.

Finally, these calculations only consider the mean fixation rate and stock from P.O. There is no comprehenisve estimate that accounts for varying compositions of different seagrass species. As P.O. is currently the dominant seagrass species in the Mediterranean, this limitation might not significantly affect the estimates at present. However, as the seagrass composition is expected to change over time, it is essential to continuously monitor and include these changes in blue carbon stock and fication calculations.

Theoretical Implications

This thesis contributed to further closing the theoretical knowledge gap by providing a more detailed and updated understanding of seagrass meadows in the Mediterranean. By incorporating diverse data sources and more recent advanced mapping techniques, a comprehensive view of seagrass distribution, composition and its associated blue carbon potential has been presented. Alongside, high seagrass conservation priorities have been highlighted for more site-specific conservation suggestions.

Future research should focus on continuous monitoring, updating seagrass maps with more accurate techniques to further map the Mediterranean seagrass habitats, studying the impacts of conservation measures, and further researching how the changing seagrass composition within the Mediterranean may affect the blue carbon stock and annual fixation.

Policy and Management Implications

The findings of this research have important implications for policymakers, conservationists, and researchers. The interactive QGIS map developed in this study serves as a valuable tool for monitoring changes in seagrass meadows, planning conservation effors, and assessing the impact of these efforts over time. This visualisation and analyisis framework can help prioritise high-value conservation areas and understand the implications of seagrass decline on carbon dynamics.

By providing a robust framework for addressing conservation challenges, this research supports informed decision-making aimed at protecting seagrass habitats and their ecosystem services for future generations. This tool can guide policy makers in developing targeted conservation policies and allocating resources effectively, ensuring efforts are directed towards the most urgent areas. Continuous monitoring and updating of seagrass data will be essential in adapting conservation strategies to changing environmental conditions and seagrass compositions.

Overall, the research set out to help close the knowledge gap regarding the current seagrass distribution, including status and composition, in the Mediterranean Sea. The interactive map and analysis provided a comprehensive baseline for future research and conservation measures, emphasising the need for targeted efforts to protect and restore seagrass meadows and their critical role in carbon storage and fixation.

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9. Annexes & Supplementary Material

9.1 Supplementary Material

This thesis has produced two documents that are too large or of incompatible file type to be within the Annex down below. Both final products can be accessed through this link.

- Final Meta Data map with all the data collected (See methods section 3.1)
- Final QGIS map with various layers (See methods section 3.2)

9.2 Annexes

9.2.1 Number of papers connected to each Country/Territory

Country/Territory	N. Papers
Italy	36
Tunisia	24
Spain	19
France	18
Greece	11
Egypt	10
Turkey	10
Cyprus	8
Libya	7
Slovenia	7
Albania	6
Algeria	6
Croatia	6
Morocco	4
Montenegro	3
Malta	3
Israel	2
Gibraltar	1
Bosnia & Herzegovina	1
Lebanon	1
Monaco	1
Syria	1
Palestine	0

Table A. *Numbers of paper per country/territory*

9.2.2 CO_2 Storage, Fixation and Sequestration for each Country Compared to Annual CO_2 Emissions

Country	Seagrass Area* (km^2)	CO_2 Stock (in million t)	CO_2 Fixation (in million t/year)	CO_2 Sequestration (in million t/year)	Annual CO_2 Emissions** (2022) (in million t/year)	Percentage Stock of Annual CO_2 Emissions	Percentage Fixation of Annual Emissions	Percentage Sequestration of Annual CO_2 Emission
Albania	149,56	39,0	0,08	0,02	4,95	788,4%	1,5%	0,4%
Algeria	167,91	43,8	0,09	0,02	176,35	24,8%	0,0%	0,0%
Bosnia and Herzegovina	6,9	1,8	0,00	0,00	19,74	9,1%	0,0%	0,0%
Croatia	2029,99	529,7	1,03	0,29	17,53	3021,7%	5,9%	1,7%
Cyprus	44,45	11,6	0,02	0,01	7,03	165,0%	0,3%	0,1%
Egypt	2,96	0,8	0,00	0,00	258,95	0,3%	0,0%	0,0%
France	900,28	234,9	0,46	0,13	297,53	79,0%	0,2%	0,0%
Gibraltar	4,2	1,1	0,00	0,00	N.A.	X	X	X
Greece	2877,78	750,9	1,46	0,42	59,66	1258,7%	2,5%	0,7%
Israel	10,43	2,7	0,01	0,00	56,12	4,8%	0,0%	0,0%
Italy	3261,23	851,0	1,66	0,47	338,10	251,7%	0,5%	0,1%
Lebanon	26,94	7,0	0,01	0,00	23,90	29,4%	0,1%	0,0%
Libya	622,03	162,3	0,32	0,09	62,96	257,8%	0,5%	0,1%
Malta	29,44	7,7	0,01	0,00	1,66	462,8%	0,9%	0,3%
Monaco	0,41	0,1	0,00	0,00	N.A.	X	X	X
Montenegro	146,62	38,3	0,07	0,02	2,29	1670,7%	3,3%	0,9%
Morocco	148,03	38,6	0,08	0,02	68,41	56,5%	0,1%	0,0%
Palestine	N.A.	X	X	X	3,50	X	X	X
Slovenia	0,00021	0,0	0,00	0,00	12,71	0,0%	0,0%	0,0%
Spain	1480,88	386,4	0,75	0,21	245,61	157,3%	0,3%	0,1%
Syria	0	0,0	0,00	0,00	27,64	0,0%	0,0%	0,0%
Tunisia	6369,05	1661,9	3,24	0,92	35,58	4670,9%	9,1%	2,6%
Turkey	740,59	193,2	0,38	0,11	435,68	44,4%	0,1%	0,0%
Total	**19019,7**	**4962,9**	**9,67**	**2,76**	**1974,6**	**251,3%*** **	**0,5%*** **	**0,1%*** **

*This estimate is based on the remote sensing study from Traganos et al. (2022), with an estimated accuracy of 72%. ** This data is based on Friedlingstein et al. (2023). *** These are the average percentages, and not the total percentages.

Table B. An overview of the Mediterranean countries and territories, and how their CO_2 stock, fixation and sequestration rates compare to their annual national emissions.