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Integrating Blue Carbon Ecosystem assessments and institutional carbon footprint: toward a holistic approach to climate mitigation

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ABSTRACT

Climate change is a global challenge with profound implications for natural ecosystems, economies and human societies. The primary driver of climate change is the rising atmospheric concentration of greenhouse gases (GHG), particularly carbon dioxide (CO_2), which reflects the balance between anthropogenic emissions and natural carbon fluxes within major carbon reservoirs, such as the terrestrial biosphere and the oceans. Effectively addressing this challenge requires strategies that reduce emissions while enhancing carbon sequestration. In this context, coastal Blue Carbon (BC) ecosystems have gained international recognition as a Nature-based Solution (NbS) for capturing and storing atmospheric CO_2, thereby contributing to global mitigation efforts. However, understanding of their ecological functions, carbon storage potential and socio-economic value remains incomplete, particularly in the European and Mediterranean regions. Building on these considerations, this research adopts a dual approach, investigating both natural BC ecosystems and institutional carbon management. It first investigated the ecological value of BC ecosystems and assessed their role as natural assets for climate mitigation, while simultaneously evaluating the environmental performance of the University of Palermo to identify emission reduction strategies consistent with 2050 decarbonisation targets. This multidisciplinary framework integrated ecological, spatial and economic assessments of BC ecosystems with an institutional Carbon Footprint analysis, quantifying GHG emissions from university activities and providing a holistic perspective on nature-based and institutional mitigation actions. Firstly, a systematic review of European and Mediterranean BC coastal habitats, focusing on saltmarshes and seagrass ecosystems, revealed significant knowledge gaps and spatial variability in carbon accumulation between protected and unprotected areas, highlighting the need for more targeted management and policy interventions. A detailed case study of Capo Feto coastal wetland (Sicily), a protected BC habitat in the Mediterranean region, combined field measurements, remote sensing and spatio-temporal modelling to assess sedimentary carbon storage patterns and processes. The results demostrated distinct spatial gradients among habitat types, indicating substantial potential for sedimentary carbon sequestration. Finally, an economic evaluation using the Social Cost of Carbon (SCC) quantified the monetary value of stored carbon, providing insights for natural capital accounting and conservation planning. The institutional Carbon Footprint analysis of the University of Palermo (UNIPA) produced the first comprehensive GHG inventory, enabling accurate measurement and communication of both direct and indirect emissions from academic activities. The analysis identified targeted mitigation measures, underlining the strategic role of universities in promoting climate accountability and operational decarbonisation. Overall, this research advanced an integrated understanding of BC ecosystems and institutional emissions,

highlighting the importance of coastal habitats for carbon mitigation and the role of universities in supporting sustainable and low-carbon practices.

Introduction

Since the latter part of the 19th century, the burning of fossil fuels (coal, oil and natural gas) and extensive deforestation have caused significant increases in the levels of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) in the atmosphere. These greenhouse gases (GHG) trap certain wavelengths of infrared radiation, which would otherwise escape into space. Although the natural greenhouse effect is essential for maintaining life-supporting temperatures on Earth, its intensification due to excess GHG re-emits more energy towards the Earth's surface, thus enhancing the planet's warming (Ledley et al., 1999).

Before industrialisation, atmosphere CO_2 levels was relatively stable at around 280 parts per million (ppm), but the advent of modern technologies such as electricity generation, steel production and the internal combustion engine, exacerbating environmental degradation and triggering a sharp and continuous rise in emissions. Today, CO_2 concentrations exceed 420 ppm, nearly 50% higher than pre-industrial levels (NOAA, 2025).

According to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (AR5, IPCC, 2014) about half of all anthropogenic CO_2 emissions since 1750 have occurred in the past 40 years. Approximately 40% of these emissions remain in the atmosphere, contributing directly to global warming, while the remaining 60% have been absorbed by terrestrial ecosystems and oceans. Notably, the oceans alone have taken up around 30% of CO_2 emissions, but warming and acidification are reducing their capacity to store carbon, disrupting marine biogeochemical cycles and threatening ecosystem stability (EEA, 2024; IUCN, 2024). The AR5 findings underpinned the Paris Agreement, which commits Parties to regularly update their nationally determined contributions (NDCs) aimed at limiting global temperature rise to well below 2°C, with efforts toward 1.5°C.

Building on this international framework, Article 4 of the Paris Agreement establishes the long-term objective *of achieving a balance between sources of anthropogenic emissions and removals by sinks of greenhouse gases (GHGs) in the latter half of this century* (UNFCCC, Art. 4, para. 1, 2015). This balance, commonly referred to as *net zero emissions*, represents a pillar of current international climate policy and highlights the dual need to drastically reduce anthropogenic GHGs emissions and enhance natural and artificial carbon sinks.

In this context, natural carbon sinks (UNFCCC, 1992), including terrestrial and marine forests, soils and oceans, have historically absorbed an average of 55–60% of anthropogenic CO_2 emissions worldwide (IPCC, 2023b). Mangroves, saltmarshes, coastal wetlands and seagrass meadows, collectively known as *Blue Carbon* (BC) ecosystems, are among the most relevant global carbon reservoirs, capable of capturing and storing substantial amounts of atmospheric CO_2 within their biomass and sediments (Duarte et al., 2008; Nellemann et al., 2009; Giri et al., 2011; Mcowen et al., 2017). Although they cover less than 1% of the ocean surface (Duarte et al., 2013), these ecosystems sequester carbon at rates up to four times greater per unit area than terrestrial forests, storing long-term organic carbon (C_{org} *stock*) in their sediments for centuries to millennia (Fourqurean et al., 2012a; Mcleod et al., 2011; Duarte, 2014). Owing to this exceptional efficiency in capturing and retaining *blue* carbon (UNEP, 2009; Alongi, 2012, 2023; Beaumont et al., 2014), BC ecosystems are recognised as being among the most effective natural carbon sinks globally (Nellemann et al., 2009; Duarte et al., 2013; Macreadie et al., 2019).

Beyond mitigating CO_2 emissions through carbon capture and storage, BC ecosystems provide a wide range of essential ecosystem services: they safeguard biodiversity, protect coastlines through climate regulation service (Brock et al., 2012; Fourqurean et al., 2012a; Lavery et al., 2013; Hiraishi et al., 2014), enhance directly and indirectly human well-being (MEA, 2005; Costanza et al., 2014; Duarte, 2014; Seddon et al., 2020) and support local economies (UNEP, 2009; Macreadie et al., 2021a; Schindler Murray & Milligan, 2023). Their ecological and socio-economic importance has led to growing recognition of BC ecosystems as key Nature-based Solutions (NbS) in supporting decarbonisation through the conservation and management of natural carbon reservoirs (MEA, 2005; Howard et al., 2017a; Wedding et al., 2021). This recognition has translated into their progressive integration into international and national climate strategies and mitigation policies (Nellemann et al., 2009; ONU, 2015; Wedding et al., 2021; IPCC, 2023a). Nonetheless, compared to terrestrial ecosystems, conservation and restoration strategies remains relatively limited (Howard, 2014; Macreadie et al., 2019). Nevertheless, BC ecosystems face increasing threats from environmental and anthropogenic pressures, which jeopardize their ability to function effectively as carbon sinks and deliver these essential services. Climate change amplifies this vulnerability, making them susceptible to heat stress, changes in hydrological regimes, biodiversity loss and Land Use and Land Cover (LULC) changes (White et al., 1999; Heinze et al., 2015; Friedlingstein et al., 2021; Bunsen et al., 2024). These stressors can reduce the capacity of sediments to sequester carbon, threatening the long-term stability of sedimentary organic carbon (C_{org}). As a result, disturbed or degraded BC coastal ecosystems may shift from carbon sinks to sources (Nellemann et al., 2009; Pendleton et al., 2012; Lovelock et al., 2017; Salinas et al., 2020; Moksnes et al., 2021), releasing previously stored organic carbon and increasing atmospheric CO_2 levels. These concerns highlight the urgent need for comprehensive, spatially explicit and detailed assessments of carbon stocks to better recognise the local conditions that influence carbon dynamics (Macreadie et al., 2019; Apostolaki et al., 2024). Furthermore, complementing field data with innovative tools such as remote sensing and predictive modelling can facilitate efficient mapping and monitoring across different spatial and temporal scales, while supporting the implementation of targeted conservation, management and restoration measures adapted to site-specific conditions (Zhao et al., 2018; L. Li et al., 2024; Yang et al., 2024). A comprehensive assessment guarantees the long-term effectiveness of BC ecosystems as Natural Capital (stock of natural assets) supporting direct and indirect benefits (flows) for society (Natural Capital Committee, 2014). BC ecosystems function as dynamic systems where the stock of natural assets generates flows of ecosystem services, sustaining environmental integrity and supporting socio-economic systems (Daily, 1997; MEA, 2005). This relationship between natural resources (geological resources, soil, air, water and all living organisms) and the services is central to understand the importance of ecosystems conservation: depletion of natural capital undermines the long-term capacity to support human well-being (Barbier et al., 2011; Costanza et al., 2014; Elliott, 2023; Feng et al., 2023), as well as compromising intergenerational equity (Costanza et al., 1997; ONU, 2015; Dasgupta, 2024). This perspective further emphasises the interdependence and circularity between natural and human systems (Costanza et al., 2014).

However, despite this growing understanding of their ecological and socio-economic importance, significant knowledge gaps remain regarding the spatial variability and long-term stability of sedimentary C_{org} stocks, particularly in European and Mediterranean habitats. To strengthen the foundation for local carbon stock assessments, this study carried out a systematic review of the current literature on carbon stocks in European BC ecosystems. This approach aimed to identify knowledge gaps and support contextually appropriate assessments, which were fundamental for developing effective conservation strategies and climate mitigation policies. Complementing the review, the study integrated field measurements, remote sensing and spatial modelling approach to provide a comprehensive assessment of sedimentary C_{org} stocks in a protected Mediterranean coastal wetland used as a local case study. Furthermore, the investigation linked ecological functions with socio-economic valuation and institutional sustainability perspectives, contributing to a more integrated understanding of BC dynamics. Building on this ecological perspective, the research extends the concept of ecosystemic functioning beyond natural habitat, exploring how universities can function as dynamic *artificial* systems. When viewed through a sustainability lens, universities can contribute to climate change mitigation by promoting resilience, innovation and long-term societal benefits. Their internal organisation, collaborative networks and feedback mechanisms between inputs (such as financial, energy, information and relational resources) and outputs (such as education, research, knowledge transfer, innovation and societal engagement) resemble the structure and functioning of natural ecosystems in terms of flows, resilience and capacity for self-regulation and adaptation (Folke et al., 2003; Levin & Greenwood, 2016). Therefore, they can function as catalysts for the transition to low-carbon models by identifying major sources of emissions, guiding mitigation policies and promoting awareness, innovation and best practices within the academic community (Scrucca & Barberio, 2021). Within this framework, the research also integrated the *carbon footprint* assessment of the University of Palermo as a strategic tool to quantify GHG emissions arising from institutional operations. The findings support the formulation of evidence-based environmental management policies and guide the university towards effective mitigation actions and a more sustainable organisational model (Wiedmann & Minx, 2008; Alvarez et al., 2016). Climate change requires an interdisciplinary and collaborative approach to address its impacts effectively. From an environmental protection and institutional sustainability perspective, the project promotes operational solutions that link environmental research with innovative management practices.

Aims and organisation of the Thesis

Building upon the ecological and institutional frameworks outlined in the introduction, this thesis examines the dynamics of carbon within natural Blue Carbon (BC) ecosystems and institutional structures. Although coastal BC habitats, including salt marshes and seagrass meadows, are widely acknowledged as highly efficient natural carbon sinks, substantial knowledge gaps persist concerning their spatial heterogeneity, long-term stability and socio-economic valuation, particularly within European and Mediterranean regions.

The overarching aim of this thesis is to advance a comprehensive understanding of carbon dynamics in both natural and institutional systems, providing actionable insights to support climate mitigation and sustainable management strategies. Concurrently, institutional greenhouse gas (GHG) emissions, assessed through carbon footprint analysis, represent a significant but often overlooked component of local carbon budgets, underscoring the need to integrate ecological and anthropogenic perspectives to inform climate action at multiple scales. To address these challenges, this Ph.D. project proposed a multidisciplinary methodological framework integrating a systematic literature review, of sedimentary carbon stocks in a protected coastal wetland, spatio-temporal modelling, economic valuation and institutional carbon footprint accounting. The framework enables the study to systematically identify knowledge gaps in European and Mediterranean Blue Carbon ecosystems through a comprehensive literature review (Chapter 1), quantify sedimentary carbon stocks in a Mediterranean coastal wetland using site-specific field measurements, remote sensing and spatio-temporal modelling (Chapter 2), and assess institutional GHG emissions via carbon footprint analysis (Chapter 3). Collectively, these approaches furnish a coherent and integrated foundation for informing climate mitigation strategies at both ecological and organisational scales.

The study is organised into three stand-alone chapters, each dedicated to a specific objective:

- Chapter 1 provides a systematic literature review to evaluate the current state of knowledge on carbon stocks in European and Mediterranean BC ecosystems, with a focus on saltmarsh and seagrasses under varying protection regimes.
- Chapter 2 investigates a Mediterranean coastal wetland in Sicily, evaluating the organic carbon storage capacity of sediments within a protected area. Remote sensing tools and modelling software are employed to analyse spatial and temporal dynamics, while assessing the impact of the land use and land cover (LULC) changes of the natural carbon sink. Economic valuation methods are utilized to quantify the natural capital of the coastal wetland, highlighting both tangible and intangible ecosystem services it provides to society.
- Chapter 3 quantifies the carbon footprint of the University of Palermo to measure GHG emissions generated by institutional activities. The analysis aims to improve emissions management by identifying primary emission sources and establishing effective mitigation strategies.

Chapter 1

1. Inventorying carbon stocks of European Blue Carbon (BC) ecosystems: insights from a systematic review

1.1. Introduction

Coastal BC ecosystems such as seagrass, saltmarshes and mangroves are widely recognised as potential Nature-based Solutions (NbS) for climate change mitigation (Macreadie et al., 2021b; Nellemann et al., 2009; Pendleton et al., 2012; Schindler Murray & Milligan, 2023). Despite occupying a much smaller area than terrestrial ecosystems, vegetated coastal habitats sequester and store roughly half of the global organic carbon (C_{org})) accumulated in marine sediments over long timescales (Duarte et al., 2005a; Fourqurean et al., 2012b; McLaren, 2012; Nellemann et al., 2009). This sedimentary carbon, known as *carbon stock* (Nellemann et al., 2009; Crooks et al., 2018), plays a key role in climate regulation by functioning as a stable carbon sink that helps offset atmospheric CO_2 emissions (Lo Iacono, et al., 2008; Fourqurean et al., 2012a; Lavery et al., 2013; Hiraishi et al., 2014; Guerry et al., 2022; L. Li et al., 2024). However, in contrast with terrestrial environments, conservation and restoration efforts targeting BC ecosystems remain comparatively underdeveloped (Howard, 2014; Macreadie et al., 2019). Organic carbon (C_{org}) stocks exhibit high spatial variability across and within vegetated coastal habitats, driven by biotic factors (e.g. plant traits such as shoot density, canopy height) and local environmental factors (such as sediment type, hydrodynamics, nutrient availability) complicating large-scale assessments and conservation efforts (De Los Santos et al., 2023). Salt marshes and seagrass meadows along Europe and the Mediterranean coasts are particularly vulnerable to degradation and anthropogenic pressures, threatening both their ecological integrity and their capacity to function as significant carbon reservoirs (Marbà et al., 2015; Dahl et al., 2025). For example, Lima et al. (2022) conducted a rigorous assessment of the mean organic carbon (C_{org}) stock in the top metre of sediment of an intertidal seagrass meadow in southern England, highlighting both the role of seagrass meadows in carbon storage and the value of direct measurements and precise calculations to improve stock estimates. Similarly, Martínez-Eixarch et al. (2024) emphasised that acquiring site-specific data in coastal wetlands can support the validation of large-scale protection and conservation projects, ensuring that carbon management strategies are grounded in local ecological conditions. Despite growing interest at the European level, quantitative regional-level assessments of carbon stocks content in BC ecosystems remain scarce, leading to significant knowledge gaps that hinder the development of effective conservation strategies. Protected Areas (PAs) are widely recognized as a fundamental tool for coastal conservation, as they

provide a structured framework to evaluate the effectiveness of management measures aimed at enhancing carbon sequestration, biodiversity preservation and overall coastal resilience (Howard et al., 2017b; Miteva et al., 2015; Sala et al., 2021). However, the effectiveness of these strategies in maintaining or enhancing carbon storage in BC ecosystems remains uncertain, as implementation is often weak and management measures rarely account explicitly for sequestration processes (Brock et al., 2012; Hutto et al., 2021; Miteva et al., 2015; Pendleton et al., 2012).
To address these gaps, this chapter presents a systematic review and meta-analysis of European coastal BC ecosystems, focusing on saltmarshes and seagrass meadows. The study aimed to:

i. assess baseline estimates of carbon stocks of European BC ecosystems;
ii. compare carbon stocks between seagrass meadows/saltmarshes in protected vs. unprotected areas;
iii. identify potential gaps and methodological biases relating to the assessment of carbon stocks at European and mediterranean scale.

1.2. Materials and methods

Data sources, search strategy, screening steps and eligibility criteria

A systematic review was carried out following the Preferred Reporting Items for Systematic reviews and Meta-Analyses (PRISMA) guidelines for literature search and data reporting (Page et al., 2021). All databases of the two main bibliographic databases, Web of Science and Scopus, were accessed on October 21, 2024 and the following search string was used to identify the relevant scientific literature by examining titles, abstracts and keywords: *(seagrass* OR "sea grass" OR eelgrass* OR posidonia OR matte OR zostera OR cymodocea OR ruppia OR halophila OR "salt marsh" OR saltmarsh*) AND (Carbon AND (blue OR sink OR storage OR stock OR organic OR "accretion rate" OR "accumulation rate")) AND (mediterranean OR europ*)*. The screening steps were conducted independently by two authors, after removal of duplicate the records generated by the two databases. Firstly, papers were screened for suitability based on title and abstract. Secondly, papers potentially meeting the inclusion criteria were sought for retrieval and assessed for eligibility. Only original research papers reporting sedimentary carbon stocks data per unit area (kg C_{org} m^{-2} or other related unit measures) or providing sufficient data for carbon stock calculations (e.g. C_{org} density and sediment dry bulk density) were retained eligible for inclusion. Exclusion criteria were: (i) studies conducted out of Mediterranean and European area; (ii) studies that did not report carbon stocks data per unit area or useful data for carbon stock calculations; (iii) studies that did not focus on seagrass or saltmarsh ecosystems; (iv) studies not presenting original data; (v) review.

Data extraction and analysis

Data extraction was focused on bibliographic details, geographic location (country, sea, coordinates), habitat type (seagrass or saltmarsh) and species composition, level of protection, technical information about the sediment core extraction (corer type and depth, sediment compression), stock depth and sedimentary organic carbon stocks per unit area.

Carbon stock data were standardised to kg C_{org} m^{-2} if retrieved in other related unit measures. If no carbon stock data was presented per unit area, but there were sufficient data for carbon stock calculations we estimated it following one of the three cases:

1) When profile data were available, carbon stock was estimated to the 100 cm using a linear regression model to fit the data (this was the case of Apostolaki et al., (2022); Wesselmann et al., (2021)) ;
2) When profile data of C_{org} density and sediment dry bulk density (DBD) were available, they were multiplied to obtain carbon stock that was then summed to obtain the stock at 100 cm or at the highest depth possible this was the case of (Röhr et al., (2016a); Röhr, Holmer, Baum, Björk, Chin, et al., (2018)) ;
3) When the total carbon stock was reported as Total Mg and the extension of the habitat was also provided, the carbon stock was estimated by dividing the total carbon stock by the surface (this was the case of (Sousa et al., 2017).

Data analysis

A georeferenced map of the distribution of the study locations across Europe was created using QGIS (3.28), where georeferenced data points were overlapped to the European distribution of saltmarshes (Mcowen et al., 2017) and seagrass (UNEP-WCMC & Short, 2021) habitats. The relationship between the C_{org} stock and the depth of the stock analysed was assessed for both habitats using the Spearman correlation. To test for differences in C_{org}, C_{inorg} and N stock (kg m^{-2}) between saltmarshes and seagrass habitats, the Kruskal-Wallis test was used on the data categorized by three sediment depth categories: ≤50, 50-|100 and >100 cm. Then the dataset was subsampled by selecting only data estimated at the standard top metre sediment core (100 cm stock depth) and the Kruskal -Wallis test was used to compare the C_{org}, C_{inorg} and N stocks: i) in protected *vs* unprotected sites, ii) between monospecies and multispecies saltmarshes habitats and iii) between species within seagrass habitats. All statistical analyses were run using R v4.4.2 (R Core Team, 2022).

1.3. Results

The search strategy produced a total of 1201 articles (863 through Web of Science and 338 through Scopus), of which 299 were removed as duplicate before screening (Figure 1.1). Of the remaining 902 articles initially screened by title and abstract, 202 were considered potentially eligible for inclusion and were retrieved in full text. Among these, 49 articles met the predefined criteria and all relevant data were extracted. Additionally, the data of 6 further articles, which were cited by some of the selected ones but were not retrieved by the search string, were extracted and included in the review, accounting for a total of 55 studies selected.

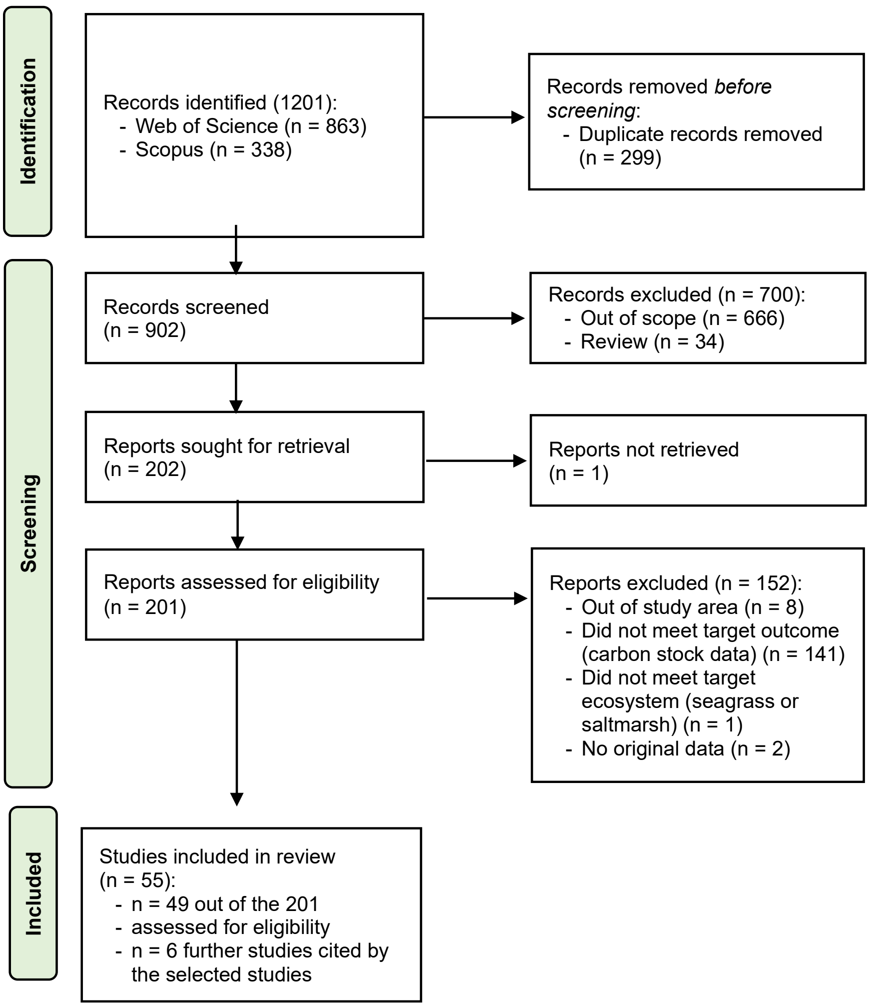


Figure 1.1 PRISMA flow diagram showing the search strategy followed to conduct the systematic review

Temporal and geographic distribution of selected studies

The number of articles reporting carbon stocks data was limited to 7 since the first one published in 1994 to the 2015, with 5 articles concerning seagrass habitats and 2 saltmarshes (Figure 1.2). It's only since 2016 that the number of published studies increased over time, with a peak of 6 articles for seagrasses in 2023 and 4 for saltmarshes in the years 2022-2024.

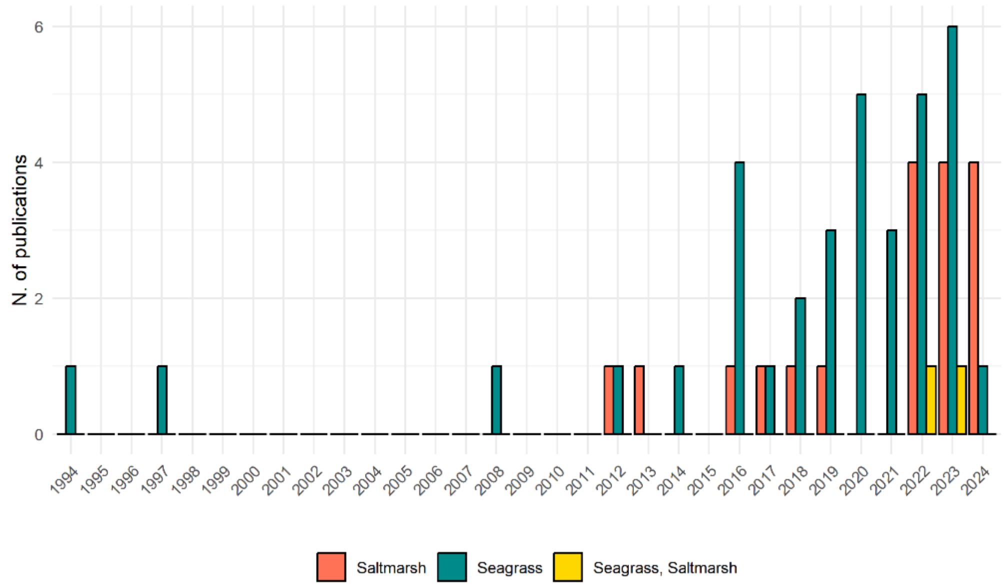


Figure 1.2 Number of selected articles published per year.

The geographic distribution of the published studies located outside of the Mediterranean Sea (n= 37) spanned from the Atlantic coasts of European countries to the Baltic Sea, across the Irish Sea, the English Channel and the North Sea (Figure 1.3, Appendix A: Additional Table). The studies published in this area regarded, almost evenly, both saltmarshes and seagrass habitats, providing data for most countries in which these habitats are present (Figure 1.3). On the contrary, studies conducted within the Mediterranean Sea (n=18) were restricted to few locations in few European countries (including Cyprus, France, Greece, Italy, Malta, Spain) dominated by seagrass habitats (Figure1.3). Looking at the level of protection of the sites investigated by the eligible studies, overall, a total of 27 studies were conducted in Natura 2000 sites while 15 considered both a Natura 2000 sites and sites not protected. In addition, 4 studies were conducted in Special Areas of Conservation (SAC), 3 in both a SAC and a non-protected site, 6 were performed only in non-protected sites (see *Supplementary Table*).

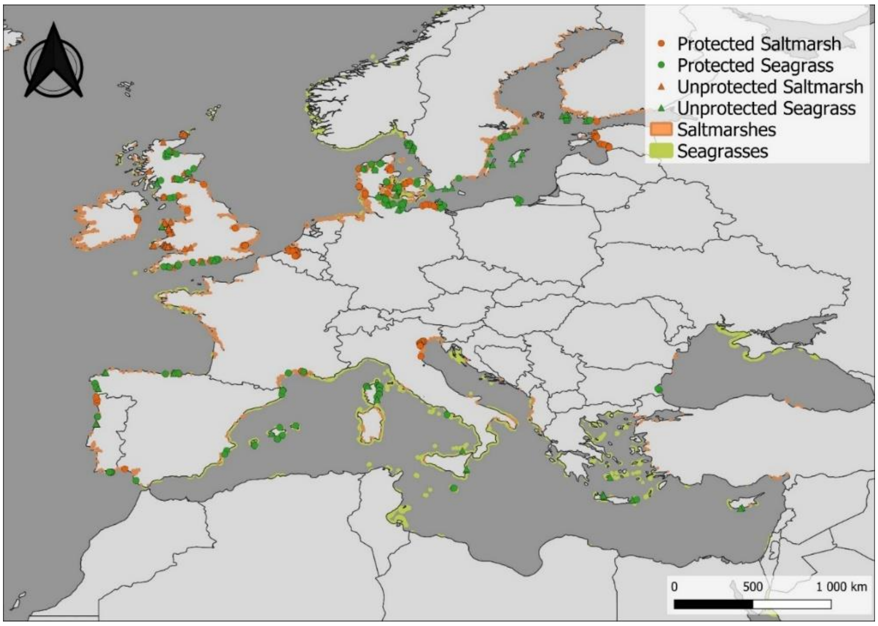


Figure 1.3 Map of locations of selected articles where carbon stock evaluation studies have been conducted in protected and non-protected saltmarsh and seagrass habitats.

Carbon stock by sediment core depth

A total of 654 sediment cores were analysed for carbon stocks in saltmarshes and seagrass habitats across the selected studies. Among these, the majority of carbon stocks were calculated at sediment depths between 2 and 50 cm (411 cores), particularly for seagrass habitats, while a half were calculated at sediment depths between 50 and 100 cm (224 cores), and only 23 sediment cores were deeper than 100 cm (Figure 1.4).

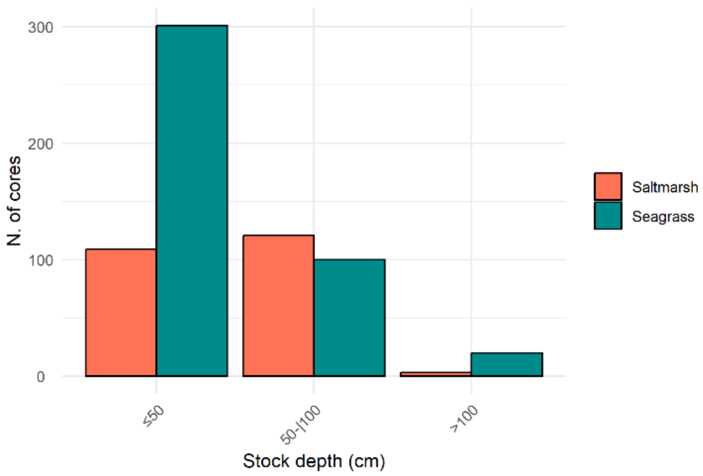


Figure 1.4 Number of cores analysed for Carbon stocks across the selected studies conducted in saltmarshes (coral bars) and seagrass (cyan bars) habitats, grouped by the following sediment depth categories: ≤50, 50-|100 and >100

Overall, the values of C_{org} stocks (kg m^{-2}) estimated across habitats ranged between 0.01 and 73.19 kg C_{org} m^{-2} for saltmarshes and between 0.02 and 180.00 kg C_{org} m^{-2} for seagrass, with a strong dependence on the depth of the sediment stock analysed (Figure 1.5). Indeed, the relationship between the C_{org} stock and the depth of the stock analysed was significantly positive in both saltmarshes and seagrass habitats (p-value<0.05, Figure 1.5). However, the different degree of dispersion suggests that the depth may be more predictable in saltmarshes compared to seagrasses, where data showed a greater variability.

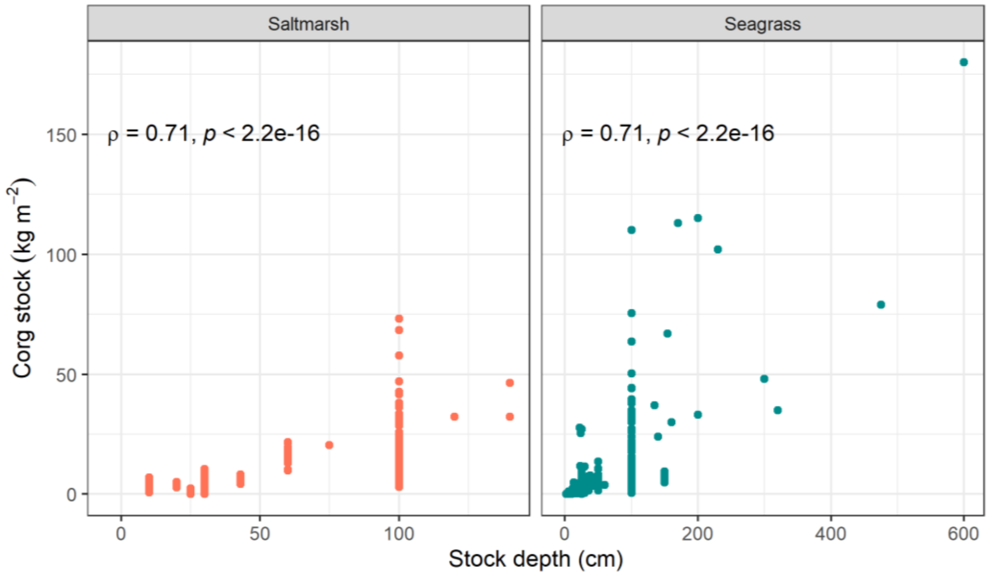


Figure 1.5 Relationship between Corg stock (kg m^{-2}) and the depth of the stock analysed in saltmarshes and seagrass habitats. ρ and p-value of the Spearman correlations are overlapped to each plot.

The C_{org}, C_{inorg} and N stocks estimated at different sediment depth categories were significantly different between the two habitats (Figure 1.6). The mean values of C_{org} stocks reported by the selected studies were respectively 4.57 ± 2.14 and 2.99 ± 3.58 kg C_{org} m^{-2} for saltmarshes and seagrass at sediment depth <50 cm, were 16.38 ± 12.23 and 16.22 ± 18.09 kg C_{org} m^{-2} at sediment depth between 50 and 100 cm, and were 37.01 ± 8.17 and 45.91 ± 48.79 at sediment depth > 100 cm. The C_{inorg} stock for saltmarshes at sediment depth 50-|100 cm (10.04 ± 8.74 kg m^{-2}) was significantly lower than seagrass (30.30 ± 19.21 kg m^{-2}), as well as the N stock (kg m^{-2}) at depth < 50 cm, but not at depth 50-|100 cm, where it was significantly higher in saltmarshes than in seagrass (Figure 1.6).

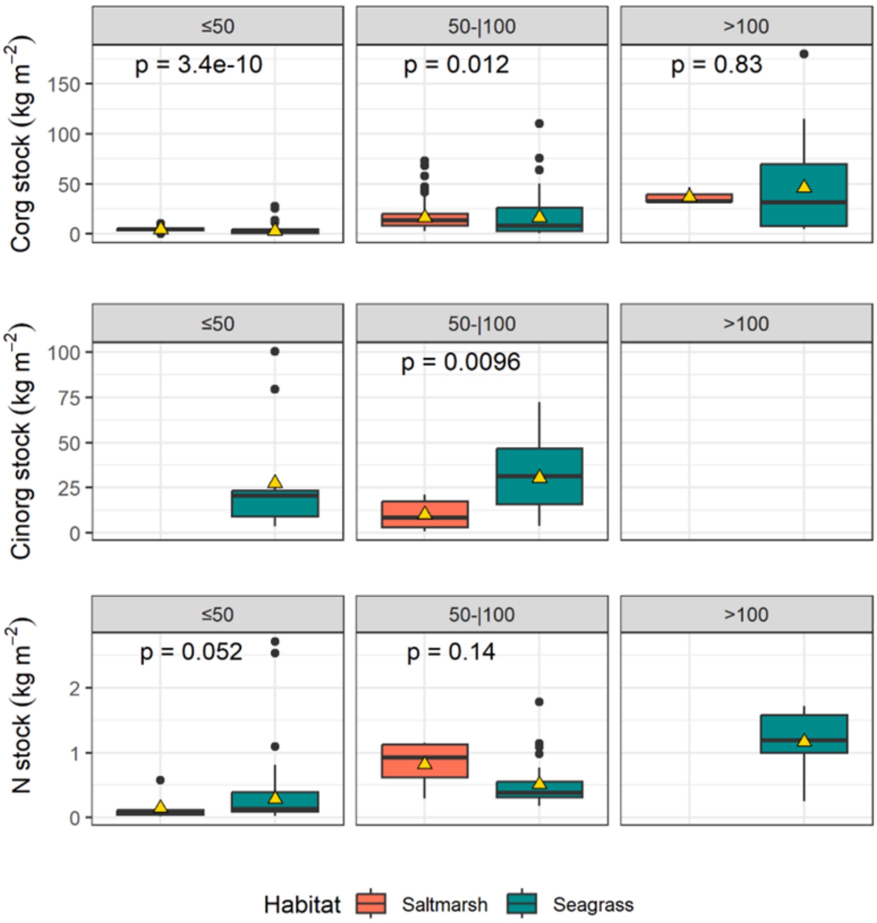


Figure 1.6 C_{org}, C_{inorg} and N stock (kg m^{-2}) of saltmarshes (coral boxes) and seagrass (cyan boxes) habitats estimated by selected studies, categorized by three sediment depth categories: ≤50, 50-|100 and >100 cm. Yellow triangles indicate the mean value of the distribution. P-values of the Kruskal-Wallis tests are reported on each graph.

Top meter sediment Carbon stock by level of protection and by species

When considering the level of protection, results showed that the top meter sediment C_{org} stocks of seagrass habitats in protected sites was significantly higher than in unprotected sites (averaging respectively 20.38 ± 19.33 kg C_{org} m^{-2} (n=61) vs 9.52 ± 13.64 kg C_{org} m^{-2} (n=38), p-value<0.05; Figure 1.7), but not for saltmarsh habitats, where the opposite occurred (on average 13.45 ± 9.58 kg C_{org} m^{-2} (n=85) in protected vs 30.41 ± 18.33 kg C_{org} m^{-2} (n=18) in unprotected sites). Conversely, the top meter C_{inorg} and N stocks were comparable between the two levels of protection in seagrass habitats, averaging overall respectively 30.30 ± 19.21 kg C_{inrg} m^{-2} and 0.51 ± 0.35 kg N m^{-2}.

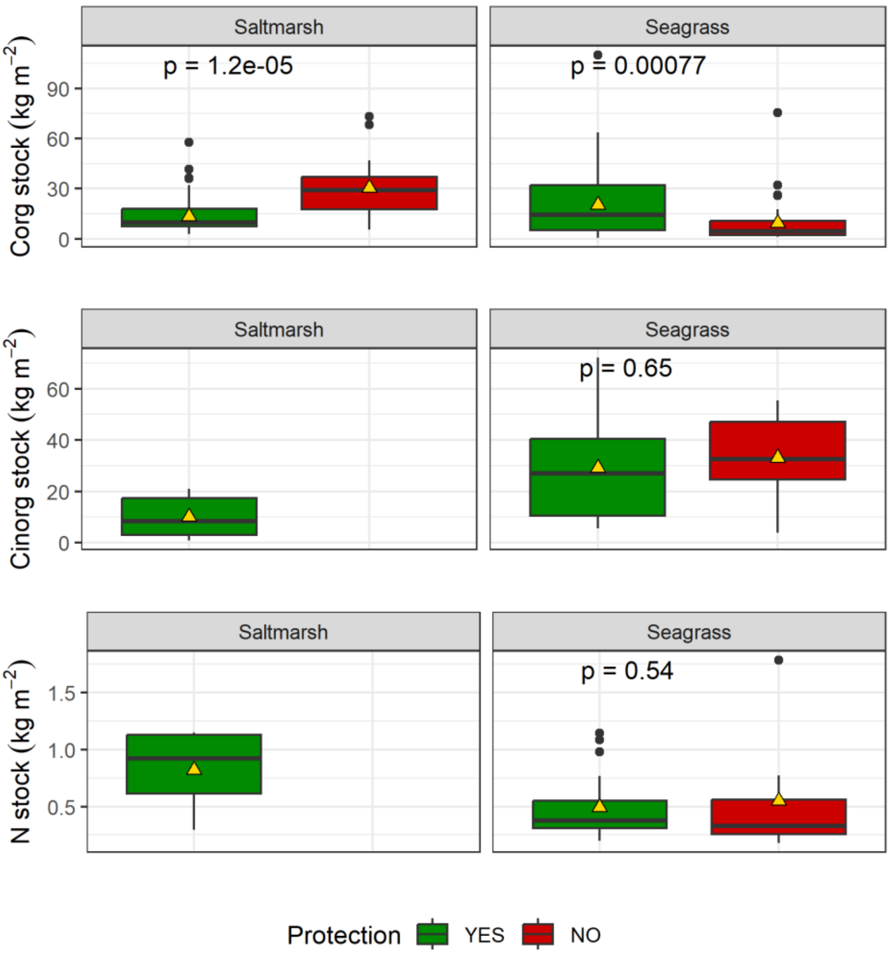


Figure 1.7 Comparisons of top meter sediment C_{org}, C_{inorg} and N stock (kg m^{-2}) in protected (green bars) vs non protected (red bars) saltmarshes and seagrass habitats. Yellow triangles indicate the mean value. P-values of the Kruskal-Wallis tests are reported on each panel. Note different y-axis scales across panels.

Considering saltmarshes, the top meter sediment C_{org} stock varied between habitats composed by single species and multiple species, with mean values respectively of 12.59 ± 10.46 kg C_{org} m^{-2} for monospecific saltmarshes and 19.50 ± 14.36 kg C_{org} m^{-2} for multi-species saltmarshes, while comparable mean values of C_{inorg} stocks were found for monospecific and multi-species saltmarshes, with 11.90 ± 7.45 kg C_{inorg} m^{-2} and 8.19 ± 11.19 kg C_{inorg} m^{-2} respectively (Figure 1.8a).

Considering seagrass, the species *Posidonia oceanica* showed significantly higher values of C_{org} stock compared with the other three species available, with a mean value of 27.71 ± 20.22 kg C_{org} m^{-2}, which was three times higher than *Zostera* spp. and eight times higher than *Cymodocea nodosa* and *Halophila stipulacea* (Figure 1.8b). Conversely, the N stock in *P. oceanica* meadows was significantly lower than in *Zostera* spp., which averaged 0.74 ± 0.45 kg N m^{-2} (Figure 1.8b).

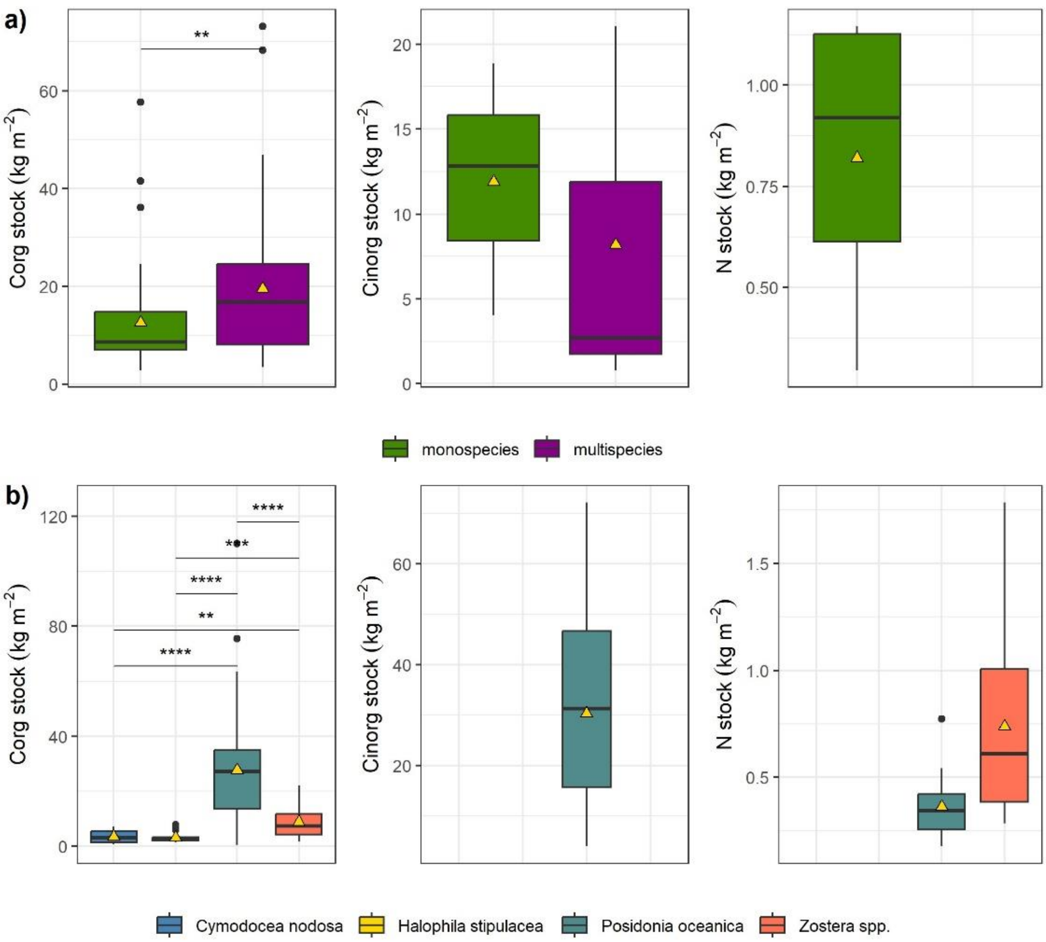


*Figure 1.8 Top meter C_{org}, C_{inorg} and N stock (kg m^{-2}) compared a) between monospecies and multispecies saltmarshes habitats and b) between species within seagrass habitats. Yellow triangles indicate the mean value. Significant levels of the Kruskal-Wallis' p-values are as follows: '****' 0 ', ***' 0.001, '**' 01, '*' 0.05. Note different y-axis scales across panels.*

1.4. Discussion

Inventorying the carbon stocks of European BC ecosystems is of crucial importance for understanding their potential contribution as a Nature-based Solution (NbS) to mitigating the impact of climate change. Beyond providing a baseline of the currently available carbon stocks data at European scale, this systematic review highlighted some key challenges in the more general field of blue carbon science. These challenges include the geographical gaps that would need to be overcome to increase the spatial resolution of the data, and the lack of standardised methodologies needed to accurately quantify stored carbon and enhance comparability across studies. All these points are discussed in the light of the importance of protecting such BC ecosystems as components of climate change mitigation and biodiversity preservation goals.

Geographic gap

Papers reporting blue carbon stock data useful to compile the inventory at European level covered a wide coastline of the northern Europe, contrasting with a considerable lack of data along the Mediterranean coasts. While studies in northern Europe cover most of the present seagrass habitats, a major effort would be needed to cover saltmarshes habitats, especially those located along the Irish and the Atlantic French coasts, as well as the Dutch and the Baltic coasts. In the Mediterranean region, despite the wide spatial extent of seagrass meadows within the basin – estimated at over 1,224,707 hectares of *Posidonia oceanica* alone (Telesca et al., 2015)– papers published to date report carbon stock data only on a limited number of seagrass habitats in the entire area. There is a gap of published data mainly along the Italian coasts of the Tyrrhenian Sea and much of the Aegean Sea. Furthermore, there are no published data of the wide *Posidonia oceanica* meadows that resides within the Marine Protected Area of the Egadi Islands, in western Sicily. This current picture highlights the need to expand carbon stock assessments across a wider range of European BC habitats as essential step for producing robust, regionally representative data to guide conservation and future climate policy.

Lack of standardised methodologies and reporting

The reviewed papers showed a wide variability in the methodologies used to collect sediment cores, both in terms of devices used and length of the cores collected. Gouge augers, Russian peat augers and stainless-steel corers were most used in saltmarshes habitats (12 out of 18 studies), plastic tubes (either PVC or acrylic) were most commonly used in seagrass meadows (20 out of 37 studies) whereas a scant number of studies (8) did not specify the coring device used. Relatively to the depth of the sediment core to be sampled for organic carbon stock quantification, the suggested standard practice is to collect the top meter sediment (Howard, 2014), since it is assumed that carbon stored at this depth is most susceptible to alteration due to habitat degradation or changes in land use and land cover (Hiraishi et al., 2014; Vaughn et al., 2021). However, among the reviewed literature, 9 of the studies conducted in saltmarshes habitats (47%) and 12 of the studies conducted in seagrass habitats (33%) reported stocks data of the top meter sediment, accounting respectively for a total of 121 and 99 values of carbon stock comparable at European level. Most of the remaining studies evaluated carbon stock in sediment cores comprised between 2 and 60 cm and very few below 100 cm of depth. While differences in research objectives, budgetary constraints and site-specific environmental or logistical conditions can explain variations in equipment choice and sampling depth, it is understandable that this heterogeneity in the choice of the equipment and the depth of the sampling reflects differences in research objectives, budgetary constraints, site-specific environmental or logistical conditions, certain fundamental details dependent on these choices — such as the percentage of core compression obtained and the correction method used — should always be clearly reported. Compression of sediment cores during sampling is known to be generally unavoidable and varies based on the type of sediment and vegetation, the coring device (Howard, 2014; Serrano et al., 2016) and the depth of sediment core collected (Morton & White, 1997). According to Howard et al. (2014) gouge augers would be the most suitable to reduce compression in organic-rich marsh soils whereas vibracorers should be preferred for seagrass and mangrove sediments, which often contain intricated tangles of rhizomes and roots. When occurring, compaction of cores changes the bulk density of the layers. Hence, if this is not properly corrected using a compression correction factor (Glew et al., 2001; Howard, 2014), it may affect the estimation of carbon stocks and carbon accumulation rates introducing a substantial source of uncertainty in large-scale assessments (Atwood et al., 2020; Smeaton et al., 2020). found that overestimation of the organic carbon stock resulting from core hammering in wetlands can reach up to 22%. However, this essential information was not consistently provided in the reviewed literature. Not always studies specified whether the compression occurred, to what extent and if corrected, or if accounted, not always it was specified what correction method was used. This was the case of 3 studies conducted in saltmarshes habitats and 4 in seagrasses, where top meter soil carbon stock was estimated without mentioning compression or if accounted, without specifying the percentage of it.

Carbon storage inventory: a baseline for European blue carbon ecosystems and comparison with global averages

In the absence of current international standard guidelines for collecting and reporting data on blue carbon stocks (Fest et al., 2022), the sparse but comparable data gathered across European countries in the context of this systematic review provided a valuable baseline for compiling a BC inventory in Europe. Overall, based on the available published literature compiled in this study, European BC ecosystems present in Europe show that saltmarshes have an average top meter sediment C_{org} stock of 16.42 ± 13.17 kg m^{-2}, a C_{inorg} stock of 10.04 ± 8.74 kg m-2 and a N stock of 0.82 ± 0.40 kg m^{-2}, whereas seagrasses contribute on average to a mean top meter sediment C_{org} stock of 16.22 ± 18.09 kg m^{-2}, a C_{inorg} stock of 30.30 ± 19.21 kg m^{-2} and a N stock of 0.51 ± 0.35 kg m^{-2}.

Compared with other regions, the average top metre C_{org} stock of European saltmarshes is considerably higher than the values reported for the Atlantic coast of South America (4.07 ± 0.27 kg m^{-2}; Martinetto et al., 2023) and China (8.11 ± 0.91 kg m^{-2}; Fu et al. (2021), but remains within the range reported for North American saltmarshes (10–25 kg m^{-2}; Chmura et al. (2003).

Similarly, the average value of C_{org} stock of the first meter of sediment found in this study for European seagrasses is noticeably higher than those reported for Pacific coast of North America

(Janousek et al., 2025) and China (Fu et al., 2021), that average respectively 7.02 kg C_{org} $m^{-2}$and 9.10 ± 2.89 kg C_{org} m^{-2}, but lower than the value of 60.19 kg C_{org} m^{-2} estimated for the Southeast Asian region (Thorhaug et al., 2020).

However, such overall average values here reported hide a high degree of inherent variability, with local stock values spanning over up to two orders of magnitude. In fact, carbon stocks in European monospecific salt marshes were found to range from 2.9 ± 0.1 kg C_{org} m^{-2} in an area dominated by *Spartina maritima* in the Ria Formosa lagoon in Portugal (Martins et al., 2022) to 57.7 ± 19.2 kg C_{org} m^{-2} in the Cromarty Firth saltmarshes in Scotland, which is dominated by *Puccinellia maritima* (Miller et al., 2023), whereas the highest values was recorded for a multispecies saltmarshes of the Atlantic coast of Scotland (73.19 ± 38.27 kg C_{org} m^{-2}, Smeaton et al., 2023).

Potential of European BC ecosystems: does protection matter?

The conservation and management of European and Mediterranean marine coastal habitats can help protecting BC ecosystems environments, increasing their resilience to climate change, conserving biodiversity and supporting local economies. Incorporating BC ecosystems into climate policy and management frameworks enables governments and environmental organisations to safeguard them over the long term and enhance their capacity for carbon sequestration and coastal protection. Nevertheless, BC ecosystems in the Mediterranean remain poorly protected. In the north-western Mediterranean, the current protection of *Posidonia oceanica* covers only about 50 per cent of the areas identified as priority habitats (Baldan et al., 2024). The EU directives and policies, such as the Natura 2000 Network, are efficacious driving forces for environmental protection in the Northern Mediterranean, particularly by accelerating the designation of protected habitats, including coastal wetlands (Beltrame et al., 2021; UNEP/MAP, 2021).

This systematic review demostrated that protection measures effectively support the maintenance of the carbon sequestration capacity and carbon sink function of BC ecosystems, particularly in seagrass habitats, where protected areas have been shown to contain significantly higher organic carbon stocks in the top meter sediment than unprotected areas. In contrast, this is less evident in saltmarshes habitats, indicating that factors beyond protection status, such as habitat degradation and residual anthropogenic pressures, such as urbanization, hydrological alterations and pollution, can substantially affect carbon storage (Duarte et al., 2013; Smeaton et al., 2023).

Although conservation efforts play an important role, they cannot prevent all the damage caused by human activities and additional pressures. This demonstrated that protection alone is not sufficient to preserve sedimentary carbon stocks, and that a deeper understanding of local degradation drivers is essential (Pendleton et al., 2012; Serrano, Lavery, Duarte, et al., 2016a).

These findings revealed persistent gaps due to scares ecological data and insufficient protective measures. Future efforts should therefore prioritise integrating long-term monitoring with site-specific ecological data to understand the multiple environmental and anthropogenic factors affecting carbon sequestration in European and Mediterranean BC ecosystems.
Innovative tools such as remote sensing validated with ground truthing, could facilitate efficient mapping to gather high-resolution estimates of marine C_{org} stocks (Atwood et al., 2020), as well as monitoring at larger scales supporting the implementation of targeted conservation, management and restoration measures at the local level (Li et al., 2024; Yang et al., 2024). Strengthening these actions will be crucial for safeguarding BC ecosystems and maximizing their role in climate mitigation and coastal resilience. If designed and managed effectively, PAs play a key role in the protection of ecosystems and, in some cases, in enhancing or restoring the productive potential of BC ecosystems. However, PAs alone cannot address all coastal and marine challenges. For example, when PAs are used in conjunction with other management tools, such as integrated coastal management (ICM), marine spatial planning and broad area fisheries management, they form the cornerstone of strategies for marine conservation. Expanding BC ecosystems or enhancing their carbon burial efficiency could increase the drawdown of additional atmospheric CO_2 in the near term. Protecting existing BC ecosystems would also help stabilize the organic carbon stored in sediments, thereby preventing future losses (Johannessen & Christian, 2023).

1.5. Conclusion

This systematic review and meta-analysis provided an initial understanding of the variability of carbon stocks across European coastal BC ecosystems, particularly seagrass meadows and saltmarshes. By integrating published data across multiple coastal habitats and management regimes, the analysis revealed substantial geographic, methodological and ecological discrepancies that continue to hinder accurate regional assessments and the development of effective climate mitigation strategies. Notably, saltmarshes and seagrass meadows demonstrated substantial potential for long-term climate resilience, as they act as significant carbon sinks. However, this potential remains underexploited due to persistent data gaps, especially in Mediterranean regions, which require urgent targeted research efforts. Although standardised protocols had been developed (e.g., Howard, 2014), significant methodological differences still persisted between studies. The review showed that variations in sampling design, reporting practices and sediment core compression had introduced considerable uncertainty into carbon stock estimates. This methodological variability highlighted the need for greater harmonisation and more comprehensive reporting of sampling strategies to improve comparability and reliability in blue carbon assessments.

Site-specific measurements of organic carbon (C_{org}) stock, such as those obtained from *Posidonia oceanica* meadows and multi-species saltmarshes, provided valuable reference points for future large-scale inventories and conservation planning, as they revealed the variability of carbon storage across species and habitat types. The findings suggested that the effectiveness of protection in preserving carbon stocks varied among coastal ecosystems. In saltmarshes, the efficacy of protection may be compromised by local ecological dynamics and anthropogenic pressures, resulting in limited carbon stock preservation. In contrast, seagrass meadows, particularly Mediterranean habitats dominated by *Posidonia oceanica*, tended to maintain higher organic carbon stocks due to their greater resilience and storage capacity, underscoring the importance of targeted conservation strategies.

This synthesis consolidated fragmented evidence from European BC ecosystems and provided a framework for comparing the influence of protection, methodology and geography on carbon storage estimates. By identifying critical gaps—particularly the underrepresentation of Mediterranean sites and the lack of methodological consistency—the study paves the way for future regionally harmonised assessments. These results accentuated the importance of developing management strategies tailored to each ecosystem, combining formal protection with adaptive interventions, long-term ecological monitoring and the inclusion of emerging technologies such as remote sensing to accurately track and safeguard carbon stocks across diverse spatial and temporal scales, thereby supporting the conservation of BC coastal habitats. Overall, this chapter provided an overview of the current knowledge of carbon stocks in European and Mediterranean coastal BC ecosystems, summarised existing research and identifying significant knowledge gaps. The findings emphasised the need for harmonised methodologies, broader geographical coverage and multiscale management approaches to enhance carbon sequestration and ecological value. By bridging scientific practice and policy, this synthesis contributed to advancing the conservation of these globally important ecosystems and their potential for climate mitigation, helping to ensure their protection for future generations.

Chapter 2

2. Spatio-temporal dynamics of Land-Use and Land-Cover (LULC) and assessment of carbon storage potential in a Mediterranean Coastal Wetland: Capo Feto case study

2.1. Introduction

Coastal wetlands are highly valuable and productive transitional habitat functionally similar to saltmarshes in terms of halophytic vegetation, intertidal dynamics and sedimentary carbon accumulation capacity, providing a wide array of ecosystem services that support environmental sustainability and socio-economic benefits (Costanza et al., 2014; Duarte, 2014; Seddon et al., 2021). Their strategic position at the interface between aquatic and terrestrial habitats, distinguish these BC ecosystems from other coastal BC habitats (Duarte et al., 2005a; UNEP, 2009; Mitsch & Gosselink, 2015). Coastal wetlands are highly effective *carbon sinks,* capturing atmospheric CO_2 and storing significant amounts of sedimentary organic carbon stocks over long timescales (Chmura et al., 2003; Duarte et al., 2005b; Ellison & Beasy, 2018; Fourqurean et al., 2012a). Their effectiveness is largely explained by high primary productivity and the slow decomposition of organic matter under waterlogged and anoxic conditions (Mcleod et al., 2011; Pendleton et al., 2012; Ouyang & Lee, 2014) which, coupled with sustained sediment accretion and the stabilization of organic matter in anaerobic soils, leads to high rates of carbon burial (Chmura et al., 2003; Lo Iacono, et al., 2008; Ouyang & Lee, 2014). Recognizing the importance of wetlands in climate mitigation, EU climate and energy policy (Regulation EU 2018/841) requires all for all Member States to account for GHG emissions and removals from managed wetlands during the second commitment period (2026–2030). In Italy, Annex II of the Regulation defines wetlands as *lands covered or saturated by water for all or part of the year, excluding reservoirs or other water bodies regulated by human activity* (MAMB, 1992). At the same time, these ecosystems remain highly vulnerable, having declined worldwide over the last fifty years (Kundu et al., 2024; Murray et al., 2022) and continuing to experience drastic permanent and seasonal changes in response to various anthropogenic pressures such as changes in land use and land cover, urban development pollution and climate change (Athukorala et al., 2021; Lovelock & Reef, 2020; Zekarias & Gelaw, 2025). This increasing vulnerability threatens their ecological integrity and carbon sequestration potential, further exacerbating global warming (Lovelock et al., 2017; Pendleton et al., 2012) and underscores the urgent need for site-specific conservation and restoration strategies to preserve their key role in climate regulation and ecosystem functioning (Howard et al., 2017a). To support such evaluations, remote sensing has emerged as a highly effective tool for the analysis and monitoring of coastal wetlands (Ioni et al., 2020; Ozesmi & Bauer, 2022), enabling the use of high-resolution imagery at regional and temporal scale (Zhao et al., 2018). Additionally, in recent years, the use of highly detailed RGB orthophotos combined with Geographic Information System (GIS) have proven successful strategy for the analysis of environmental pressures in wetlands worldwide (Melendez-Pastor et al., 2010). This chapter examines the first assessment of carbon storage capacity in Capo Feto coastal wetland, a representative Mediterranean coastal ecosystem located along the south-western coast of Sicily. The study focused on spatial and temporal changes in Land Use and Land Cover (LULC) between 2016 and 2024, using Sentinel-2 satellite imagery to identify patterns and trends across the coastal wetland area. Remote sensing analysis was combined with field measurements of sedimentary organic carbon stocks (C_{org} kg m^{-2}) along the coastal continuum, from the shoreline to the inner wetland, allowing the quantification of the carbon sequestration potential of the habitat and highlight its role as a long-term carbon reservoir. In addition to quantifying carbon stocks, an economic valuation based on the social cost of carbon (SCC) emphasised the effectiveness of Capo Feto coastal wetland as an effective nature-based solution (NbS) for climate change mitigation at both regional and national scales. This approach provides a robust basis for communicating the value of BC habitats to policymakers and stakeholders by translating carbon sequestration into societal benefits.

The methodology is structured around three main objectives, aiming to:

i) analyse spatio-temporal changes in Land Use and Land Cover (LULC) between 2016 and 2024 using remote sensing data to detect patterns and trends;
ii) assess the organic carbon (C_{org}, kg m^{-2}) stored in the ecosystem, integrating field data with spatial analysis;
iii) evaluate the economic value of carbon sequestration using the Social Cost of Carbon (SCC).

2.2. Study Area

Capo Feto is a natural coastal wetland (37.68° N, 12.48° E) located in southwestern Sicily, within the municipality of Mazara del Vallo (TP). The "*Paludi di Capo Feto e Margi Spanò*" (SIC ITA010006, Site of Community Importance) covers 350 hectare and was designated in 1995 as a Special Protection Area (SPA) under both the EU Birds Directive and the Habitats Directive (Directives 79/409/EEC; 92/43/EEC). The site is also recognised under the Ramsar Convention on Wetland (1971) as a wetland of international importance (Ramsar Convention, 2018). The ecological features of Capo Feto are strongly influenced by its geomorphological and hydrological characteristics. The marshy landscape is the result of the interaction between the specific soil morphology and the dynamics of the underlying hydrographic basin. This combination creates a dynamic environment that remains flooded in winter but dries out in summer, except for the reclamation drains and scattered marshes (Pernice et al., 2004). This inland wetland hosts a rich terrestrial flora and supports terrestrial and avian biodiversity, serving as a crucial resting site for migratory birds associated with marsh ecosystems. The surrounding marsh land is dominated by halophytic species that are typical of silty-clay soils, such as *Salicornia perennis* and *Limonium cancellatum* (Pernice et al., 2016). In addition, the marshy areas are largely covered by typical wetland vegetation communities, including *Juncetum maritimi* and *Phragmitetum australis* (Pernice et al., 2004). These plant associations are characterised by a complex network of roots and rhizomes, which stabilise the soil and trap suspended particles and organic matter from tidal waters, thereby enhancing the ability of ecosystem to store and sequester carbon over time (Duarte et al., 2005b; Wang et al., 2021; Burke et al., 2022a). The wetland is separated from the sea by coastal dunes and is bordered by a large *Posidonia oceanica* meadow offshore, which is one of the widest in the Mediterranean Sea (Calvo et al., 2010).This endemic seagrass system forms an extensive *reef barrier* running parallel to the shoreline, which helps to mitigate the effects of wave energy and reduce coastal erosion. In this way, it plays a crucial role in protecting the shoreline by retaining sediment and forming seasonal accumulations of seagrass biomass detritus, known as *banquettes*, along the beaches (Boudouresque et al., 2016; Gómez-Pujol et al., 2013; Maccarrone, 2010; Tomasello et al., 2022). Large accumulations of *aegagropili,* light, tangled balls of *Posidonia oceanica* fibres, formed by the action of waves, are also present along the coast reaching the saltmarshes being transported by winds. Capo Feto wetland has highly adapted to the saline influence of the adjacent sea, which in turn plays a key role in coastal defence. It acts as natural filter system, helping to prevent pollutants and excess nutrients from entering the marine environment. In this way, wetlands and seagrass function synergistically to support and preserve the ecological integrity of the coastal zone. Despite its ecological value, Capo Feto coastal wetland and the adjacent Margi Spanò area have experienced significant degradation due to intensive human activity over time. The habitat remained largely in its natural state until the 1950s, when several surrounding areas were reclaimed for agricultural use through the construction of a net of canals and a water-scooping ("Idrovora") or converted for military activities and urban development. In the 1980s, the construction of the Algerian-Italian methane pipeline further impacted the area (Pernice et al., 2004). Over time, the abandonment of some agricultural lands led to illegal dumping of waste and construction debris from urban demolition. Ongoing climate change, especially the decline in precipitation and unsustainable groundwater extraction are further exacerbating ecosystem stress (Pernice et al., 2016). Despite these pressures, to support environmental recovery, a restoration project was launched under the EU LIFE programme between 2000 -2004, involving the removal of military and civil infrastructures, waste clearance, and the implementation of integrated ecological and ecosystem-based management strategies (*Reclamation and environmental remediation of the Capo Feto biotope - LIFE 99 NAT/IT/006270*). Similar to Capo Feto, Margi Spanò has experienced environmental changes over time, primarily due to agricultural expansion and the construction of an aquaculture facility adjacent to the wetland (Figure 2.1).

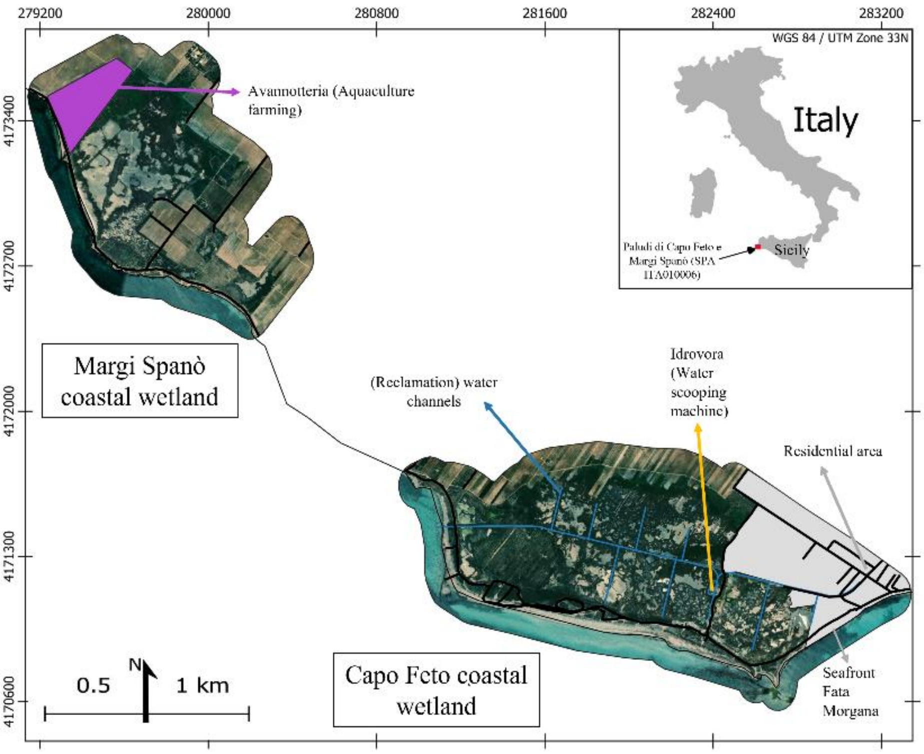


Figure 2.1 - Study Area Location

2.3. Land Use and Land Cover (LULC) dynamics in Capo Feto coastal wetland: A Remote Sensing Approach

2.3.1. Introduction

Over the past few decades, the application of remote sensing techniques has profoundly transformed how BC ecosystems are studied, monitored and managed. While field-based surveys and in situ sampling have traditionally provided highly accurate data, their use has often been constrained by high costs, logistical challenges and limited spatial and temporal coverage (Lee et al., 1996).

The integration of satellite imagery, aerial surveys and, more recently, unmanned aerial vehicles (UAVs or drones) has significantly advanced spatial and temporal monitoring capabilities, providing high-resolution data over broad geographic areas and thus overcoming many of the limitations of traditional field approaches (Ozesmi & Bauer, 2022; Zhao et al., 2018). Remote sensing began to be applied to coastal wetland studies in the 1980s, when multispectral satellite data were used to map vegetation distribution and estimate the biophysical and biochemical properties of these ecosystems (Hardisky et al., 1986; Jensen, 1987). Subsequent advances in optical and radar sensor technologies have greatly enhanced both spatial and spectral resolution of remote sensing, expanding its potential for BC ecosystems researches (Adam et al., 2010; Pettorelli et al., 2018). Furthermore, the integration of cloud-based platforms such as Google Earth Engine (GEE) with machine learning algorithms enables the efficient processing of multi-source datasets and long-term time series, facilitating comprehensive assessments of spatial ecological condition of wetlands and temporal dynamics (Cohen & Goward, 2004; Conroy et al., 2022). While remote sensing cannot directly quantify organic carbon stocks, it constitutes a valuable and innovative approach for characterizsing the spatial and temporal heterogeneity of coastal wetlands. Accurate interpretation of remote sensing data for carbon stock estimation requires understanding the underlying biophysical processes and the relevant spatial, temporal and spectral scales of the sensors used. By linking global-scale observations with local ecological processes, remote sensing provides a deeper understanding of how environmental dynamics influence carbon sequestration capacity and storage variability (Simpson et al., 2022). Among the available satellite sensors, Sentinel-2 represents a highly effective Earth observation system developed within the Copernicus Programme of the European Space Agency (ESA).

It supports a wide range of environmental applications, including land cover change detection and classification, coastal zone monitoring and flood mapping and management. Sentinel-2 Multispectral Instrument (MSI) acquires images with resolutions of 10, 20 and 60 m (four bands at 10 m, six at 20 m and three at 60 m) across 13 spectral bands, in the visible, near-infrared and short-wave infrared regions of the electromagnetic spectrum, combined with a revisit cycle of 10 days for a single satellite (around 5 days with the two-satellite constellation). These characteristics make Sentinel-2 particularly suitable for detecting fine-scale environmental variations and for characterizing spatio-temporal dynamics in coastal ecosystems such as Capo Feto, thereby supporting the quantification of blue carbon storage and changes in wetland condition over time. The main objective of this study was to generate high-resolution Land Use and Land Cover (LULC) maps of Capo Feto coastal wetland using Sentinel-2 satellite imagery across three time points (2016, 2020, 2024), in order to analyse the spatial and temporal dynamics of the area over an 8-year period. This approach enabled the detailed spatial detection of environmental changes, providing valuable insights to support effective conservation planning.

2.3.2. Materials and methods

Land use and land cover classification

Sentinel-2 imagery was processed to assess Land Use and Land Cover (LULC) changes for the years 2016, 2020 and 2024, using selected spectral bands (B2−B12) and derived indices (https://gisgeography.com/sentinel-2-bands-combinations/). Bands B2 (blue), B3 (green), B4 (red) and B8 (near-infrared) have a spatial resolution of 10 m and are particularly suitable for vegetation analysis and land cover classification. Bands B5, B6, B7 and B8A (red edge) have a resolution of 20 m, used to assess variations in vegetation structure, while bands B11 and B12 (shortwave infrared) at 20 m are used to assess soil and vegetation moisture. Band B9 (water vapour) at 60 m is employed for monitoring atmospheric moisture. The combined use of these bands enables the calculation of spectral indices for a detailed evaluation of vegetation dynamics, soil exposure, water presence, and anthropogenic features within the wetland. Spectral indices include the Normalized Difference Vegetation Index (NDVI) for assessing vegetation health, the Enhanced Vegetation Index (EVI and its variants EVI2 and EVI2_2) for improved sensitivity in densely vegetated areas, the Kernel-based NDVI (KNDVI) to enhance vegetation-soil separation, the Normalized Difference Built-up Index (NDBI) for detecting urbanized areas, the Modified Normalized Difference Water Index (MNDWI) for water body mapping and the Bare Soil Index (BSI) to highlight exposed soil surfaces. Elevation data derived from a Digital Elevation Model (DEM) were also incorporated to support terrain-related analyses. An unsupervised classification was performed within Google Earth Engine (GEE) platform. The K-means spectral clustering algorithm was employed due to its efficiency and simplicity in handling high-dimensional spectral data without predefined training samples and prior ground truth (Ozesmi & Bauer, 2002). The algorithm aims to minimize the within-cluster variance by reducing the sum of squared Euclidean distances between each data point and the centroid (cluster centre) to which it is assigned.

This objective can be expressed as:

$$J = \sum_{i=1}^{k} \sum_{x \in C_i} \|x - \mu_i\|^2$$

where C_i is the set of points assigned to cluster *i*, μi is the cluster centre, and $\|x - \mu i\|^2$ is the squared Euclidean distance between a data point *x* and its corresponding cluster centre. Euclidean distance was used as the similarity metric and a maximum of 100 iterations was set to ensure convergence and algorithmic stability. For each year (2016, 2020, 2024) the classification produced ten spectral clusters based on pixel reflectance values. These clusters were then manually interpreted and aggregated into six thematic land cover classes, forming the final LULC map for each year. The reclassification was informed by multiple sources, including field observations, local ecological expertise, a visual inspection of false-colour composite imagery and existing land use maps, which contributed to the refinement of class boundaries and the improvement of thematic accuracy. Although this procedure enhanced the reliability of the classification, unsupervised approaches inherently face challenges in correctly identifying mixed pixels, as traditional per-pixel classifiers cannot fully capture the proportional composition of each land cover type. Although the unsupervised classification approach facilitated the initial delineation of land cover classes, inherent challenges may compromise the overall accuracy and reliability of the results. A primary challenge is spectral confusion, arising from the similarity of spectral signatures between certain land cover types, which can compromise classification precision. Limited temporal resolution, due to cloud cover and satellite revisit intervals, further reduces the availability of high-quality imagery and the consistency of temporal datasets. Additionally, weakly flooded zones and mixed-pixel effects—where water and soil coexist within a single pixel—introduce uncertainties in accurately delineating wetland boundaries. The lack of adequate ground-truth data, inherent to the unsupervised approach, may also introduce classification biases and reduce ecological validity. Therefore, although Sentinel-2 provides sufficient spatial resolution for many environmental monitoring tasks, it may still fail to capture fine-scale features such as narrow drainage channels or ephemeral water bodies. Finally, the inherent dynamism of wetland ecosystems, with rapid seasonal and interannual variations, makes it challenging to accurately track their evolution over multi-year intervals. A post-classification comparison was carried out to quantify landscape transformations between the classification outputs for the two-time intervals (2016–2020 and 2020–2024). The analysis focused on two distinct areas: Capo Feto and Margi Spanò coastal wetlands. Change matrices and area statistics were generated to quantify land cover gains, losses and conversions, with particular focus on three representative classes of the marshy area (*saltmarsh vegetation, swamp/mudflat, shrubland*). The spatial distribution of these changes was visualised using classified raster layers and thematic change maps. As the classification was unsupervised, validation primarily conducted through visual comparison with high-resolution satellite imagery on the Google Earth Engine (GEE) platform. These initial land cover classes will form the basis of subsequent supervised classifications performed using machine learning algorithms, such as Random Forest (RF) and Support Vector Machine (SVM).

2.3.3. Results

The LULC analysis revealed distinct spatial and temporal patterns in Capo Feto and Margi Spanò coastal wetlands. Wetland areas were classified into six main land cover classes: s*altmarsh vegetation, swamp/mudflat, shrubland, cultivated land, seawater, coastal dunes* (including areas with scattered built structures) and *industrial area*. Changes between 2016, 2020 and 2024 were quantified using transition maps and change matrices, providing detailed insights into the spatio-temporal dynamics of the study areas (Figure 2.2).

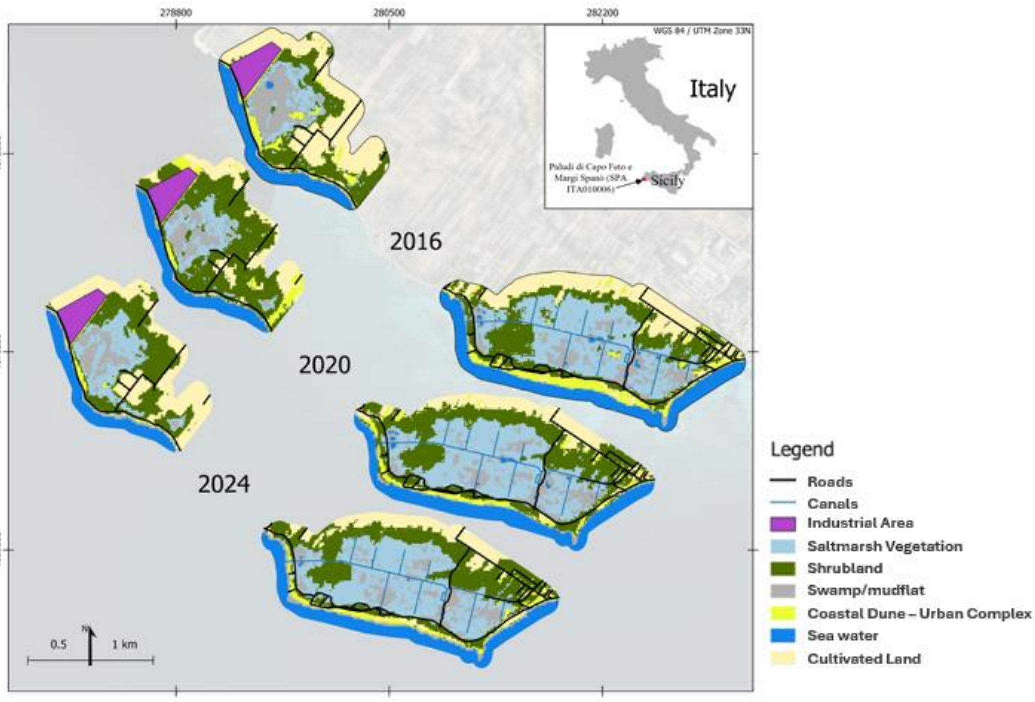


Figure 2.2- Land use land cover maps in 2016, 2020 and 2024 in Margi Spanò (left) and Capo Feto (right) wetlands

The analysis particularly focused on three ecologically important wetland classes − *saltmarsh vegetation, swamp/mudflat and shrubland* − due to their sensitivity to environmental changes, in line with the research objectives of assessing wetlands dynamics (Figure 2.3).

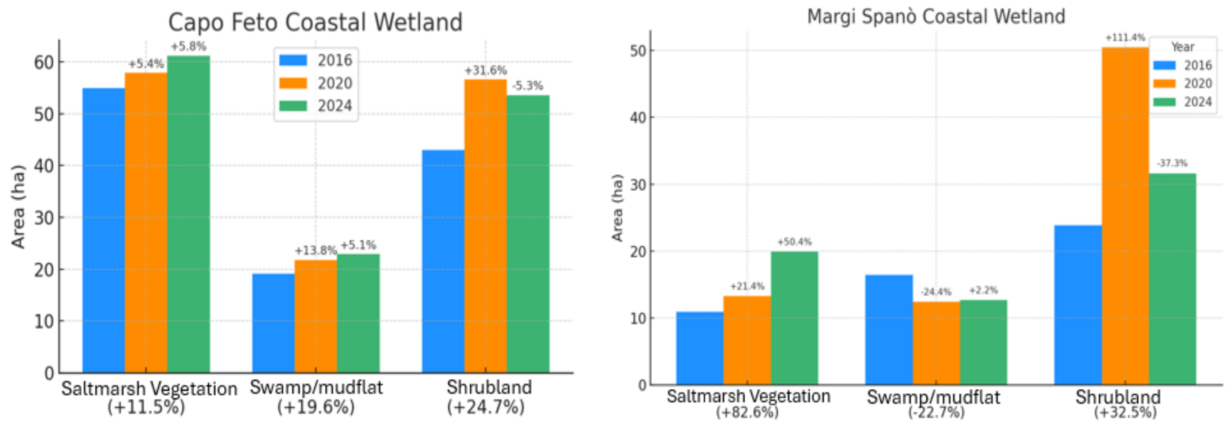


Figure 2.3 - Temporal changes in land-cover classes (saltmarsh, swamp/mudflat, shrubland) at Capo Feto and Margi Spanò coastal wetlands between 2016 and 2024

The results revealed significant temporal variations in the spatial distribution and extent of these habitats, highlighting areas of loss, expansion and conversion over the eight-year period. In Capo Feto coastal wetland, saltmarsh vegetation increased from 54.92 ha to 61.22 ha, corresponding to a total growth of approximately 11.5% over the eight-year period. Specifically, an increase of 5.4% was recorded between 2016 and 2020, followed by a further rise of 5.75% from 2020 to 2024. This consistent upward trend suggests that saltmarsh vegetation, primarily composed of *Salicornia spp*. and *Juncetum maritimi*, is steadily expanding, possibly due to conservation efforts or to its natural adaptability. The swamp/mudflat area grew from 19.14 ha in 2016 to 22.89 ha in 2024, with a positive trend increase of 13.8% increase in the first phase (2016–2020) and a more modest 5.1% increase in the second phase (2020–2024). The overall growth of 19.6% indicates positive changes in wetland hydrology and probably in ecological conditions and suggests signs of resilience in the marshy area. Meanwhile, shrubland expanded by 31.6%, growing from 42.99 ha in 2016 to 56.59 ha in 2020. A subsequent contraction was observed between 2020 and 2024, with a decrease of 5.3%, resulting in a final vegetation cover of 53.60 ha around the marshy area. Overall, the total vegetation cover in Capo Feto increased substantially by 24.7% over the eight-year period, reflecting dynamic changes in wetland vegetation. In contrast, Margi Spanò exhibited a more variable pattern. Saltmarsh vegetation increased by 82.6%, at the expense of swamp/mudflat, which suffered a net loss of 22.7%, with a significant decline between 2016 and 2020 (-24.4%), followed by only a slight recovery between 2020 and 2024 (2.2%). The surrounding shrubland experienced a substantial increase of

111.4% in 2020, followed by a notable decline of 37.3% in 2024. While Capo Feto exhibits a relatively stable trend of ecological recovery, Margi Spanò shows more pronounced and abrupt transitions in land cover, potentially reflecting stronger anthropogenic pressure.

2.3.4. Discussion

This study produced a high-resolution Land Use and Land Cover (LULC) map of Capo Feto and Margi Spanò coastal wetlands for the years 2016, 2020 and 2024, based on Sentinel-2 satellite imagery, which allows efficient monitoring of spatial patterns, detection of ecological changes and assessment of landscape dynamics over time (Ray & Mandal, 2014; Sanyal et al., 2021). When combined with QGIS and satellite-derived information, these remotely sensed datasets support efficient and cost-effective land cover classification, enhancing the analysis of land use transformations in and around wetland areas (Pham et al., 2019). Comparing the evolution of land cover over eight years revealed that Capo Feto is more stable than Margi Spanò. In the former, a moderate but constant increases of the entire marshy area occurred, comprising saltmarsh vegetation, as well as swamp/mudflat class. This suggests a resilient ecological habitat despite continued anthropogenic influences and pressures. In contrast, Margi Spanò experienced more abrupt and variable changes, including significant vegetation growth outside the wetland. These patterns indicate a landscape increasingly affected by anthropogenic pressures, driven by land-use changes for economic purposes and exacerbated by the impacts of climate change. According to literature data (Pernice et al., 2016), average annual precipitation has declined since the 1990s in the entire area. Combined with unsustainable groundwater extraction for civil use, this has led to a progressive lowering of the groundwater table. The resulting impacts include reduced water availability for the ecosystem, increased soil salinity and the loss of seasonally flooded wetland areas during the summer months. The analysis provided clear insights into the spatial distribution of anthropogenic impacts threatening the ecological integrity and functionality of this fragile ecosystem. GIS-based spatial analyses and LULC maps were instrumental in identifying the most vulnerable areas, offering an initial overview of how the wetland and its surroundings have changed over time.

2.4. Assessment of Carbon Sequestration

2.4.1. Introduction

Building upon the insights gained from the literature review, this section applied a site-specific approach to explore carbon storage dynamics in a Mediterranean coastal wetland. Capo Feto coastal wetland served as the focal site for this analysis. The study progressed from a comprehensive, literature-based understanding to a direct quantitative assessment of carbon storage through field measurements and laboratory analyses. Specifically, the study aimed to quantify sedimentary organic carbon (C_{org} kg m^{-2}) stock and to examine spatial variability along coastal–inland gradient, providing an empirical perspective on the processes that regulate carbon accumulation in coastal ecosystems. By integrating these data, the section offers new insights into the role of Mediterranean wetlands as blue carbon reservoirs and their potential contribution to climate regulation. Ultimately, this site-based assessment complements the broader findings of the systematic review, reinforcing the link between scientific evidence and applied research, contributing to the development of strategies for the sustainable management and conservation of coastal wetlands as key components of natural capital.

2.4.2. Materials and Methods

Field Sampling

Sampling was conducted in June 2024 exclusively within Capo Feto coastal wetland, following a preliminary survey that guided the experimental design. Capo Feto habitat encompasses approximately 150 hectares and is characterized by a drainage network of 10 artificial canals (Figure 2.4). The primary channel extends west to east, while secondary channels run perpendicular, allowing for efficient drainage of surface and groundwater (Pernice et al., 2004) a benefit that is maximised in the innermost area. To estimate organic carbon (C_{org}, kg m^{-2}) stock, two perpendicular transects were established at increasing distances from the coastline to capture ecological heterogeneity and site-specific environmental conditions (Figure 2.4). Each transect comprised three sampling sites designated as A1–B1 (seaward site), A2–B2 (intermediate site) and A3–B3 (landward site), representing the gradient from coastal to inland wetland zones, precisely located using GPS coordinates. Duplicate sampling at each site yielded a total of 12 sediment cores.

Figure 2.4 - Survey area of Capo Feto coastal wetland and sampling stations along a coastal -inland gradient: seaward (A1-B1) intermediate (A2-B2) and landward (A3 - B3) sites identified by GPS coordinates.

Soil samples were collected at the top sediment metre (Howard, 2014b), using a manual PVC corer (1 m length, 5.8 cm diameter) inserted vertically to minimize sediment compaction. Cores were extracted as close as possible to the marsh vegetation edge to include root and rhizome systems. Immediately after collection, samples were sealed on-site, transported under refrigeration and stored at –20 °C until laboratory processing.

Laboratory Analysis

In the laboratory, the cores were gradually defrosted at room temperature, then split longitudinally and sectioned into 1 cm-thick slices using a stainless-steel hand knife. The slices corresponded to regular depth intervals and were divided into two subsamples. One portion was stored in a plastic bag and frozen again at -20 °C for further grain size analysis. The other portion was measured with a syringe and weighed to determine wet bulk density and the isotopic composition of carbon and nitrogen. It was then labelled and stored at -80 °C until further analysis. This subsample was freeze-dried (lyophilised) for 72 hours using a laboratory freeze-dryer (Christ Alpha 2-4 LD Plus) to remove water content without thermally degrading the organic matter. After drying, the entire sample was ground into a fine powder and homogenised for further bulk analysis. For the determination of the organic carbon content and $\delta^{13}C_{org}$ composition, approximately 10 ± 1 mg of each sediment sample was placed into a pre-cleaned silver capsule (5 × 9 mm; n-hexane rinsed). Inorganic carbon was removed by acidification treating the samples with hydrochloric acid HCl (1 N), converting the carbonates ($CaCO_3$) into carbon dioxide (CO_2) and retaining only organic carbon (%C_{org}). The reaction was completed by adding concentrated HCl (18%), and the samples were subsequently heated in an oven (Tecnovetro S.R.L. Monza, M 150-VN) at 50 °C for 30 minutes. This acid-drying step was repeated twice, followed by 24 hours of oven drying to ensure complete dehydration. Prior to analysis with the Elemental Analyzer–Isotope Ratio Mass Spectrometer (EA-IRMS), each silver capsule was placed into a tin capsule, carefully sealed and pressed into a spherical shape to facilitate efficient combustion. For nitrogen analysis (($\delta^{15}N_{tot}$, N_{tot}), approximately 30 ± 1 mg of the sample was weighed directly into tin capsules (5 × 9 mm), which then were sealed and shaped into spheres following the same procedure used for the C_{org} samples. Although isotopic analyses were performed, the results are not presented here as this section focuses exclusively on the estimation of sedimentary carbon stocks.

Data processing

Manual PVC corers are particularly susceptible to sediment compression, as the material tends to compact during penetration and extraction (Howard, 2014). Core compression was initially assessed in the field by comparing the total penetration depth of the tube with the recovered core length, calculated as the difference between the internal tube length and the unfilled (empty) portion (Figure 2.5). In the laboratory, cores were re-measured before and after extrusion to detect additional volumetric changes. Such compression leads to an underestimation of the actual in situ core volume and, consequently, an overestimation of Dry Bulk Density (DBD) and sedimentary organic carbon (C_{org}) stock values. To minimise this bias, a core compression correction factor (Glew et al., 2001; Howard, 2014b) was applied to recalculate the original in situ volume of each sediment core, providing more reliable estimates of carbon storage. The correction factor was calculated as the ratio between the recovered core length and the effective penetration length, defined as the total tube length minus the unfilled portion.

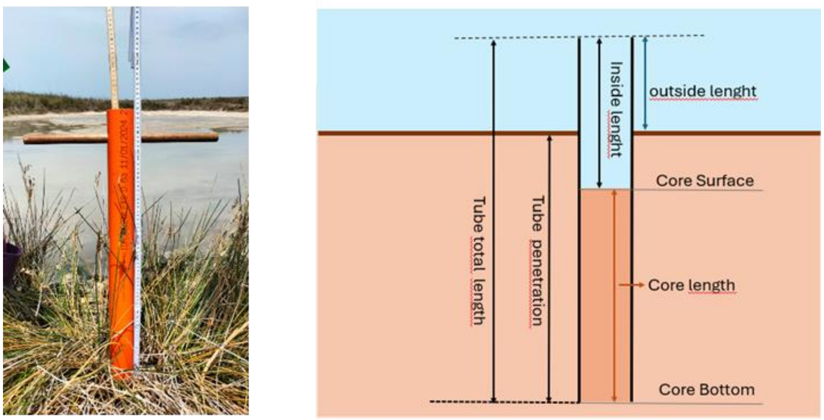


Figure 2.5 Field photograph and schematic illustration of the sediment core sampling procedure for sediment analysis.

Dry bulk density (DBD, g cm^{-3}) was determined from the dry weight of each core sample (g) and its original in situ volume (cm^3). The organic carbon density (C_{org}; $g\ cm^{-3}$) for each depth interval of the analysed cores was calculated using the following equation:

$$C_{org}\ density = DBD \times \frac{\%C_{org}}{100}$$

The C_{org} density of each interval was multiplied by the slice thickness (cm) to calculate the carbon content per unit surface area (g m^{-2}):

$$C_{org}\ in\ core\ section = C_{org}\ density \times interval\ slice\ thickness$$

The total C_{org} stock calculated by summing the carbon stock of each depth interval within the upper metre of the sediment core. Results were expressed in megagrams of carbon per hectare (Mg C_{org} ha^{-1}), a unit widely used in carbon stock assessments, calculated by summing the carbon stock of each depth interval within the upper metre of the sediment core (IPCC, 2006; Howard, 2014). The same approach was applied to quantify inorganic carbon (C_{inorg}) and total nitrogen (N_{tot}) contents.

2.4.3. Results

Observation of sediment cores collected along both transects, extending from the shoreline to inland habitats, revealed a distinct variation in texture and composition: sediments were predominantly sandy-silty near the shore, becoming progressively muddier toward the landward stations. Fine roots and fibrous organic material were abundant throughout the cores, indicating active belowground biomass input and ongoing organic matter accumulation. Reducing (anoxic) conditions were observed at depths of approximately 25–30 cm, likely slowing decomposition and favouring organic matter preservation. These variations characterize spatial heterogeneity, that is crucial for understanding blue carbon dynamics and sediment carbon stocks (C_{org}, Mg ha^{-1}) within the upper metre sediment across seaward, intermediate and landward stations along Transects A and B (Figure 2.6).

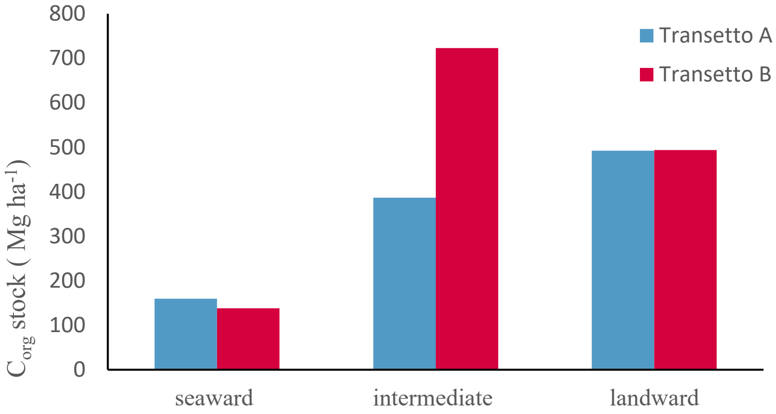


Figure 2.6 Variation in C_{org} (Mg ha^{-1}) within the upper meter sediment across the seaward, intermediate, and landward stations along Transects A and B.

C_{org} stocks increased from the seaward to the inland stations along both transects. Intermediate sites exhibited the highest C_{org} stock values, reaching 723 Mg C_{org} ha^{-1} in transect B, nearly double the value observed in Transect A (386 Mg C_{org} ha^{-1}), suggesting that site-specific factors, such as sediment composition or organic matter input, may enhance carbon accumulation. In contrast, seaward stations showed the lowest C_{org} stocks, which were similar between the two transects (A: 160 Mg C_{org} ha^{-1}; B:138 Mg C_{org} ha^{-1}), reflecting potentially lower organic matter deposition at the wetland edge. Landward stations displayed comparable C_{org} stocks in Transect A and Transect B (492 Mg C_{org} ha^{-1}and 494 Mg C_{org} ha^{-1} respectively) likely reflecting similar environmental conditions or organic matter inputs. Figure 2.7 shows C_{inorg} and N_{tot} stocks in the upper 1 metre of sediments for both transects. C_{inorg} stocks exhibited a decreasing trend from the seaward to landward stations. Seaward stations had the highest values, reaching 1700 Mg C_{inorg} ha^{-1} in Transect A and 1290 Mg C_{inorg} ha^{-1} in Transect B. At intermediate stations, C_{inorg} stocks decreased to 1092 Mg C_{inorg} ha^{-1} in Transect A and dropped sharply to 109 Mg C_{inorg} ha^{-1} in Transect B. Landward stations also showed reduced C_{inorg} stocks, with Transect A maintaining higher values (466 Mg C_{inorg} ha^{-1}) than Transect B (292 Mg C_{inorg} ha^{-1}). Total nitrogen (N_{tot}) stocks showed the opposite pattern. The highest values were observed at intermediate stations (Transect A: 34.06 Mg N_{tot} ha^{-1}; Transect B: 41.97 Mg N_{tot} ha^{-1}) and at landward stations (Transect A: 36.92 Mg N_{tot} ha^{-1}; Transect B: 30.08 Mg N_{tot} ha^{-1}). In contrast, seaward stations had the lowest N_{tot} stocks, with values below 10 Mg N_{tot} ha^{-1}. Overall, N_{tot} stocks along each transect corresponded closely to the spatial pattern of C_{org} stocks.

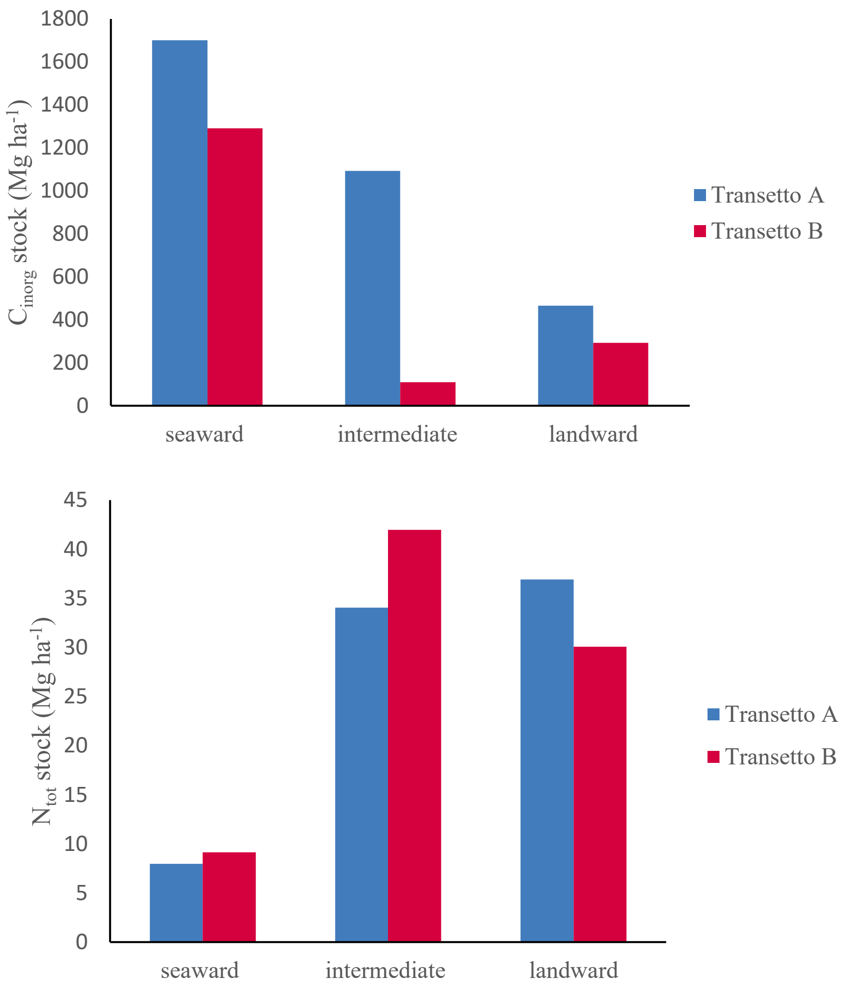


Figure 2.7 Variation in C_{inorg} and N_{tot} stocks (Mg ha^{-1}) within the upper meter of sediment across the seaward, intermediate, and landward stations along Transects A and B.

2.4.4. Discussion

The evaluation of organic carbon (C_{org}) stock in the upper metre of sediment in Capo Feto coastal wetland exhibited a clear spatial gradient along the seaward–inland transects, with intermediate wetland zones showing the highest C_{org} stocks values: up to 723 Mg C_{org} ha^{-1} in transect B and 386 Mg C_{org} ha^{-1} in transect A. These spatial patterns likely reflect local factors influencing carbon sequestration, including sediment composition, vegetation density and organic matter inputs. In contrast, seaward stations showed consistently lower C_{org} stocks, likely due to reduced organic matter deposition near the marsh edge, while landward stations maintained intermediate values, reflecting more uniform environmental conditions and organic matter inputs across these sites.

These findings are coherent with previous studies showing that Mediterranean and temperate wetlands tend to accumulate the highest organic carbon stock in areas with dense vegetation and high organic matter deposition (Osman et al., 2023; Jia et al., 2024). Stable vegetation and favourable hydrological conditions further promote carbon preservation (Owers et al., 2020; Rodríguez-Murillo et al., 2011), while efficient wetland management and conservation measures may help maintain these stocks by preventing degradation and organic matter loss (Pendleton et al., 2012; M. Mateo et al., 2006). Inorganic carbon (C_{inorg}) displayed the opposite distribution, reaching maximum values at seaward stations and progressively declining toward the inner wetland stations, likely reflecting greater carbonate inputs near the coast and the progressive enrichment of organic matter inland, which reduces the relative proportion of inorganic carbon in the sediments without necessarily reducing its absolute concentration (Howard, 2014; Serrano, Lavery, Duarte, et al., 2016b). Total nitrogen (N_{tot}) stocks reflected C_{org} patterns, peaking at the intermediate stations (Transect A: 34.06 Mg N_{tot} ha^{-1}; Transect B: 41.97 Mg N_{tot} ha^{-1}). This correspondence shown the close relationship between organic matter deposition and nitrogen storage highlighting the importance of organic matter inputs and sediment retention in controlling both carbon and nitrogen dynamics in coastal wetlands. The mean C_{org} stock in the upper one metre of sediment at Capo Feto coastal wetland (399 Mg C_{org} ha^{-1}) exceeds the European average for saltmarshes (164.2 ± 132 Mg C_{org} ha^{-1}) estimated through the systematic analysis of the literature (see Chapter 1) and is comparable to, or even higher than, sediment stocks values reported for coastal wetlands globally (Chmura et al., 2003; Alongi, 2012; Pendleton et al., 2012; Wang et al., 2021). Such broad variability in sedimentary carbon stocks has been documented, with values ranging from 14 to 963 Mg C_{org} ha^{-1} in Australia (Macreadie et al., 2017) and from 12.5 to 328 Mg C_{org} ha^{-1} in China (Fu et al., 2021). In temperate coastal wetlands, the carbon stock in the upper metre of Capo Feto coastal wetland is among the highest documented, highlighting the potential of the habitat for regional carbon sequestration and providing a benchmark for comparing carbon stocks across Mediterranean and temperate wetland ecosystems.

2.5. Economic valuation using the Social Cost of Carbon (SCC)

2.5.1. Introduction

Natural capital, the stock of natural assets, including geological resources, soil, air, water and all living organisms, provides both biophysical inputs (e.g., raw materials, food, freshwater) and regulating functions that maintain ecological balance (e.g., climate regulation, nutrient cycling, soil fertility). These functions give rise to ecosystem services, defined as *the benefits that humans, directly or indirectly, obtain from the functioning of ecosystems* (MEA, 2005). However, the provision of these services does not automatically translate into human well-being: their value emerges through interaction with other forms of capital, human, social and built capital, within a dynamic system of mutual feedback and co-dependence (Costanza et al., 2014). In this context, natural capital should be understood not as a static reservoir of resources, but as a dynamic system whose stock sustains the generation of service flows over time (Daily, 1997; MEA, 2005). Recognizing this asset stock–flow relationship is crucial for understanding ecosystem sustainability: depleting natural capital stock undermines the long-term capacity to deliver services activities (Y. Li et al., 2023; Zeng et al., 2024), as well as compromises intergenerational equity (Dasgupta, 2024). This awareness has driven the development of frameworks and tools that translate ecological value into economic terms and integrate environmental with socio-economic accounting (Costanza et al., 1997; MEA, 2005; TEEB, 2010; Díaz et al., 2018). Ecosystem services, as classified by the Millennium Ecosystem Assessment (MEA) into provisioning (e.g. food, water and raw materials), regulating (e.g. water purification and regulation, climate regulation, air and water quality maintenance, erosion control), cultural (e.g. aesthetic, recreational and spiritual values) and supporting (e.g. nutrient recycling, biodiversity maintenance and primary production) categories, serve as a bridge between ecological science and economic policy. Frameworks such as the System of Environmental-Economic Accounting – Ecosystem Accounting (SEEA-EA), treat these services as measurable economic flows, enabling their inclusion in national accounting systems and policy evaluations. Within this integrated perspective, assigning an economic value to ecosystem services helps measure the cost of environmental degradation and supports more sustainable decision-making. A particularly relevant application is the Social Cost of Carbon (SCC), which estimates the present value of the long-term damages caused by an additional tonne of CO_2 (tCO_2) emitted into the atmosphere (US IWG SCC, 2021; EPA, 2023). The SCC provides a monetary bridge between greenhouse gas emissions, climate impacts and socio-economic consequences, allowing decision-makers to internalize the external costs of carbon emissions. By translating ecological and climatic effects into tangible economic terms, the SCC becomes a critical tool for climate policy, carbon pricing and investment in mitigation strategies. In coastal wetlands, such as Capo Feto, assessing carbon storage through the SCC illustrates the practical value of ecosystem services for location-specific climate mitigation and sustainable resource management. By linking local ecological processes to global climate and economic outcomes, the SCC underscores the importance of preserving natural capital as an asset whose depletion carries measurable social and financial costs.

2.5.2. Materials and methods

The total organic carbon (C_{org}) stock within Capo Feto coastal wetland was calculated as:

$$C_{org\ stock,\ tot} = C_{org}\ \text{stock average}\ (Mg\ C\ ha^{-1})\ x\ site\ area\ (ha)$$

The potential maximum CO_2 equivalent (CO_{2eq}) emissions were then calculated by applying a standard molecular conversion factor 3.67, which represents the ratio between the molecular weights of CO_2 (44) and elemental carbon (C,12) (Howard, 2014; IPCC, 2006). The resulting values were expressed in Megagrams (Mg) of CO_{2eq}, equivalent to metric tonnes of CO_2 equivalent (tCO_{2eq}) (1 Mg = 1t), the standard unit for global carbon accounting framework and BC ecosystems assessments (IPCC, 2006; Pendleton et al., 2012; Howard, 2014). The Social Cost of Carbon (SCC) evaluation followed a site-specific (bottom-up) logic, in which local biophysical and socio-economic data were used to estimate carbon stocks and their corresponding economic value (IPCC, 2006).

SCC was initially set at 70 USD per metric tonne of CO_2eq (70USD/tCO_{2eq} in 2007 USD), corresponding to a 3% discount rate and derived from the Integrated Assessment Models (IAMs) that combine scientific evidence on climate change impacts, socio-economic projections and discounting approaches (Nordhaus, 2017; US IWG SCC, 2021). This value was applied to the estimated CO_2eq stock of the study area to assess its economic significance in terms of avoided climate damages.

The SCC is sensitive to the choice of the *discount rate* used to calculate the present value (PV) of future damages (US IWG SCC, 2021). The rate, typically set at 2.5%, 3%, or 5%, determines how future costs and benefits are translated into present monetary terms. A low rate (2.5%) places greater weight on long-term benefits, whereas a high rate (5%) prioritises immediate outcomes and diminish the importance of future impacts. In this analysis, a discount rate of 3% was adopted, consistent with the central value recommended by the *U.S. Interagency Working Group*, which is widely applied in climate policy assessments (US IWG SCC, 2021). This rate reflects a balanced approach between intergenerational equity and economic realism, incorporating moderate assumptions about future economic growth and social time preferences. It ensures comparability with major international studies while maintaining internal consistency across valuation scenarios (Nordhaus, 2017; IPCC, 2023b). Through this approach, the biophysical data of carbon sequestration were converted into economic values expressed in CO_2 equivalents. This supports the consideration of the strategic role of coastal wetlands in climate mitigation and in generating important socio-economic benefits for society. Values expressed in 2007 USD were updated to 2024 USD using the *U.S. Consumer Price Index* (CPI), applying a historical inflation factor of 1.53 (U.S. Bureau of Labor Statistics - BLS) and subsequently converted to EUR using the average2024 exchange rate (1USD = 0.92 EUR).

2.5.3. Results

The total C_{org} stock in the upper metre of sediment within Capo Feto coastal wetland was estimated at 59,850 Mg C_{org}, corresponding to a mean value of 399 Mg C_{org} ha^{-1} across the 150 ha wetland area. Using the molecular conversion factor (3.67) to express carbon in terms of CO_2 equivalents, the total carbon stock corresponds to 219,650 tCO_2eq, representing the maximum potential CO_2 emissions if all the sedimentary C_{org} stock were disrupted or fully oxidised, thus potentially converting the coastal wetland from an efficient carbon sink into a carbon source. The economic value of the carbon stored in Capo Feto coastal wetland sediments for the year 2024, was estimated at approximately 23,524,515 USD. Applying the average 2024 exchange rate (1 USD = 0.92 EUR), this corresponds to about 21,642,553 EUR. This valuation emphasizes the significant climate mitigation service provided by coastal wetlands as carbon sinks (EPA, 2023; Pendleton et al., 2012). As shown in Table 2.1, the estimated economic value varies depending on the discount rate applied, highlighting the sensitivity of SCC-based assessments to assumptions about the present value of future climate damages.

Tabel 2.1- Social Cost of Carbon estimates for the sediment carbon stock of Capo Feto Coastal wetland under different discount rates, with values converted to euros

Discount rate %	SCC (USD/tCO_{2eq}) 2007 USD	SCC (USD/tCO_{2eq}) 2024 USD	SCC (USD/tCO_{2eq}) 2024 EUR	CO_{2eq} (tCO_{2eq})	Valore USD (USD)	Valore EUR (EUR)
2.5%	78	119.3	108.5	219,650	26,204,245	23,107,905
3%	**70**	**107.1**	**97.4**	**219,650**	**23,524,515**	**21,642,553**
5%	58	88.7	80.7	219,650	19,482,955	17,924,319

2.5.4. Discussion

The results of this study underscored the effective role of Capo Feto coastal wetland in climate regulation and broader ecosystem services. The estimated total organic carbon stock of 59,850 Mg C_{org}, equivalent to 219,650 tCO_2eq, indicates that Capo Feto sediments function as a substantial carbon reservoir. If disturbed or subjected to land-use changes, this stock could be mobilised, potentially transforming the wetland from a carbon sink into a carbon source. This emphasises the vulnerability of coastal wetlands to anthropogenic pressures and environmental changes, with subsequent implications for GHG emissions and socio-economic benefits. Beyond carbon sequestration, Capo Feto coastal wetland provides key ecosystem services, including habitat biodiversity support, coastal protection and cultural services that sustain tourism and recreational activities such as kite surfing. These functions illustrate how the ecological integrity of the wetland is closely linked to local human well-being. Translating the total sediment organic carbon (C_{org}) stocks into economic terms using the Social Cost of Carbon (SCC) further illustrated the tangible value of this natural capital, estimated at approximately $23.5 million (€21.6 million) in 2024.

This valuation demonstrated how the SCC can be used as a practical tool for quantifying the economic value of carbon sequestration within the ecosystem services framework. The valuation presented considers only sedimentary organic carbon stocks, while other key carbon pools, such as aboveground and belowground biomass, living roots and litter, remain unaccounted for.

Consequently, estimates based solely on sedimentary carbon may underestimate the total climate mitigation potential of Capo Feto coastal wetland. Including these additional pools in future assessments would provide a more comprehensive measure of the BC ecosystem's carbon storage capacity and mitigation potential. The findings demonstrated that Capo Feto plays a substantial role in long-term carbon sequestration within Mediterranean coastal environments, provided a preliminary support for the development of conservation initiatives and management actions aimed at enhancing the long-term resilience and carbon storage capacity of the habitat. Moreover, they emphasised the strategic importance of Mediterranean coastal wetlands as key contributors to climate regulation, local ecosystem service provision and natural capital preservation, linking site-specific ecological processes at a local level to broader climatic and socio-economic dynamics. (Duarte et al., 2013; Malak et al., 2021; Mcleod et al., 2011; Martínez-Eixarch et al., 2024).

2.6. Conclusion

This research demonstrated the effectiveness of integrating high-resolution satellite imagery and GIS-based spatial analysis for monitoring Land Use and Land Cover (LULC) dynamics in Capo Feto and Margi Spanò coastal wetlands. Despite the inherent limitations of the unsupervised classification, the analysis provided valuable insights into the spatial dynamics and anthropogenic pressures affecting coastal wetlands over the eight-year period (2016–2024). Notably, analysis of the vegetation cover at Capo Feto coastal wetland indicated an overall improvement in the *saltmarsh vegetation* and *shrubland* classes, suggesting positive ecological dynamics and good habitat conditions. Observed enhancement of classes supports ecosystem resilience and favours carbon accumulation by promoting sediment retention and the deposition of organic matter. The findings offered a solid foundation for adopting supervised classification approaches in future research, expected to increase thematic accuracy and allow more detailed characterization of land cover types, thereby improving ecological interpretation and management relevance. The sediment analysis revealed a clear seaward-to-inland gradient in carbon storage in the top metre of the sediment. Intermediate wetland zones exhibited the highest C_{org} stocks, reaching up to 723 Mg C_{org} ha^{-1} in Transect B and 386 Mg C_{org} ha^{-1} in Transect A. The distribution pattern reflects site-level environmental controls, where sediment properties and vegetation dynamics jointly drive the retention and storage of organic carbon. The average C_{org} stocks estimated for the upper metre of sediment (399 Mg C_{org} ha^{-1}) notably exceeds the European mean for saltmarshes (164.2 ± 132 Mg C_{org} ha^{-1}) derived from literature systematic review and aligns with or surpasses global values reported for marsh habitats (Chmura et al., 2003; Pendleton et al., 2012; Macreadie et al., 2017; Fu et al., 2021; Wang et al., 2021; Alongi, 2023). This finding positions Capo Feto coastal wetland as one of the most efficient Blue Carbon (BC) sinks in the Mediterranean region, reflecting both the ecological resilience of the habitat and its potential contribution to regional carbon budgets. The spatial distribution of inorganic carbon (C_{inorg}) showed an inverse trend compared to organic carbon (C_{org}), with higher concentrations observed near the seaward stations and a gradual decline towards the inner wetland. This pattern reflects enhanced carbonate precipitation in areas with a stronger marine influence, where biogenic and chemical processes promote carbonate formation and the dilution of carbonates by organic matter is lower. Similarly, total nitrogen (N_{tot}) followed the same trend as organic carbon (C_{org}), with peaks at intermediate sites, highlighting the close coupling between organic matter accumulation and nitrogen sequestration. Overall, these patterns suggest that the dynamics of sedimentary C_{org} and N_{tot} stock in Capo Feto are jointly regulated by vegetation productivity, hydrological conditions and the balance between marine and terrestrial inputs.

This confirms the complex biogeochemical interactions that sustain the retention of carbon and nutrients in coastal wetland ecosystems (Chmura et al., 2003; Fourqurean et al., 2012a; Burke et al., 2022a; De Los Santos et al., 2023). Capo Feto coastal wetland is one of the few remaining transitional habitats in Sicily, recognised for its high biological and biogeographical value, although it is currently not adequately protected or managed. Persistent human pressures highlight the urgent need for improved strategies to prevent further degradation and loss of ecosystem functions.

Applying the Social Cost of Carbon (SCC) to the economic valuation of carbon sequestration and storage in Capo Feto provided a quantitative estimate of its contribution to climate change mitigation. The analysis revealed that the carbon stored in the upper metre of sediments corresponds to an economic value of approximately USD 23.5 million (EUR 21.6 million) in 2024, reflecting the economic significance of sedimentary carbon stocks as a key component of the wetland's natural capital. Expressing carbon stocks in monetary terms establishes a direct connection between biophysical assessments and policy-relevant frameworks, such as carbon pricing and social cost analyses (Anthoff & Tol, 2013; Nordhaus, 2017).

The study of Capo Feto coastal wetland showed that applying the SCC approach to conserving coastal habitat delivers ecological benefits and generates measurable economic value. This reinforces the need to integrate coastal wetlands into regional and national climate and management strategies and simultaneously safeguard the ecosystem services that underpin coastal protection and local socioeconomic well-being, including recreational and tourism activities. More broadly, this study provided the first comprehensive assessment of BC dynamics in Capo Feto habitat.

By integrating high-resolution spatial data, long-term ecological monitoring and economic valuation, the study offers new insights into the role of a Mediterranean BC coastal wetland in global carbon budgets and contributes to advancing methodologies for blue carbon accounting, while providing new empirical evidence from regions where data remain scarce.

Chapter 3.

3. Institutional Carbon Footprint Assessment: UNIPA GHG Emissions Inventory

3.1. Preliminary Considerations

Systematic reviews of the European and Mediterranean BC ecosystems and Capo Feto coastal wetlands were conducted to consolidate the growing evidence of the strategic role of vegetated coastal habitats in mitigating climate change. These natural ecosystems are governed by complex, self-regulating ecological dynamics determined by interactions between biotic (living) and abiotic (non-living) components, which generate cyclic flows of energy and matter (Fourqurean et al., 2012a; Lovelock & Duarte, 2019). These processes ensure ecological stability, resilience to environmental and anthropogenic pressures, while the regulating service reduces atmospheric CO_2 concentrations, thereby directly influencing the global greenhouse gas balance (Macreadie et al., 2021a) and supporting socio-economic activities in coastal areas (Barbier et al., 2011). By extending the ecosystem paradigm to universities, we can conceptualise them as artificial organisational ecosystems. Universities exhibit structural and functional characteristics analogous to those of ecological systems: internal organization, collaborative networks and feedback mechanisms between inputs (such as flows of financial and relational resources) and outputs (such as education, research innovation and societal engagement) emulate the structure and function of natural ecosystems in terms of material and energy flows, self-regulating and adaptive capacity (Folke et al., 2003).

From this perspective, these organisations can be conceptualised as complex socio-technical systems (Geels, 2004; Smith & Stirling, 2008; Levin & Greenwood, 2016), in which different components, ranging from the academic community and territorial stakeholders to decision-making processes, infrastructures and policy frameworks, interact through co-regulatory dynamics. This systemic perspective emphasises the mutual dependence between human, institutional and technological component and displays how universities adapt and evolve in response to broader social and environmental changes. This conceptualisation of universities as socio-ecological systems is also reflected in the activities of the University of Palermo, which combines institutional sustainability initiatives with applied ecological research. The study of Capo Feto coastal wetland exemplifies how academic research can enhance environmental responsibility and generate tangible sustainability outcomes. This knowledge enables the university to align its operational strategies with natural mitigation processes, improving its GHG emissions performance while advancing institutional sustainability. Active engagement of universities is crucial to accelerate the transition toward low-carbon models, starting with a systematic awareness of the environmental impacts generated by their own activities. The adoption of environmental performance assessment and reporting tools provides essential operational support. The carbon footprint is one of the most effective indicators for GHG emissions accounting and management, as it allows the estimation of the direct and indirect emissions associated with a product, a process or a service, expressed in tonnes of CO_2 equivalent (tCO_2eq) (Pandey et al., 2010; Scrucca & Barberio, 2021). GHG emissions accounting at universities helps to identify the main sources of emissions and define mitigation policies and actions, thereby strengthening the role of higher education institutions in the ecological transition. This commitment is part of the broader framework promoted by the *Italian Network of the Universities for Sustainable Development – RUS*, which encourages member institutions to measure and monitor GHG emissions, promoting sustainable management models and shared decarbonisation strategies.

This chapter presents the first quantitative GHG emissions inventory for the University of Palermo, developed through a comprehensive carbon footprint assessment. Drawing on the methodological framework of RUS (2016), this work introduces a structured and standardised approach to GHG emissions accounting for the University, providing the basis for future monitoring and strategic planning. Originally published in the *UNIPA Sustainable and Transition Ecology (STE) journal*, the study offers a detailed analysis of both direct and indirect GHG emissions, identifies the main emission sources and highlights potential mitigation strategies. By linking institutional operational data with sustainability and ecological research, this study demonstrated how universities can actively integrate environmental responsibility into decision-making processes, supporting the transition towards low-carbon strategies. Overall, the findings provided a robust foundation for academic research and guide GHG emissions management at the University of Palermo, embedding sustainability within operational and strategic planning.

3.2. Introduction

Climate change is one of the major global challenges, with deep and multidimensional impacts on natural ecosystems, the economy and society. The Paris Agreement (UNFCC, 2015) and the UN Agenda 2030 for Sustainable Development (ONU, 2015) call for governments worldwide to take stronger action and enhance international cooperation in tackling the climate crisis and promoting an integrated vision of sustainable development. The Intergovernmental Panel on Climate Changes (IPCC) has finalised the Synthesis Report for the Sixth Assessment Report (IPCC, 2023b) which issues a clear and urgent scientific warning about the need to limit global temperature rise, emphasising the rapid decarbonisation of key productive sectors to achieve climate neutrality by 2050. Within this context, it is crucial to engage institutions, businesses, citizens and the academic community translating global objectives into concrete local actions. Universities play a strategic role by generating scientific knowledge, implementing sustainable practices, and spreading a culture of environmental responsibility. Higher education institutions are also emerging as key players in climate governance, actively contributing to the development and implementation of policies to reduce greenhouse gas emissions. Their commitment is crucial for accelerating the transition towards a sustainable, low-carbon development model (Mazhar et al., 2017), an objective that can be achieved by starting from an awareness of the environmental impact generated by their activities, an essential precondition for adopting sustainable and long-lasting management models. At both national and international levels, universities are taking on an increasingly active role in developing strategies and projects aimed at reducing their environmental footprint. In this regard, specific sustainability indicators are fundamental for measuring the dynamics and impacts generated by human activities, particularly water consumption, natural resource use and greenhouse gas emissions (Matuštík & Kočí, 2021). Among these indicators, the *carbon footprint* (CF) (Wackernagel & Yount, 1998; Wiedmann & Minx, 2008; Alvarez et al., 2016) represents one of the most effective for assessing climate change impacts, as it quantifies the potential direct and indirect environmental impacts associated with a product, process or service, expressed in tonnes of carbon dioxide equivalent (tCO_2eq) (Pandey et al., 2010; Scrucca & Barberio, 2021). For a complex organisation such as a university, calculating the carbon footprint is a strategic tool for identifying major emission sources, guiding environmental management decisions, and supporting the most effective mitigation actions. The University of Palermo, in collaboration with the Centre for Sustainability and Ecological Transition (CSTE), is an active member of the Network of Universities for Sustainable Development (RUS) and actively participates in thematic working groups focused on cross-cutting and priority issues. These groups aim to disseminate a culture of sustainability and promote best practices within academic institutions.

The University of Palermo

The University of Palermo (hereafter *UNIPA*) is a public institution whose primary mission is to promote culture, research, advanced education, and technology. The university is a large community of students, faculty members, technical-administrative and library staff (PTAB) who have a direct or indirect relationship with the institution and its services. The community is characterised by strong institutional interactions, collaboration, and partnerships, with the fundamental goal of fostering cooperation among the various cultural domains that define education, research and knowledge transfer.

The UNIPA organisation (Bilancio Sociale Unipa, 2021; Performance di Ateneo Unipa, 2023) provides 163 academic programs including bachelor's, master's and single-cycle master's degrees, along with 44 specialization schools and 33 PhD programs. UNIPA offers a wide range of disciplines, combining tradition with innovation, while maintaining a strong committed to social and professional development. The University Hospital "Paolo Giaccone" (AOUP) operates in close synergy with the School of Medicine and Surgery. To reinforce its regional presence, UNIPA has also established campuses in three other Sicilian cities — Agrigento, Caltanissetta and Trapani —besides the main campus in Palermo. UNIPA also includes the University Museum System (UNIPA Cultural Heritage SIMUA), the Centre for Sustainability and Ecological Transition (CSTE), the Italian Language School for Foreigners (ITASTRA), the University Language Centre (CLA), the Library Services and Historical Archive (SBA), the University Sports Centre (CSU), the University Medical Clinic (AMU), the Advanced Technologies Network Centre (ATeN) and the Advanced Studies Centre (A.S.CENT.) (Figure 1).

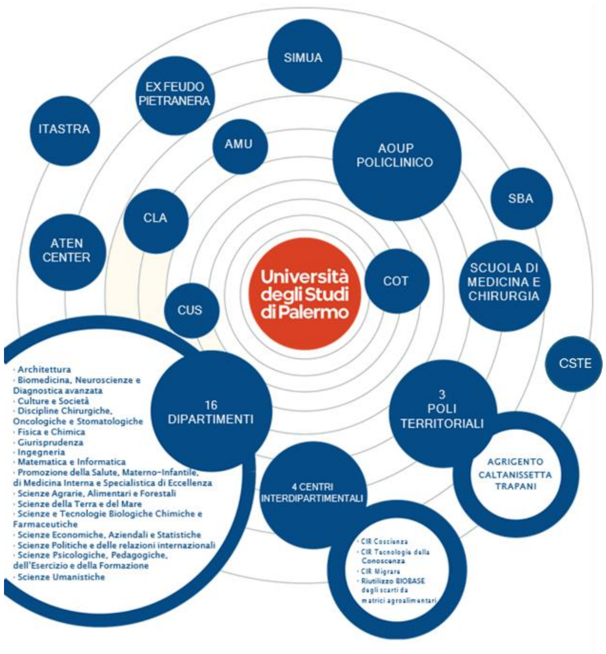


Figure 1 - UNIPA Organisational Chart (Source: Bilancio Sociale 2021 Unipa)

Objectives

The Climate Change Working Group (GdL-CC) at UNIPA, operating within the Centre for Sustainability and Ecological Transition (CSTE), established the organisational and operational processes necessary to quantify and report UNIPA's first GHG emissions accounting for the 2023 reporting year. This baseline year provides a crucial reference point for tracking emission trends over time and assessing the effectiveness of the mitigation measures that UNIPA plans to implement to reduce its overall environmental impact. This report outlines the analytical methodology adopted and presents the results obtained. The reporting process and its annual update serve as useful tools to: i) enhance UNIPA's contribution to reducing GHG emissions; ii) identify areas of highest impact and determine the most effective mitigation opportunities; iii) provide information to support the development of planning and reporting tools (e.g. sustainability reports and mitigation plans); iv) verify and monitor the measures implemented over time; v) strengthen relationships with stakeholders, emphasising internal initiatives and promoting social and environmental responsibility policies; vi) demonstrate UNIPA's commitment as a model and reference point in the local context.

Emissions inventories – International standards and regulations

The UNIPA GHG emissions inventory follows the methodology proposed in the "*Linee guida operative per la redazione degli inventari delle emissioni di gas serra degli Atenei italiani*", drafted and published by the Climate Change Working Group (GdL-CC) of the national RUS network (RUS, 2023). The quantification and calculation of GHG emissions was conducted in accordance with the principles of th*e International Standard ISO 14064-Part 1:2019* (UNI EN ISO 14064 -1, 2018) and the *Green House Gas Protocol Corporate Standard* (GHG Protocol, 2014). This approach ensures relevance, completeness and consistency of the assessment through a standardised, verifiable and replicable approach. GHG emissions are classified according to the GHG Protocol and ISO 14064-1:2019, as shown in Table 1. The GHG Protocol categorises emissions as Scope 1, 2 or 3 based on the level of control that the university exercises over the respective emission sources. ISO 14064-1 further complements this framework by introducing a more detailed subdivision into six categories, providing a more precise structure for emission analysis. This level of detail helps to identify areas where intervention is most needed, enhances transparency and facilitates comparisons with results derived from other reporting frameworks.

Table 1- Classification of the GHG emissions: GHG Protocol and ISO 14064-1:2019

GHG PROTOCOL	ISO 14064-1:2019
Scope 1 — Direct GHG emissions Emissions from sources that are owned or controlled by the reporting organization.	**Category 1 — Direct GHG emissions** Emissions from GHG sources owned or controlled by the organization.
Scope 2 — Indirect GHG emissions from purchased energy Emissions from the generation of purchased electricity, steam, heating, or cooling consumed by the organization.	**Category 2 — Indirect GHG emissions from imported energy** Emissions from the generation of imported (purchased) energy: electricity, heat, steam, or cooling.
Scope 3 — Indirect GHG emissions (not included in Scope 2) All other indirect emissions that occur in the **value chain** of the reporting company, including both upstream and downstream emissions.	**Category 3 — Indirect GHG emissions from transportation** Emissions from transport activities not owned or controlled by the organization.
	Category 4 — Indirect GHG emissions from products used by the organization Emissions associated with acquired goods and services used by the organization.
	Category 5 — Indirect GHG emissions associated with the use of the organization's products Emissions arising from the use of goods or services provided by the organization.
	Category 6 — Other indirect GHG emissions Other indirect emissions not included in the previous categories.

3.3. Material and Methods

The methodological sequence adopted for quantifying and reporting emissions is outlined in Figure 2. The phases illustrated define the logical steps applied, designed to ensure transparency, consistency and replicability of the reporting process. Each phase is described in detail in the following paragraphs.

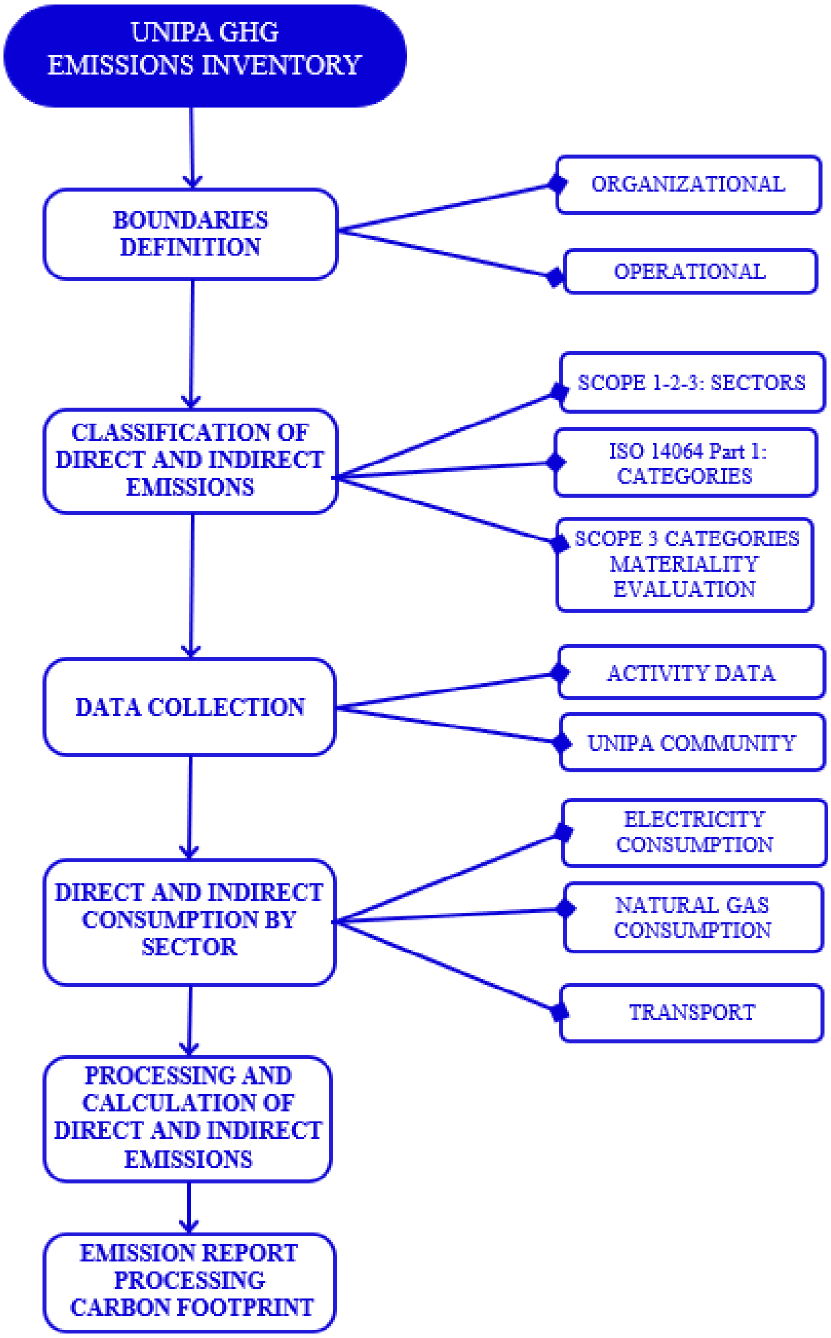


Figure 2 – Methodological flow chart for estimating and reporting GHG emissions

Reporting Boundaries

The methodological framework for reporting the UNIPA GHG emissions requires a clear definition of the boundaries of the inventory system itself, both in organisational and operational terms (RUS, 2023). The adoption of the RUS methodology is pivotal in guaranteeing methodological consistency and facilitating the comparability of results among universities that report their emissions. To proceed with the selection of emissions to be included in the inventory, a methodological approach was adopted that involved: i) a preliminary analysis of the GHG sources and removals associated with the facilities identified during the definition of the organisational boundaries; ii) the application of the RUS methodology and international standards to define the operational boundaries, select and classify the relevant sources/removals into the following categories: direct emissions, indirect emissions from energy consumption and other indirect emissions.

Organisational and Operational Boundaries

An operational control approach was adopted, including emissions from activities over which the University exercises operational and/or financial control (UNI EN ISO 14064 -1, 2018). The inventory covers all activities carried out within the following boundaries: i) UNIPA's geographic borders, ii) buildings owned and/or directly managed by the institution, and iii) buildings for which UNIPA is responsible for electricity payment (RUS, 2023). In this initial report, only the Palermo campus was included among the campuses and territorial facilities relating to the University of Palermo. The inventory considers buildings used for: i) teaching and research activities, ii) administrative functions, iii) teaching support, iv) research support, v) events and conferences, and vi) libraries and study spaces. In addition to the facilities defined at the organisational level, the inventory also includes some buildings hosting external service providers, such as canteen, copy shops and nursery. Student residences and UNIPA-owned apartments leased to students and/or staff were excluded from the inventory, both due to the difficulty of obtaining accurate data and because occupants would generate greenhouse gas emissions regardless of whether they lived in University-owned or private accommodation (RUS, 2023). The Palermo campus consists of multiple buildings and offices located in different areas of the city. Specifically, only those buildings for which the university administration held energy utilities for the year 2023 were considered (see Table 2).

Table 2 - List of buildings included in the study (Palermo Campus)

Palermo Campus - Buildings	Address	Surface area m^2
Campus	Viale delle Scienze	212,798.38
Archirafi Sub campus	Via Archirafi Nos.18 - 38	32,251.56
Abatellis Complex **Neoclassical Building**	Piazza Marina No. 61	2,560.72
Sant'Antonino Complex	Piazza S. Antonino No. 1	9,078.99
G.G. Gemmellaro Geological and Paleontological Museum	Corso Tukory No. 131	2,623.24
Department of Law	Piazza Bologni No. 8	2,376.77
Department of Political and International Sciences	Via Maqueda No. 324	2,900.80
Department of Psychological, Pedagogical, Sport and Educational Sciences	Via G. Pascoli No. 6	1,958.44
COT office – Guidance and Tutoring Centre	Via A. Veneziano No.120	230.50
Botanical garden	Via Lincoln No. 2	3,414.78

The University campus on “Viale delle Scienze” is the largest complex of buildings and facilities (see Figure 3), covering a total area of 212,798.38 m². The area hosts administrative offices, teaching and research laboratories, faculty offices, classrooms, study space and the University Medical Clinic (AMU), as well as of the six university residences managed by the Regional Authority for the Right to University Education (ERSU). The campus also includes sports facilities and a canteen for students and staff, along with additional structures such as the ATeN Centre and an on-site childcare facility.

Figure 3- Unipa Campus on viale delle Scienze

Classification of emissions types

Once the operating boundaries had been defined, the most significant indirect GHG emissions categories were selected for inclusion in the inventory to provide an accurate assessment of UNIPA's carbon footprint.

Materiality Assessment of Indirect GHG emissions (Scope 3)

The GHG Protocol provides detailed guidance for assessing the materiality of indirect GHG emissions categories. By applying a combination of qualitative and quantitative criteria, the standard allows organisations to include only the material emissions in their Scope 3 inventory, those that significantly impact the organisation’s overall carbon footprint (WRI & WBCSD, 2011). This approach prioritises mitigation efforts in areas where the university can exert meaningful influence, whether directly or indirectly, thereby enhancing the effectiveness of its emission reduction strategies. To ensure both accuracy and consistency in accounting, the following materiality criteria were applied:

i) **Magnitude:** this reflects the contribution of a category to the total Scope 3 emissions. A score from 1 (low) to 3 (high) was assigned based on qualitative assessments and the relative significance of emission sources.

ii) **Sector relevance**: evaluates whether the emission source is recognised in national or international standards for the higher education sector. Values range from 1 (not recognised) to 4 (fully recognised by established standards).

iii) **Data availability and quality**: accounts for the accessibility and reliability of data. Scores were assigned as follows: 1 if data are unavailable within the reporting timeframe; 2 if data can be obtained with reasonable effort; and 3 if data are available and/or can be easily processed.
Based on these criteria, an emission source is considered material if:

$$\textbf{Magnitude * Sector Relevance * Data Availability} \geq \textbf{4}$$

The values assigned to the 15 indirect GHG emissions categories (Scope 3) are reported in Table 3. The rationale for the individual scores is provided in Table 4. Emission categories relating to “employees and students commuting”, and “waste disposal”, distinguished between waste generated within departments and waste managed by external company, were subject to the materiality assessment. While both categories have significance according to the magnitude and sector relevance criteria, the absence of data has prevented their inclusion in the current report. These emissions will therefore be estimated and reported in the updated inventory for 2024.

Table 3 -Results of the Materiality Assessment for indirect GHG emissions (Scope 3)

Scope 3 (categories) Indirect GHG Emissions	Magnitude	Sector relevance	Data availability	Product	Material?
Travel and business travel emissions	2	4	2	16	YES
Employees and student commuting emissions	2	3	1	6	YES
Emissions from waste disposal	2	2	1	4	YES
Emissions from purchased goods and services	N/A	N/A	N/A	N/A	N/A
Emissions from capital goods	N/A	N/A	N/A	N/A	N/A
Emissions from fuel- and energy-related activities	N/A	N/A	N/A	N/A	N/A
Upstream transportation and distribution emissions	N/A	N/A	N/A	N/A	N/A
Upstream leased assets emissions	N/A	N/A	N/A	N/A	N/A
Downstream transportation and distribution emissions	N/A	N/A	N/A	N/A	N/A
Emissions from processing of sold products	N/A	N/A	N/A	N/A	N/A
Emissions from the use phase of sold products	N/A	N/A	N/A	N/A	N/A
Emissions from end-of-life treatment of sold products	N/A	N/A	N/A	N/A	N/A
Downstream leased assets emissions	N/A	N/A	N/A	N/A	N/A
Franchising emissions	N/A	N/A	N/A	N/A	N/A
Investment-related emissions	N/A	N/A	N/A	N/A	N/A

Table 4 - Scoring of significant indirect GHG emissions categories

Source	Parameter	Value	Explanation
Business travel	Magnitude	2	The estimate was obtained by analysing the annual number of business travel and international mobility trips
	Sector Relevance	4	As required by RUS
	Data Availability	2	Processing data relating to staff missions and international mobility.
Emissions from staff and students commuting to UNIPA campus	Magnitude	2	Estimates are based on data collected for the previous year.
	Sector Relevance	3	As required by RUS
	Data Availability	1	The data can be obtained from the home-UNIPA travel survey, which is provided by the Mobility Manager.
Emissions from waste disposal (via forms).	Magnitude	2	Estimates based on data collected by the departments.
	Sector Relevance	2	Conduct the study using an LCA (Life Cycle Assessment) approach
	Data Availability	1	The data collected from the “modulo carico/scarico” of each department
Emissions from waste disposal (delivered to the municipal collection system)	Magnitude	2	Estimates based on annual data
	Sector Relevance	2	Conduct the study using an LCA (Life Cycle Assessment) approach
	Data Availability	1	The data collected and provided by the UNIPA Waste Manager

Classification of Direct and Indirect GHG emissions

Following the materiality assessment, Table 5 shows the direct and significant indirect GHG emissions that have been selected for the UNIPA GHG emissions accounting study. The table classifies emissions by *Emission Sector* in line with the RUS guidelines and by *Scopes* and *Categories* as defined by international standards. For all greenhouse gas sources and reservoirs, only carbon dioxide (CO_2) emissions were considered. Quantification is expressed in tonnes of CO_2 (reported as tCO_2)

Table 5 - Classification of GHG Emissions/Removals by Sector, Category, and Scope

			ACTIVITY INDICATOR: GHG source/sink
CATEGORY 1: Direct GHG emissions generated by sources owned or controlled by UNIPA (SCOPE 1)			
SECTOR	**ENERGY CONSUMPTION**	Fossil fuel consumption	Annual diesel consumption
	TRASPORT	UNIPA vehicle fleet	Annual fuel consumption for company vehicle fleet
	ENERGY CONSUMPTION	Air-conditioning systems (refrigerant gases)	Refrigerant GHG emissions from the refilling and maintenance of air-conditioning systems
CATEGORY 2: Indirect GHG emissions from consumption of purchased electricity (SCOPE 2)			
SECTOR	**ENERGY CONSUMPTION**	Electricity consumption	Annual electricity consumption for teaching, research, administrative, and service activities
CATEGORY 3: Indirect GHG emissions related to transport for various purposes (SCOPE 3)			
SECTOR	**TRASPORT**	Employees business travel	Fuel use associated with travel and missions undertaken by students, academic staff, researchers and PTAB.
		International student mobility (Erasmus and similar programmes)	Fuel use from student international mobility travel
		UNIPA employees and students commuting	Energy and fuel consumption for home–university commuting by students, academic staff, and PTAB
CATEGORIY 4: Indirect GHG emissions from products used by the University (SCOPE 3)			
SECTOR		Emissions from purchased goods associated with the production of the purchased product	N/A
		Emissions from the end-of-life treatment of products produced by UNIPA	N/A
CATEGORY 5: Indirect GHG emissions associated with the use of products supplied by the University (SCOPE 3)			
SECTOR		Solid waste disposal	N/A
		Water consumption	N/A
		Wastewater treatment	N/A
CATEGORY 6: Indirect emissions from other sources (SCOPE 3)			
SECTOR		Electricity generated by the on-site photovoltaic systems	N/A

Activity Data

The collection of data related to significant direct and indirect GHG emission sources, as well as other information necessary for their processing, was provided, upon request, by the relevant university offices, which actively contributed to this study. The data collection system, organised through a designated contact person for each type of activity, provides a streamlined method to facilitate and accelerate future reporting updates (see Table 6).

Table 6 – UNIPA contacts for activity data collection

Activity data Category	Responsible Unit
University population	Statistical Analysis and Decision Support Unit for Internal Controls
University buildings	"Censimento aree dipartimentali amministrazione centrale e spazi Policlinico" Unit
Energy consumption / Fugitive F-Gas emissions	Energy Manager
Employees and student commuting	Mobility Manager
Employees business travel	Department of Earth and Marine Sciences (DiSTeM) Administrative Unit
International student mobility	International Relations Office
University vehicle fleet	"Facility management e servizi di gestione ordinaria del patrimonio immobiliare" Unit; Departmental Administration

University population

The types of personnel included in the inventory are categorized as shown in Table 7. The term '*employees*' is used collectively to refer to professors, PhD students, research fellows, scholarship holders, medical residents and researchers, together with technical, administrative and library staff (PTAB).

Table 7 -UNIPA community, 2023 – Palermo campus

University Community	Years 2023
Students	
Bachelor's, Master's, Single-Cycle Students	43,067
PhD Students	1,189
Research Fellows	90
Medical Residents	1,517
Professors and Researchers	
Full Professors	439
Associate Professors	644
Fixed-Term Researchers (RTDa/RTDb)	470
Permanent Researchers	180
Technical, Administrative and Library Staff (PTAB)	1,370
Total UNIPA Community	48,966

Methodology for Estimating Emissions

The methodology used to estimate GHG emissions is based on the product of an **activity indicator** (A), which represents the source activity, and a specific **emission factor** (EF_1) for that type of source (RUS, 2023)

$$\mathbf{E_i = A \cdot EF_i}$$

Where:

E_i = emissions of the i-th pollutant (g/year);
A = activity indicator, e.g., quantity produced, fuel consumption (t/year);
EF_i = emission factor of the i-th pollutant (g/t of product)

For GHG emissions reporting purposes, the RUS methodology provided guidance on the standard emission factors to be applied to: i) electricity consumption; ii) the consumption of natural gas, LPG and diesel; iii) fuel and/or electricity consumption associated with commuting and business travel (Caserini et al., 2019). Table 8 shows the emission factors used in the calculations for this study and their sources. For energy-related sectors (electricity and natural gas), the RUS guidelines specify that emission factors refer to national parameter tables published by ISPRA (ISPRA, 2023) and the Ministry of Environment and Energy Security (MASE, 2023) updated for 2023.

Table 8 – Emissions Factors for the Surveyed Sectors

Sector		Emission Factor	Data source
Electricity consumption		236.3 gCO_2/kWh	ISPRA Report: Emission Factors for the Production and Consumption of Electricity in Italy. Reference 1990-2022. (ISPRA, 2023)
Natural gas consumption (methane)		2.004 $kgCO_2/Smc$	National Standard Parameter Table 2023 – EU ETS – ITALY. Ministry of Environment and Energy Security (MASE, 2023)
Business travel	Car	163 gCO_2/km	Average emission factor per km travelled by road vehicle (gCO_2/km). Source: Ispra 2022b (RUS, 2023)
Business travel	Bus	15 $gCO_2/pass/km$	Average emission factor per km traveled by road vehicle per passenger ($gCO_2/pass/km$). Source: Ispra 2022b (RUS, 2023)
Business travel	Motorcycle/ scooter	81.5 $gCO_2/pass/km$	Average between motorcycles and scooter, calculated from average emission factors per km traveled by road vehicle per passenger ($gCO_2/pass/km$). Source: Ispra 2022b (RUS, 2023)
Business travel	Tram	11 $gCO_2/pass/km$	Average emission factor per kilometre travelled by a rail vehicle at full capacity during a peak hour (gCO2/pass/km). Source: Ispra 2022b (RUS, 2023)
Business travel	Metro/Train	8.3 $gCO_2/pass/km$	Average emission factor per kilometre travelled by a rail vehicle at full capacity during a peak hour (gCO2/pass/km). Source: Ispra 2022b (RUS, 2023)
Business travel	Ship	113 $gCO_2/pass/km$	Average emission factor per km traveled by waterborne vehicle per passenger ($gCO_2/pass/km$). Source: Ispra 2022b (RUS, 2023)

To estimate CO_2 emissions from air travel related to business travel and international mobility, the average emission factors proposed by the RUS guidelines for three route types (short, medium and long-haul flight) were considered, as shown in Table 9.

Table 9 - Emission Factors for Air Travel proposed by RUS for Italian University Inventories

Flight Type	Distance (km)	Average Emission Factor ($gCO_2/pass/km$)
Short - Haul	< 1,500	123
Medium – Haul	1,501 – 4,000	93
Long - Haul	>4,000	52

Consumption by Sector Type

Energy Consumption

Data on electricity and heating consumption were requested from the UNIPA Energy Manager, who provided summary tables of annual electricity use (expressed in kWh) and fuel consumption (expressed in Smc). These figures were obtained directly from energy provider invoices. Table 10 reports the total annual consumption for the Palermo Campus in 2023.

Table 10 - Electricity and Natural Gas Consumption – Palermo Campus

University Campus	Elettricity Consumption 2023	Natural Gas Consumption 2023	Data Responsible
Palermo	15,944,95 kWh	143,520 Smc	Energy Manager

Additionally, data on fugitive GHG emissions from air-conditioning systems were collected. Table 11 reports these quantities by gas type. In 2023, the amounts of gas in the systems were the same as in the previous year, as no maintenance or refilling activities were reported. For the purposes of this study, only the quantities of gas present in the systems in 2023 are considered, in order to ensure comparability with future reporting updates.

Table 11 - F-gas Quantities by Type

F-gas	Quantity [kg]
R134a	1,037
R32	188
R407C	533.15
R410A	1,777.77
R422A	318

The annual total natural gas (methane) consumption, expressed in standard cubic metres per year (Smc/year), was multiplied by the specific emission factor (kg/CO_2) for 2023 (see Table 8). Regarding air-conditioning systems, since no changes in gas charge were reported, no refrigerant gas losses are included in the 2023 inventory.

Transport

The RUS guidelines classify the transport sector within a university context into four groups: i) university-owned vehicles, representing direct and relevant emissions for reporting purposes (*Scope* 1); ii) daily commuting by students and staff between home and university (*Scope* 3); iii) staff business travel (*Scope* 3) and iv) student travels for mobility programmes, representing indirect emissions (*Scope* 3).

1. *University vehicle fleet*

UNIPA’s vehicle fleet is managed by both the central administration and the departmental administations. Table 12 provides a complete list of UNIPA vehicles. The "Facility management e servizi di gestione ordinaria del patrimonio immobiliare" Unit provided the annual mileage data for the vehicles under it responsibility, reporting estimated kilometres travelled. For vehicles managed directly by individual departments, annual mileage was obtained from the corresponding vehicle usage logs. Fuel consumption for road transport was calculated by multiplying the annual mileage (km/year) of each vehicle by the CO_2 emissions per kilometre (gCO_2/km), as specified in the vehicle registration documents or provided by the manufacturer for the specific vehicle model.

Table 12- List of UNIPA-owned and leased vehicles for the year 2023

Vehicle	No of vehicles	Fuel	Annual distance travelled (km)	Data Manager
Audi A6 TDI	1	Diesel oil	12,000 km	"Facility management e servizi di gestione ordinaria del patrimonio immobiliare" Unit
Dacia Dokker TDI	1	Diesel oil	6,000 km	"Facility management e servizi di gestione ordinaria del patrimonio immobiliare" Unit
Piaggio Porter Maxxi (Ecopower)	2	Petrol/LPG	600 km	"Facility management e servizi di gestione ordinaria del patrimonio immobiliare" Unit
Land Rover LJ Discovery TDI	1	Diesel oil	1,200 km	"Facility management e servizi di gestione ordinaria del patrimonio immobiliare" Unit
Fiat Panda Van	1	Petrol	600 km	"Facility management e servizi di gestione ordinaria del patrimonio immobiliare" Unit
Piaggio Porter Max S90	1	Petrol	600 km	"Facility management e servizi di gestione ordinaria del patrimonio immobiliare" Unit
Fiat 16 1.9 MJT 4X4 Emotional	1	Diesel oil	9,971 km	DiSTeM Department
Fiat Panda1.3 MJT 16V 4x4 Climbing	1	Diesel oil	11,258 km	DiSTeM Department
Opel Combo Furgone	1	Diesel oil	12,808 km	DiSTeM Department
Mitsubishi L200 – Pick-up Gls	1	Diesel oil	4,800 km	Engineering Department
TOTAL	11		60,437 km	

2. *Employees and students commuting*

The primary source of information and the methodology for collecting and estimating data in this category is an online questionnaire designed to assess the commuting habits of the university community. CSTE developed a locally tailored online survey in collaboration with the UNIPA Mobility Manager, in accordance with the latest RUS directives and the guidelines provided by the RUS Mobility Working Group. The data were collected by analysing the annual distances travelled by staff and students during daily commuting, based on their main modes of transport. The most recent survey was conducted prior to this study, and a new one is currently underway. This work focuses exclusively on assessing the potential significance of emissions from this sector, with data from the ongoing survey to be incorporated into the 2024 reporting.

3. *Employees Business Travel*

For the purposes of this study, "business travel" is defined as any trip undertaken by university staff as part of their professional duties and therefore falls under UNIPA's direct control. Each department has its own procedure for authorising such travel, typically via paper-based or online forms (e.g. *Google forms*). This section also considers travel undertaken by students, scholarship holders, PhD candidates, research fellows and medical residents for study or research periods abroad, as travel expenses are consistently reported using the forms provided by the relevant department. Collecting data on business travel is challenging, particularly for departments that still rely on paper-based forms. These systems are often disconnected from centralised data platforms, making it difficult to access and compile the information required for accurate emissions estimates. This fragmentation has been a major obstacle to expanding emissions analyses across the university. Therefore, emissions reporting in this category is limited to the Department of Earth and Marine Sciences (DiSTeM), which was selected as an initial case study to evaluate GHG emissions in this sector. Although DiSTeM has relatively few employees (190), it is one of the most active departments in terms of business travel for educational and research purposes. Data provided by the DiSTeM administrative unit enabled the identification of a total of 256 trips undertaken in 2023 (see Table 13). The annual distance travelled was estimated for each type of vehicle, with the trips categorised by departure location (Palermo), destination (Sicily, elsewhere in Italy or abroad) and round-trip distance. Notably, trips from Palermo to the smaller Sicilian islands (the Egadi, Pelagie and Aeolian Islands, Pantelleria, and Ustica) predominantly involve air or sea transport, as a significant portion of DiSTeM's research activites take place on these islands.

Table 13 - Summary of business travel travel by DiSTeM employees in 2023

Departure	Destination	N° of business travel	Round-trip (km)				
			Airplane	Bus	Car	Ship	Train
Palermo	Sicily	117	5,412	2,337	16,102	10,013	0
Palermo	Italy	101	86,732	0	0	12,070	5,628
Palermo	Other countries	38	155,444	0	0	3,337	0
Total Trips		256	247,588	2,337	16,102	25,419	5,628

The following assumptions were applied in order to estimate indirect emissions: i) Palermo was taken as the departure point for all trips; ii) trips made using university-owned vehicles were excluded, as their GHG emissions are already accounted for in the university fleet inventory; iii) for journeys involving multiple modes of transport, only the primary mode was considered (based on distance travelled); iv) travel to the smaller Sicilian islands (Ustica, the Egadi Islands and the Aeolian Islands) was assumed to occur solely by ferry and v) for the Pelagie Islands and Pantelleria, travel was assumed to occur solely by air.

Based on these assumptions, annual indirect GHG emissions from business travel were calculated by multiplying the distance travelled per round trip (km per trip) by the average emission factor for the transport mode used (gCO_2/pass/km) (see Table 8).

4. *International Student Mobility*

The University International Relations Office provided Excel datasets detailing the total number of students participating in international mobility programmes. Table 14 presents this information for European (EU) and non-European (non-EU) destinations, distinguishing between incoming and outgoing students. Round-trip distances were calculated assuming travel by air only, using the *International Civil Aviation Organization* (ICAO) online tool to obtain accurate emission estimates (*ICAO Carbon Emission Calculator*).

Table 14 -Number of students participating in international mobility programmes in 2023

Country	Incoming students n.	Outgoing students n.
Austria	3	1
Belgium	3	12
Bulgaria	0	11
Cyprus	0	1
Croatia	3	13
Denmark	0	1
Estonia	0	1
Finland	9	1
France	49	75
Germany	103	59
Greece	13	21
Irland	1	4
Latvia	4	0
Lithuania	17	23
Malta	0	2
Norway	6	3
Netherlands	2	6
Poland	65	101
Portugal	24	64
Czech Republic	12	42
Romania	28	68
Serbia	5	6
Slovakia	5	12
Slovenia	1	6
Spain	205	406
Sweden	2	1
Ukraine	12	0
Hungary	7	6
Non-EU countries	76	24
Total	655	970

The following assumptions were applied in order to estimate indirect GHG emissions: i) all student mobility trips were assumed to occur by air; ii) each student was assigned a round-trip flight; iii) "Falcone–Borsellino" Palermo Airport was used as the baseline departure airport, while the destination was matched to the major airport closest to the student's final EU or non-EU location; iv) for most EU and non-EU destinations, flights were assumed to include a connection via Rome

“Fiumicino Airport” or Milan “Malpensa Airport” and the additional distances for these segments were included.

A total of 1,625 mobility trips were considered, involving 655 incoming students and 970 outgoing students. Annual indirect GHG emissions were then estimated by combining the distance of each short-, medium- or long-haul round-trip flight with the corresponding average emission factor (gCO_2/pass/km) (see Tabella 8).

3.4. Results

Data Processing and Emissions Estimation

- *Direct GHG emissions (Scope 1) and indirect GHG emissions from energy consumption (Scope 2)*

Direct emissions from natural gas consumption amounted to 288 tCO_2, while fuel use by the UNIPA vehicle fleet contributed n additional 9.1 tCO_2. Among the most significant indirect sources, electricity purchased to operate the buildings and facilities of the Palermo campus resulted in 3,768 tCO_2 in 2023. Table 15 also reports per capita GHG emissions associated with energy use and fuel consumption.

Table 15 - Annual and per capita CO_2 emissions from energy use and fleet fuel consumption

SOURCE	EMISSIONS 2023	
Energy Consumption	**[tCO_2/ year]**	**[tCO_2/ person]**
Fossil fuel consumption	288	0.006
Electricity consumption	3,768	0.08
Vehicles Fuel Consumption	9.10	0.00

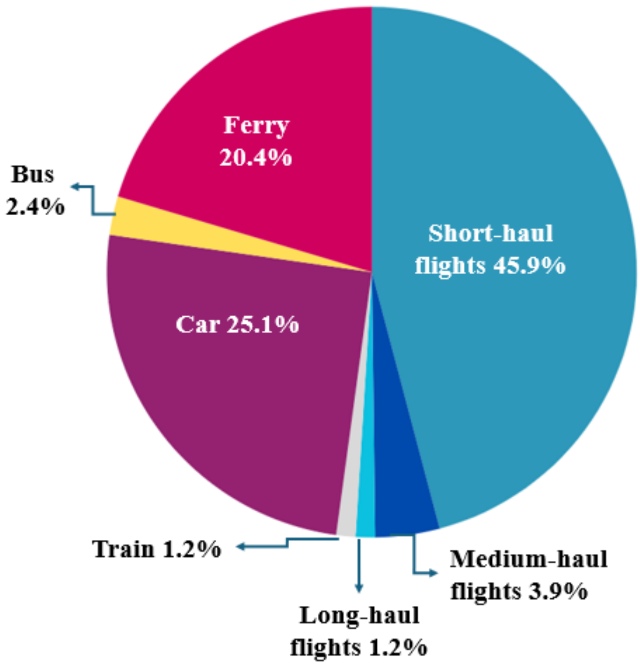
- *Indirect GHG emissions from business travel (Scope 3)*

Figure 4a illustrates the percentage contribution of annual GHG emissions from business travel by DiSTeM staff, categorised by mode of transport. In 2023, a total of 256 trips were recorded.

Short-haul flights represented the primary source of GHG emissions, accounting for 117 trips and 17.89 tCO_2. Although there were far fewer medium- and long-haul flights (13 trips total), the longer distances travelled resulted in significant emissions of 3.96 tCO_2 and 3.10 tCO_2, respectively.

Rail travel (3 trips) and bus travel (6 trips) generated much lower emissions: 0.05 tCO_2 for rail and 0.04 tCO_2 for buses, reflecting their comparatively smaller environmental impact. Ferry transport notably contributed, with 52 trips producing 2.87 tCO_2, while 64 car trips generated 2.62 tCO_2, primarily due to travel within Sicily and to smaller islands (the Egadi Islands, the Pelagie Islands, the Aeolian Islands, Pantelleria and Ustica).

Figure 4b shows that the majority of trips (45.7%) occurred within Sicily (117), followed by 101 domestic trips elsewhere in Italy and 38 international trips. Calculating the average emissions per employee, air travel accounted for 0.19 tCO_2 per person per trip (approximately 61% total GHG emissions), followed by ferry (0.06 tCO_2, 19%), car (0.04 tCO_2, 13%), train (0.02 tCO_2, 6%) and bus (0.01 tCO_2, 3%). Overall, average per-employee GHG emissions from business travel amounted to 0.31 tCO_2, highlighting the significant influence of transport mode on individual travel-related carbon footprints (see Table 16).



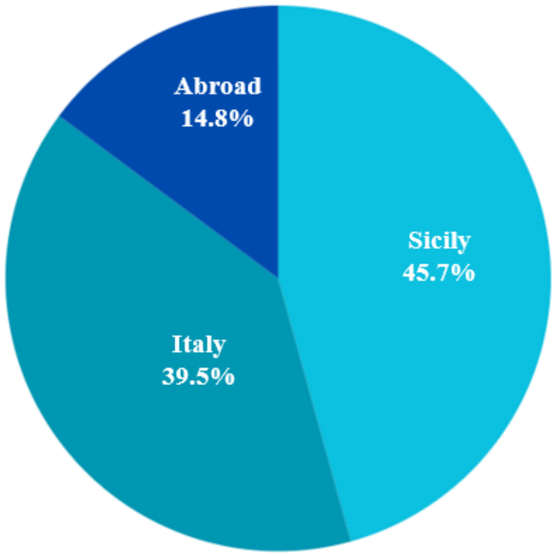


Figura 4b- Contribution of indirect GHG emissions by transport mode for DiSTeM employee's business travel (2023). Figure 4b: Distribution of destinations for DiSTeM employee's business travel (2023)

Table 16 - Indirect GHG emissions from business travel, per trip and per employee

Source		Emissions [tCO_2]	Emissions [tCO_2/ trip]
Airplane	Short – haul flights	17.89	0.19
	Medium – haul flights	3.96	
	Long – haul flights	3.10	
Train		0.05	0.02
Car		2.62	0.04
Bus		0.04	0.01
Ferry		2.87	0.06
Total DiSTeM travels		30.53	0.31

Indirect GHG emissions from international student mobility (Scope 3)

In 2023, total CO_2 emissions from international student mobility amounted to 556.46 tCO_2, with incoming students contributing 222.31 tCO_2 and outgoing students 334.16 tCO_2, resulting in an average of 0.34 tCO_2 per mobile student. Figure 5 indicates that the majority of these indirect GHG emissions are associated with short-haul flights to and from European countries within a 4,000 km distance, accounting for 68.9% of outgoing student emissions. This suggests that most international student mobility is to relatively nearby destinations. For incoming students, medium-haul flights accounted for a significant share of emissions (44.7%), nearly comparable to short-haul flights (53%). These results suggested that many international students come from countries at intermediate distances (approximately 1,500–4,000 km), which are typical of destinations in Eastern and Northern Europe, as well as nearby non-European regions such as Africa.

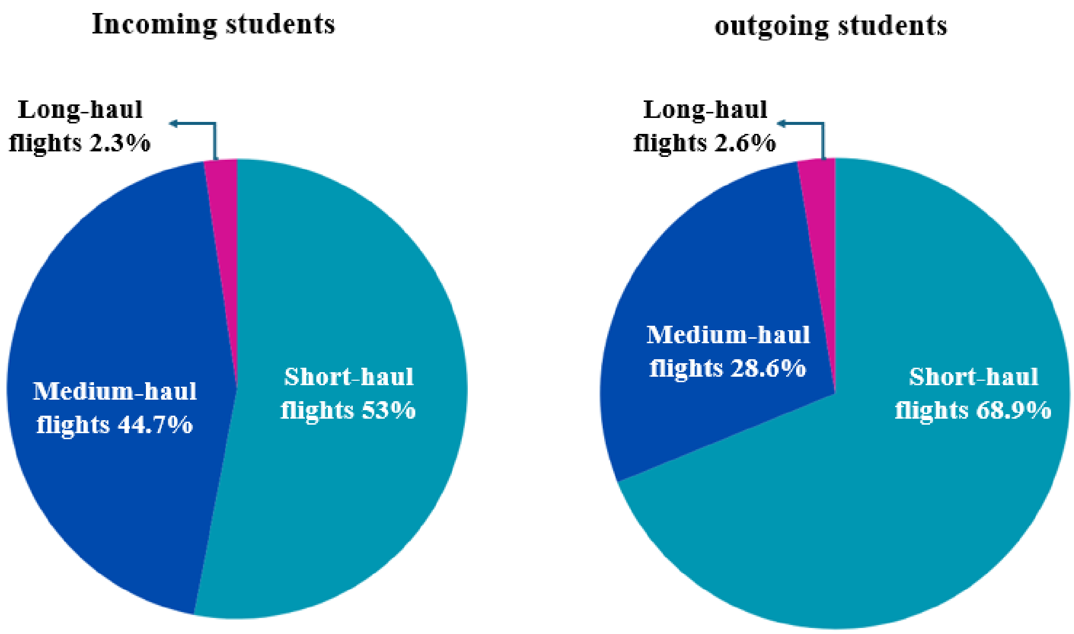


Figure 5 - Distribution of indirect GHG emissions by flight for incoming and outgoing international students in 2023

Emission Reporting

The Emission reporting and the estimated *carbon footprint* of UNIPA are presented below both in total amounts and as percentage contributions relative to: i) activity *Sectors* according to the RUS methodology; and ii) *Scopes* associated with impact activities that generated emissions, as defined by the GHG Protocol.

- *Emissions Reporting by Activity Sector (RUS)*

Table 17 summarises the emission contributions from UNIPA's main activity sectors.
Electricity consumption is the dominant source, accounting for 3,768 tCO_2 (81% of the total). International student mobility follows with 556.46 tCO_2 (12.5%), while fossil fuel consumption (288 tCO_2) and motor fuel consumption for UNIPA vehicle fleet (9.1 tCO_2) contribute smaller amounts.
While reflecting only one of UNIPA's sixteen departments, GHG emissions from DiSTeM employees business travel (30.53 tCO_2) offers an initial indication of the potential contribution from departments active in this sector. Extrapolating to the entire university, with DiSTeM representing roughly 3.22% of UNIPA employees undertaking business travel (5,899), and assuming similar average emissions across departments, total emissions are estimated at 947.88 tCO_2. This preliminary estimate provided insight into UNIPA's emissions from business travel, serving as a reference for developing a comprehensive reporting system in the future. Based on this projection, total emissions for UNIPA

in 2023 are estimated at 5,569.4 tCO_2, corresponding to roughly 113.74 kg CO_2 per member of the university community.

Table 17 - Emissions (tCO_2/year) per Activity Sector (2023)- RUS methodology

Sectors	**Emissions [tCO_2 / year]**	**Emissions [tCO_2/ UNIPA member]**
Electricity consumption	3,768	0.08
Fossil fuel consumption	288	0.006
Fuel consumption – UNIPA vehicle fleet	9.1	0.0015
Employees business travel	947.88	0.16
International student mobility	556.46	0.34
Total	**5,569.4**	**0.11**

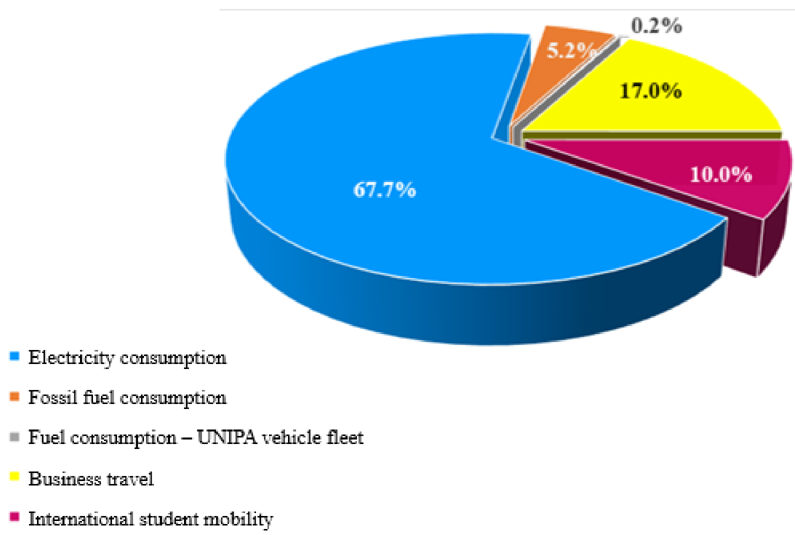


Figure 6 - Contribution of UNIPA's emission activity Sector in 2023

- *Emission Reporting by Scope*

Table 18 shows aggregated GHG emissions by source, classified according to *GHG Protocol*. Indirect emissions from electricity consumption (Scope 2) are the largest contributor, amounting to 3,768 tCO_2, which is approximately 68% of total emissions. Direct emissions (Scope 1) are limited to 297.10 tCO_2 (5%), mainly originate from fuel consumption by Unipa fleet vehicle. Scope 3 indirect

GHG emissions, associated with business travel across all UNIPA departments and international student mobility, account for 1,504.34 tCO_2, approximately 27% of total 2023 emissions.
This profile highlights the significant contribution of the energy sector, followed by emissions related to mobility. Table 19 also presents the emissions (kg/CO_2) per member of the academic community, for a total of 48,966 people in 2023.

Table 18 –Emissions (tCO_2/year) by Scope in 2023

Sources	Emissions [tCO_2/ year]
Scope 1 – Direct emissions	
Fossil fuel consumption Fuel consumption - UNIPA vehicle fleet	**297.10**
Scope 2 – Indirect emissions	
Electricity consumption	**3,768**
Scope 3 – Others indirect emissions	
Business travel International student mobility	**1,504.34**
Total	**5,569.4**

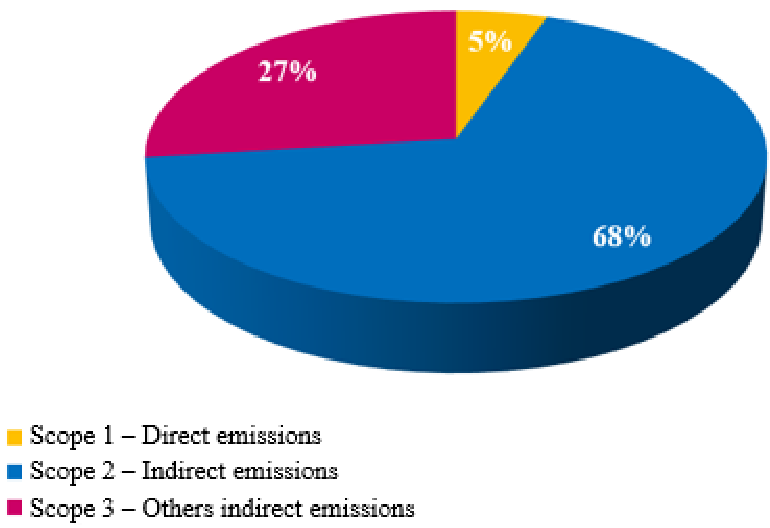


Figure 6- Contribution of UNIPA's emissions by Scope in 2023

Table 19 – GHG Emissions per UNIPA member (kg/CO_2) by SCOPE

SOURCE	EMISSIONS [kgCO_2/ UNIPA member]
Scope 1 – Direct emissions	6,07
Scope 2 – Indirect emissions	76,95
Scope 3 – Others indirect emissions	30,72

3.5. Discussion

The results of the UNIPA greenhouse gas (GHG) emissions quantification study, although limited to selected sectors and the Palermo campus, clearly demonstrate the predominance of indirect GHG emissions from electricity consumption (Scope 2). These emissions account for around 68% of the UNIPA's overall carbon footprint. This highlights the need to prioritise energy-efficiency interventions and accelerate the transition to renewable energy sources, particularly through the purchase of certified low-emission electricity. Such actions are crucial for reducing the environmental impact of university activities, providing an effective and immediately actionable pathway for reducing UNIPA's carbon footprint. (EEA, 2024). UNIPA has already begun implementing a structured pathway to enhance energy efficiency and promote decarbonisation across its buildings. Measures already implemented on the "Viale delle Scienze" campus include the installation of more than 1,300 kW of photovoltaic capacity to increase on-site renewable energy production and the upgrading of the external lighting system to reduce energy consumption. The University is also preparing an institutional *Energy Plan* to progressively integrate technologies powered by renewable sources, as well as introducing digital tools to analyse the energy performance of campus buildings. These tools will enable the systematic identification of retrofit opportunities and foster a monitored, data-driven approach that supports continuous improvements in energy efficiency across the University. UNIPA is also engaged in projects that support the broader energy transition through research and educational activities, promoting virtuous behaviours and encouraging positive experiences such as participation in *Renewable Energy Communities*. Moreover, estimating the organisation's carbon footprint and analysing emission trends provides a valuable benchmark for comparison with similar institutions, and serves as a key indicator for assessing the effectiveness of ongoing and future improvement processes. Another critical area that emerged from the analysis is

Scope 3 emissions, particularly those associated with international mobility (556.46 tCO_2). While this type of mobility provides valuable educational opportunities, it also has a significant environmental impact. According to the “Sustainability Report 2022-2023” of the University of Padova (UNIPD, 2023), a large institution with a community of over 80,000 people, the GHG inventory 2023, compiled using the RUS methodology, reports 1,710 tCO_2 attributable to international mobility. Although higher than UNIPA’s value, this difference is proportional to the smaller size of the UNIPA community (48,966 people). This comparison is useful for identifying areas for improvement and guiding UNIPA in adopting mitigation and compensation strategies aligned with good practices already established in institutions that have been reporting their emissions for several years. Therefore, it is a priority to implement specific measures to reduce emissions associated with international mobility by promoting more sustainable travel options and more deliberate trip planning. Similar approaches can also be applied to business travel, which presents comparable challenges and requires analogous interventions.

3.6. Conclusion

UNIPA’s direct and indirect GHG emissions were systematically estimated for 2023 using the RUS methodology. The analysis identified the main emission sectors, highlighted challenges related to data availability and revealed potential areas for improvement. Measuring the carbon footprint represent a crucial preliminary step in developing effective decarbonisation strategies, encouraging innovative practices and establishing clear, measurable and trackable climate objectives. Adopting the RUS guidelines enhances UNIPA's decision-making capabilities and facilitates comparability of GHG emissions inventories among institutions committed to transparent reporting. UNIPA has already implemented concrete mitigation measures and energy-efficiency initiatives at an operational level, with the aim of gradually reducing emissions. These include optimising energy consumption, increasing the use of renewable energy, upgrading building systems across the campus and maintaining continuous engagement and awareness campaigns within the academic community. The effectiveness of these actions will be monitored through regular updates of the carbon footprint, supporting a progressive and measurable reduction in the UNIPA GHG emissions. Future reporting will be extended to cover additional emission categories and specific sectors, including commuting and waste management. This structured approach to annual reporting will enable environmental considerations to be integrated into institutional governance, fostering more conscious and responsible management of academic, administrative and infrastructural activities. Furthermore, the integration of the *Global Reporting Initiative* (GRI, 2021) indicators with the RUS methodology will strengthen the alignment between environmental data and the organisation's strategic decarbonisation and sustainability goals.

The GRI 305 standard will be applied in future carbon footprint updates, covering Scope 1, 2, and 3 emissions. This will enable the full integration of GHG emissions data into *Sustainability Reports*, thereby enhancing the environmental content of UNIPA's annual *Social Report*, increasing transparency for stakeholders and facilitating comparability across institutions.

Furthermore, this approach will improve alignment with international best practices and contribute to achieving the emission reduction targets established in the UN Agenda 2030 for Sustainable Development, particularly SDG 13 (Climate Action).

Chapter 4

4. Conclusion

The objective of this research was to explore the dynamic interconnection between natural carbon sinks and human systems, with a particular focus on their combined role in mitigating climate change. The study examined the implementation of effective mitigation actions that require the conservation of ecosystems and the responsible management of anthropogenic emissions. As Nature-based solutions are increasingly recognised as an essential component of global climate strategies (MEA, 2005; Wedding et al., 2021; Schindler Murray & Milligan, 2023), this work strengthened the scientific and methodological foundations for integrating BC ecosystems into policy and decision-making frameworks. The primary strand of the investigation focused on Mediterranean and European BC ecosystems, specifically seagrass meadows and saltmarshes, revealing their pivotal but historically underestimated contribution to climate regulation (Macreadie et al., 2021b). However, the scarcity of reliable information on carbon storage and sequestration has often led to their exclusion from national mitigation policies (Howard et al., 2017b; Macreadie et al., 2019). The systematic review provided a comprehensive overview of the current state of knowledge on BC ecosystems potential across Mediterranean and Europe regions, synthesising existing literature to highlight research gaps, methodological inconsistencies and potential approaches for improving their management. Moreover, given the current absence of a comprehensive inventory of marine carbon stocks, it emphasised the urgent need to expand the spatial coverage and resolution of these assessments, an essential step towards improving data quality and guiding effective conservation and policy strategies.

Capo Feto coastal wetland case study broadened the scope of this research by providing a detailed, site-specific assessment. It generated new empirical data and enhanced understanding of BC ecosystem dynamics within Mediterranean coastal wetlands through high-resolution Land Use and Land Cover (LULC) mapping, direct sedimentary carbon stock analysis, and economic valuation based on the Social Cost of Carbon (SCC). The results demonstrated that conserving coastal wetlands not only sustains ecological resilience and enhances efficiency as carbon sinks, but also support multiple ecosystem services, including coastal protection, biodiversity conservation and recreational opportunities such as tourism, which collectively generate measurable economic and social benefits. The estimated monetary value of the sedimentary organic carbon stored in Capo Feto coastal wetland, approximately USD 23.5 million (EUR 21.4 million) in 2024, underscored the tangible contribution of the habitat to climate mitigation and natural capital accounting. Presenting carbon storage in monetary terms further facilitates effective communication with decision-makers and stakeholders by bridging ecological knowledge and economic reasoning, thereby supporting evidence-based management decisions. As a site-scale demonstration, Capo Feto habitat exemplified how integrating ecological, spatial-temporal and economic analyses can generate actionable knowledge for wetland conservation initiatives and climate policy. Despite certain methodological limitations, such as the use of unsupervised classification or the temporal constraint of sediment sampling, the approach adopted in this thesis established a replicable framework for assessing, valuing and managing BC ecosystems across the Mediterranean and other temperate coastal regions. Future research could refine this approach through the application of machine learning techniques, multi-temporal monitoring and the inclusion of parameters such as the assessment of aboveground and belowground biomass, organic carbon accumulation rates and greenhouse gas fluxes, contributing to a more comprehensive understanding of the carbon budget and ecosystem functionality. Moreover, this case study also reflected the commitment of the University of Palermo to advancing sustainability through applied research and environmental monitoring, linking scientific investigation with institutional efforts toward climate action. This connection between knowledge generation and operational responsibility reinforced the idea that universities can play an active role not only as research institutions but also as agents of change in the wider transition toward low-carbon development.

Complementing the ecological assessment, the Carbon Footprint analysis of the University of Palermo demonstrated that complex organizations can function as laboratories for decarbonisation, where institutional, technological and behavioural components interact to determine environmental outcomes. This strand of the research highlighted the role of universities as socio-technical systems, emphasizing the importance of integrating systematic monitoring, evaluation, and reporting tools to guide operational decisions and promote sustainable practices. Taken together, these research strands demonstrated that climate change mitigation is most effective when pursued through a dual approach that enhances the capacity of natural ecosystems to store carbon while reducing emissions from human activities. This integrated perspective revealed that ecological and organisational actions are mutually reinforcing strategies that generate environmental, economic and social co-benefits.

This thesis advances a replicable framework that integrates scientific research and operational responsibility by linking the conservation of Blue Carbon ecosystems, exemplified by Capo Feto coastal wetland, with the University of Palermo’s (UNIPA) efforts to assess and manage greenhouse gas (GHG) emissions. By connecting ecological research with practical action, the framework demonstrates how environmental knowledge can directly inform sustainable practices, supporting the development of more resilient and climate-conscious societies.

Ultimately, this research advocates a unified vision of climate action, in which the protection of natural carbon sinks and the transformation of organisational behaviours operate as complementary strategies for a sustainable, low-carbon future.

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Glossary of Terms

Adaptation: A set of strategies, actions and practices that aim to anticipate and manage the adverse effects of climate change to prevent or reduce potential impacts. It represents the process of adjusting to current and expected climatic effects in order to strengthen the resilience of systems.

Carbon Footprint: Total quantification of direct and indirect greenhouse gas (GHG) emissions associated with an activity, organisation or product, expressed in tonnes of CO_2 equivalent (tCO_2eq). CO_2 equivalent (CO_2eq) is a unit of measurement that expresses the impact of each greenhouse gasses in terms of the equivalent amount of CO_2.

Offsetting: A set of strategies, actions, and practices that compensate, either fully or partially, for residual emissions within an organisation's value chain (for a product or service). This occurs through investments in activities outside organisational boundaries (or the considered system) that remove or reduce an equivalent number of emissions.

Operational Boundaries: Define the types of direct and GHG indirect emissions (Scope 1, 2, 3) that will be included in the inventory. These definitions establish the scope of the activities and emission flows that are considered, in line with reporting objectives.

Organisational Boundaries: Define the scope within which a company operates, establishing limits for responsibility, control, and operations. These can be set according to a direct control approach (financial or operational) or an equity share approach (economic interest). In a university context, they generally include campuses, departments, and facilities under the direct control of the institution.

Decarbonization: The process of transitioning towards a low-carbon economy, involves reducing of GHG emissions, particularly carbon dioxide (CO_2), to mitigate climate change. Decarbonization can be pursued through various actions, such as using renewable energy sources, low-carbon fuels and improving energy efficiency in production processes.

Direct GHG Emissions - Scope 1: Greenhouse gas (GHG) emissions from sources owned or directly controlled by the organisation.

Indirect GHG Emissions - Scope 2, Scope 3: Greenhouse gas (GHG) emissions resulting from the activities of an organization but occurring from sources not owned or directly controlled by the institution.

Greenhouse gases - GHGs: Natural and anthropogenic gaseous constituents that absorb and trap the sun's heat (infrared radiation) in the Earth's atmosphere, thereby contributing to the greenhouse effect. These gases include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), sulfur hexafluoride (SF_6) and nitrogen trifluoride (NF_3).

GHG Protocol: The international standard for quantifying and reporting greenhouse gas emissions, developed by the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD). It categorises emissions as Scope 1, 2 or 3 based on the principles of relevance, completeness, accuracy, consistency and transparency, thereby ensuring comparable and reliable GHG inventories.

GRI 305: A standard from the **Global Reporting Initiative (GRI)** dedicated to reporting greenhouse gas (GHG) emissions, including indicators for Scope 1, 2, and 3. It is part of the GRI sustainability reporting framework.

Global Reporting Initiative (GRI): An international standard used to prepare sustainability reports reflecting an organization's environmental, social, and economic impacts, promoting transparency and accountability towards stakeholders.

ISO 14064 – Part 1 (International Organization for Standardization): A voluntary standard that defines the principles and requirements for the systematic quantification and reporting of greenhouse gas (GHG) emissions and removals at the organisational level. This standard ensures that emission balances are transparent, consistent, and comparable, providing a robust basis for strategic emissions management.

Mitigation: A set of strategies, actions and practices aimed at reducing or containing greenhouse gas emissions, thereby limiting the environmental impact of human activities. This is achieved by addressing emission sources, for instance by improving energy efficiency, decarbonising and adopting low-emission technologies.

Reduction: This is a set of strategies, actions and practices that can be implemented within the company's production chain or associated communities to reduce or eliminate emissions through measurable and certifiable projects.

Network of Universities for Sustainable Development (Rete delle Università per lo Sviluppo Sostenibile - RUS): An initiative promoted by the Conference of Italian University Rectors (CRUI) to support the implementation of sustainability in Italian universities. It provides shared guidelines, including methodologies for GHG emissions reporting in the academic context.

Scope 1 (GHG Protocol): Direct emissions generated from sources owned or controlled by the organization, such as stationary combustion units, company vehicles or industrial processes.

Scope 2 (GHG Protocol): Indirect GHG emissions resulting from the production and consumption of electricity, heat and steam by the organisation.

Scope 3 (GHG Protocol): Indirect GHG emissions not included in Scope 2 that occur throughout an organization’s value chain, both upstream and downstream. These include emissions associated with purchased good and services, transportation, waste management, employees and student commuting, and business travel. This category includes emission sources directly controlled by the organization but resulting from its operations. Scope 3 GHG emissions are often the most challenging to measure yet typically represent the largest share of an organization’s total carbon footprint.

Energy Transition: The process of transforming the energy system from a fossil fuel-dependent energy system to one that is based on renewable energy sources, low- or zero-carbon technologies, and high energy efficiency. The aim is to reduce greenhouse gas emissions and promote environmental sustainability.

Supplementary Table – Summary of studies included in the systematic review: main site characteristics and sediment C_{org} stocks

Author	Year	Country	Area	Habitat	Species	Level of protection	C_{org} stock depth (cm)
Billman et al.	2023	Sweden	Baltic	Seagrass	*Zostera marina, Z. noltei, Ruppia spp., P. perfoliatus,* bare sediment	Natura 2000, none	25
Leduc et al.	2023	France	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000	100
Leiva-Duenas et al.	2023	Denmark	Baltic	Seagrass	*Zostera marina,* bare sediment	Natura 2000, none	100
Mazarrasa et al.	2023	Spain	Atlantic sea	Seagrass	*Zostera noltei*	Natura 2000, none	30
Miller et al.	2023	Scotland	North Sea	Saltmarsh	Multi-species	Special Area of Conservation (SAC)	100
Mueller et al.	2023	Denmark, Germany	North Sea	Saltmarsh	Multi-species	Natura 2000	100
Stevenson et al.	2023	Germany	Baltic	Seagrass	*Zostera marina,* bare sediment	Natura 2000, none	25
Apostolaki et al.	2022	Italy	Mediterranean sea	Seagrass	*Posidonia oceanica*	none	100
Buczko et al.	2022	Germany	Baltic	Saltmarsh	*Phragmites australis*	Natura 2000	100
Burke et al.	2022	Ireland	Irish Sea	Saltmarsh	Multi-species	Natura 2000	100
Casal-Porras et al.	2022	Portugal	Atlantic sea	Seagrass	*Zostera noltei*	Natura 2000	150
Graversen et al.	2022	Denmark	Baltic	Saltmarsh	Multi-species	Natura 2000	43
Guerra et al.	2022	Italy	Mediterranean sea	Saltmarsh	Multi-species, bare sediment	Natura 2000	25
Lima et al.	2022	UK	English channel	Seagrass	*Zostera marina, Z. noltei, Z. angustifolia, Ruppia spp.*	Special Area of Conservation (SAC), none	100
Martins et al.	2022	Portugal	Atlantic sea	Seagrass, Saltmarsh	*Zostera noltei, Spartina maritima*	Natura 2000	100
Monnier et al.	2022	France	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000	100
Roman et al.	2022	Spain	Atlantic sea	Seagrass	*Zostera noltei*	Natura 2000, none	5
Moksnes et al.	2021	Sweden	Skagerrak	Seagrass	*Zostera marina,* bare sediment	Natura 2000, none	35
Potouroglou et al.	2021	Scotland, UK	North Sea	Seagrass	*Zostera marina, Z. noltei,* bare sediment	Special Area of Conservation (SAC), Special Protection Areas, none	50
Wesselmann et al.	2021	Greece, Cyprus	Mediterranean sea	Seagrass	*Posidonia oceanica, Halophila stipulacea, Cymodocea nodosa*	Natura 2000, none	100

Bañolas et al.	2020	Spain	Atlantic sea	Seagrass	*Cymodocea nodosa*	Natura 2000	30
Dahl et al.	2020a	Sweden	Skagerrak	Seagrass	*Zostera marina*	Natura 2000, none	25
Dahl et al.	2020b	Sweden	Skagerrak	Seagrass	*Zostera marina*	Natura 2000, none	25
Green	2020	UK	English channel	Seagrass	*Zostera marina, Z. noltei, Ruppia cirrhosa, Ruppia maritima*	Special Area of Conservation (SAC)	100
Lima et al.	2020	UK	English channel	Seagrass	*Zostera marina, Z. noltei, Z. angustifolia, Ruppia spp.*	Special Area of Conservation (SAC)	30
Monnier et al.	2020	France	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000	100
Apostolaki et al.	2019	Greece	Mediterranean sea	Seagrass	*Posidonia oceanica, Halophila stipulacea, Cymodocea nodosa*	none	20
Ford Hillary et al.	2019	UK	Celtic sea	Saltmarsh	Multi-species	none	10
Sousa et al.	2019	Portugal	Atlantic sea	Seagrass	*Zostera noltei*	Natura 2000	10
Vizzini et al.	2019	Greece, Italy	Mediterranean sea	Seagrass	*Cymodocea nodosa*	none	2
Green et al.	2018	UK	English channel	Seagrass	*Zostera marina*	Special Area of Conservation (SAC) , none	30
Röhr et al.	2018	Finland, Denmark, Sweden, UK	Baltic, Kattegat, Skagerrak, Irish sea	Seagrass	*Zostera marina*	Natura 2000, none	8 - 42
Van de Broek M. et al.	2018	Netherlands	North Sea	Saltmarsh	Multi-species	Natura 2000	60
Mazarrasa et al.	2017	Spain	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000, none	100
Sousa et al.	2017	Portugal	Atlantic sea	Saltmarsh	*Multi-species*	Natura 2000	25
Dahl et al.	2016	Sweden, Portugal, Bulgary	Skagerrak, Atlantic sea, Baltic, Black sea	Seagrass	*Zostera marina, Z. noltei, Ruppia maritima, Cymodocea nodosa,* bare sediment	Natura 2000	25
Jankowska et al.	2016	Poland	Baltic	Seagrass	*Zostera marina,* bare sediment	Natura 2000, none	10, 60
Röhr et al.	2016	Finland, Denmark	Baltic, Kattegat	Seagrass	*Zostera marina*	Natura 2000, none	25
Serrano et al.	2016	Malta	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000, none	154, 230
Van de Broek et al.	2016	Netherlands	Baltic	Saltmarsh	Multi-species	Natura 2000	20-140
Serrano et al.	2014	Spain	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000, none	100
Curado et al.	2013	Spain	Atlantic sea	Saltmarsh	*Spartina maritima*	Natura 2000	10
Sammul et al.	2012	Estonia	Baltic	Saltmarsh	Multi-species	Natura 2000	100
Serrano et al.	2012	Spain	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000	475

Lo Iacono et al.	2008	Spain	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000	600
Mateo et al.	1997	Spain	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000	100 - 320
Romero et al.	1994	Italy, Spain	Mediterranean sea	Seagrass	*Posidonia oceanica*	Natura 2000	300, 140