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Temporal Change of Seagrass Meadows: Estimating Species Composition, Coverage and Carbon Stock Trends Over 16 Years in NIOF Studied Area, Hurghada, Egypt

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ABSTRACT

Seagrass ecosystems are essential coastal habitats, providing refuge for marine biodiversity and acting as significant carbon sinks. This study examined the temporal dynamics of seagrass coverage, species composition, and carbon stock at the NIOF station in Hurghada, Egypt, from 2007 to 2023, integrating field surveys with remote sensing. Field assessments quantified shoot density, biomass, and carbon stock per ground area (C_{AGA}) with historical records data contextualized observed trends in species composition. Five seagrass species were identified, including the dominant *Halophila stipulacea*, *Halophila ovalis*, *Halodule uninervis*, *Thalassodendron ciliatum*, and the newly recorded *Thalassia hemprichii*. *H. uninervis* exhibited the highest shoot density (808 shoots/m²) and carbon stock (C_{AGA}: 129.12g/ m²), underscoring its pivotal role in carbon sequestration. Seagrass coverage declined from 160.91 ha (59.8%) in 2007 to 115.16 ha (42.8%) in 2014, marking a 28.43% reduction. However, subsequent recovery was evident, reaching 171.13 ha (63.6%) in 2019 and 175.97 ha (65.4%) in 2023, indicative of successful conservation or improving environmental conditions. Concurrently, carbon stock increased from 203.57 to 222.63 tons. These findings emphasize the ecological significance of seagrass meadows in climate change mitigation and advocate for strategic conservation, restoration, and policy interventions to enhance ecosystem resilience, biodiversity, and long-term carbon sequestration.

INTRODUCTION

Seagrass meadows are important coastal ecosystems that contribute to coastal resilience and marine biodiversity in a variety of ways. As keystone elements of marine environments, these underwater prairies play a crucial role in nutrient cycling, habitat provision, and carbon sequestration **(Duarte *et al.*, 2013; Unsworth *et al.*, 2019; Shayka *et al.*, 2023)**. Seagrasses' extraordinary ability to act as "blue carbon" sinks has attracted a lot of scientific interest. Due to their capacity to store large amounts of carbon in biomass and sediments, seagrasses are essential partners in efforts to mitigate the effects of climate change worldwide **(Mcleod *et al.*, 2011; Liu *et al.*, 2022)**. Globally, seagrasses store approximately 4.2–8.4 Pg of organic carbon (Corg) in their sediments **(Fourqurean *et al.*, 2012; Shrestha *et al.*, 2019)**. The health of marine environments depends on these underwater meadows, which are among the globe's most productive ecosystems **(Fourqurean *et al.*, 2012)**. According to **Gullström *et al.* (2002)**, seagrasses stabilize coastal areas by acting as sediment traps. Seagrass meadows support biodiversity by providing marine organisms a place to live and a place for reproduction **(Hemminga & Duarte, 2000)**. However, local communities often disregard the sustainability aspects of seagrass habitats, despite their massive ecological value **(Zulkifli *et al.*, 2021)**. Unfortunately, anthropogenic stresses like pollution, climate change, and coastal development are the main causes of the global decline in seagrass meadows **(Waycott *et al.*, 2009; Orth *et al.*, 2020; Tang & Hadibarata, 2022)**. These stressors have caused habitat fragmentation and degradation, which has led to a gradual decline in ecosystem services besides biodiversity **(Bujang *et al.*, 2006; Grech *et al.*, 2012)**. While this is a global phenomenon, certain regions face unique challenges. One example of a particularly vulnerable scenario is the Red Sea, which includes the coast of Hurghada, Egypt. Seagrass ecosystems in this area are seriously threatened by the rapidly growing tourism sector and the development of coastline infrastructure **(El-Asmar *et al.*, 2015; Chaidez *et al.*, 2017)**. The effects of global warming carry an additional threat to the seagrass meadows of the Red Sea, which are home to species like *Thalassodendron ciliatum*, *Halophila stipulacea*, and Thalassia hemprichii **(El Shaffai, 2016)**. The heat stress and thermal collapse of these vital habitats may result from increasing sea surface temperatures in this already warm region **(Thomas *et al.*, 2012; Sawall *et al.*, 2014)**. The preservation of these crucial ecosystems requires a multifaceted approach, combining local conservation efforts with global climate change mitigation strategies. Understanding the unique characteristics and challenges of the Red Sea seagrass meadows is essential for developing targeted conservation measures that can protect these vital "blue carbon" sinks and biodiversity hotspots.

Trends in seagrass coverage, species composition, and carbon stock can be discovered via long-term monitoring, which is necessary for evaluating the impacts of human activity and environmental change **(Lefcheck *et al.*, 2018; Griffiths *et al.*, 2020)**. Knowledge of the factor's influencing change is essential to discover and address the gaps that lead to ineffective seagrass management, given the high variability in individual meadow evolution and the significant gaps in current meadow management practices **(Griffiths *et al.*, 2020)**. Since then, numerous monitoring efforts have given us an extensive amount of new data, which has enabled us to reevaluate patterns of seagrass changes internationally considering the growing influence of environmental factors as well as human effects. Recent developments in European seagrass pastures have been stabilized and recovered **(de los Santos *et al.*, 2019)**. The community's support for conserving and beneficial management of coastal habitats is promoted by the seagrass surveillance program. The community as a whole turns into greatly affected by the need for protecting their local marine environment. Seagrass protection via environmental management of seagrass strategies and baseline monitoring parameters is essentially nonexistent in many countries' programs **(Duffy *et al.*, 2019)**. The monitoring may be carried out for a variety of reasons, such as assessment the effects of an environmental policy or determining the reasons behind changes. It may also be utilized for condition evaluation, detecting changes, and early warning. A wide variety of indicators may be employed for monitoring, that can be completed at local, regional, and global scales **(Neckles *et al.*, 2012)**. Multiple monitoring methods and approaches are used, depending on the goal and scope of the different monitoring strategies, and indicators can be recommended **(Phillips & McRoy 1990; Short & Coles 2001)**. Physical and biological instabilities often result in gaps in our attentiveness of seagrass dynamics **(Nakaoka & Aioi, 1999)**. The seagrass abundance and distribution, both spatially and temporally, are potential markers that have been determined in several studies to assist managers select the best indicator for following seagrass health and alterations. In accordance with recent studies, monitoring seagrass meadow changes and shifts is essential for spotting possible hazards and guiding adaptive management strategies **(de los Santos *et al.*, 2019; Orth *et al.*, 2023)**. However, the increasing threats to these ecosystems necessitate immediate conservation efforts. The primary aim of this study was to investigate the temporal changes in seagrass meadows coverage, species composition, and carbon stock at the NIOF station in Hurghada, Egypt, over a period from 2007 to 2023. The specific objectives were as follows: To assess the spatial and temporal variability of seagrass composition by integrating field study data with historical records from the NIOF study area; to evaluate the temporal changes in seagrass meadow coverage using a combined approach of remote sensing techniques and field-based observations in the NIOF study area, and to estimate the carbon stock associated with seagrass meadows over a 16-year period for assessment their role in coastal carbon sequestration and potential contributions to climate change mitigation.

By achieving these objectives, the study will contribute to a better understanding of the ecological functions of seagrass meadows and their role in mitigating climate change impacts in arid coastal regions **(Chaidez *et al.*, 2017; Liu *et al.*, 2022)**. **Tupan and Uneputty (2017)** and **Liu *et al.* (2022)** have provided valuable insights into the dynamics of seagrass ecosystems in the Red Sea and their role in carbon sequestration, biodiversity conservation, and coastal protection. The findings of the current study will serve as a baseline for future monitoring and conservation efforts, ensuring the long-term sustainability of these vital ecosystems.

MATERIALS AND METHODS

Study area

The study area, covering 269.073ha, is located in the Egyptian coast of the Red Sea at Hurghada site, north of Hurghada Harbor Marine Station of the National Institute of Oceanography and Fisheries (NIOF) (27°16'59.60” N and 33°46'24.26" E) (Fig. 1).

Fig. 1. The study area of seagrasses meadows in NIOF studied area, Hurghada Egypt

Field studies

Field studies, where samples were collected from monospecific meadows, and their exact locations were recorded using Differential GPS (Trimble Geo 7X). These ground-truth data points were incorporated into the classification process after necessary image corrections.

Floristic analysis

Seagrass sampling was conducted using the quadrat method (0.5 x 0.5m), following **English *et al.* (1997)**. Samples were transported to the laboratory in ice boxes for species identification. Identification was based on classifications by **Den Hartog (1970)**, **Green and Short (2003)**, **Short (2006)**, **Boulos (2008)**, and **El Shaffai (2011)**. The specimens were preserved in the Botany Department at Ain Shams University. The global geographical distribution of seagrass species was determined according to **Short *et al.* (2007)**, categorizing them into the floral regions: TA (Tropical Atlantic), ME (Mediterranean), TI-P (Tropical Indo-Pacific), TNP (Tropical North Pacific), and TSO (Tropical South Ocean). Temporal seagrass composition data from field studies conducted at the study area (NIOF) before 2019 were determined by integrating them with historical records of seagrass composition in the same area.

Seagrass density and carbon stock estimation for each species

Seagrass density was assessed within quadrats (0.5 × 0.5 m) using methods outlined by **Rahmawati and Kiswara (2012)**. An individual seagrass was defined as a single stem with leaves, sheaths, rhizome, and roots. Carbon stock assessment followed methodologies from **Howard *et al.* (2018)**, **Rahman *et al.* (2018)** and **Wahyudi *et al.* (2020)**. Seagrass samples were oven-dried at 60°C for 24 hours to obtain stable dry weight. Organic carbon content was analyzed using the method of **Walkley and Black (1934)**.

Remote-sensing data and its processing

Preprocessing by Radiometric and atmospheric corrections were applied to Landsat (2007, 2014) and Sentinel (2019, 2023) imagery using ERDAS IMAGINE software. Unsupervised classification: An initial unsupervised classification was performed to categorize general cover types. Supervised Classification: Ground-truth data were used to train a supervised classification model, improving species differentiation and mapping accuracy. Class 1 included submerged sand substrate, land, water, reefs including coral reefs and dead coral/rubble substrate and Class 2 included seagrass. A seagrass coverage map was generated by integrating image data with field observations, and accuracy assessment was conducted using 41 validation points from field study 2019. The spectral reflectance of seagrass mono specific meadows was extracted from field-verified samples and was used to enhance classification accuracy. The spectral reflectance characteristics of different species were analyzed, allowing for distinct species identification. Subsequently, the classes were merged with all the dominant species to assess the total seagrasses coverage during each selected year.

Temporal mapping of seagrass coverage area and estimation of carbon stock (2007-2023)

The area of seagrass meadows was calculated by analyzing classified pixels using the zone statistics plugin for each image Landsat (2007, 2014) and Sentinel (2019, 2023). The classified imagery was converted into polygons to provide clear seagrasses coverage maps and extract seagrass coverage area value in selected years. The total carbon stock of seagrasses for each selected year was estimated by summing the carbon stock values (per m²) of each species from the field study. These values were then converted from square meters to hectares (1 ha = 10,000m²). Finally, the total carbon stock per hectare was multiplied by the seagrass coverage area for each selected year.

RESULTS

Table 1. Floristic properties of the recorded species

Species	Family	Habit	Life form	Bioregion
Halophila stipulacea (Forssk.) Asch.,	Hydrocharitaceae	Perennial	Helophyte	TA+M+TI-P
Halophila ovalis (R.Br.) Hook. f.,	Hydrocharitaceae	Perennial	Helophyte	TNP+ TI-P+TSO
Halodule uninervis (Forssk.) Boiss.,	Cymodoceaceae	Perennial	Helophyte	TI-P
Thalassodendron ciliatum (Forssk.) Hartog	Cymodoceaceae	Perennial	Helophyte	TI-P+TSO
Thalassia hemprichii (Ehrenb.) Asch.	Hydrocharitaceae	Perennial	Helophyte	TA +TI-P

Table (1) presents the floristic characteristics of the recorded seagrass species. The species include *Halophila stipulacea, Halophila ovalis,* and *Thalassia hemprichii*, all belonging to the Hydrocharitaceae family. In contrast, *Halodule uninervis* and *Thalassodendron ciliatum* are part of the Cymodoceaceae family. Each species is classified as perennial, indicating a life span of multiple years and established life cycles, which are essential for ecosystem stability. All species are categorized as helophytes, adapted to shallow aquatic environments, where they help stabilize sediments and provide habitats for various marine organisms.

Table 2. Temporal seagrasses composition data over the years before 2019 from field studies in studied area NIOF

	H. stipulacea	***H. uninervis***	***H. ovalis***	***Th. ciliatum***	***Th.hemprichii***	**depth(m)**	**soil texture**	**references**
2007	+	+	+	+	-	0.75 -2	Fine sand (ranged from 53.8 to 62.8%)	Geneid,2009
2014	+	+	+	+	-	0.5-1.5	Mainley fine sand	El-Kafrawy et al.,2016
2019	+	+	+	+	+	0.5-2	Mainley fine sand	present study
2021	+	+	+	+	+	0.5-2	Mainley fine sand	present study

The data presented in Table (2) indicate the composition of seagrass species and their associated environmental conditions over the years from 2007 to 2021. The species *Halophila stipulacea, Halophila uninervis, Halophila ovalis,* and *Thalassodendron ciliatum* were consistently recorded across all surveyed years, demonstrating their established presence in the studied area. Notably, *Thalassia hemprichii* was documented in 2019 and 2021, suggesting a potential ecological shift or expansion into the region. The observed depth range for seagrass occurrence remained stable, predominantly between 0.5 to 2 meters. The soil texture across all years was primarily fine sand, with a composition varying from 53.8 to 62.8%.

Table 3. Seagrass shoot density, biomass and carbon stock (C_{AGA} /m^2) for studied species in the years (2019-2021) in studied area NIOF, Hurghada

	Shoot denisty/m2	**Biomass (Dry wt g/m^2)**	**C_{AGA}/individual**	**C_{AGA} /m^2**
H.stipulacea	172 ±34	11.18±0.17	0.03±0.00	5.25±0.11
Th.ciliatum	186±11	14.88±0.97	0.038±0.00	6.99±0.4
H.uninervis	808±55	274.72±29	0.16±0.01	129.12±15.4
H.ovalis	5.3±0.81	0.037±0.00	0.003±0.0	0.02±0.00
Th. hemprichii	252±16.5	24.192±1.01	0.045±0.0	11.37±0.10

The presented data in Table (3) highlight the shoot density, biomass, and carbon stock potential (C_{AGA}) of five seagrass species in the NIOF studied area over the period of

2019-2021. Understanding these parameters is crucial for assessing the ecological role of seagrasses in carbon sequestration and their overall health.

The assessment of shoot density and biomass across five seagrass species revealed significant variability, reflecting their distinct ecological roles and contributions to ecosystem structure. *Halodule uninervis* exhibited the highest values for both shoot density (808 shoots/m²) and biomass (274.72g/ m²), highlighting its dominance in the seagrass community. In contrast, *H. ovalis* displayed the lowest values, with a shoot density of 5.3 shoots/m² and a biomass of 0.037g/ m², indicating its limited presence and ecological contribution. Intermediate values were observed for *Th. hemprichii* (252 shoots/m² and 24.192g/ m²), *Th. ciliatum* (186 shoots/m² and 14.88g/ m²), and *Halophila stipulacea* (172 shoots/m² and 11.18g/ m²), suggesting their moderate but meaningful roles in the ecosystem. These findings align with global patterns of seagrass distribution and productivity, where fast-growing species like *H. uninervis* often dominate in terms of biomass and shoot density.

The C_{AGA} values demonstrate the potential of each species to sequester carbon. Carbon stock (C_{AGA}) was obtained by conversion from seagrass biomass using carbon contents of seagrass tissues. *H. uninervis* contributes the most to carbon storage per square meter (129.12 ± 15.4g C/ m²), highlighting its dominance in carbon sequestration. *H. stipulacea*, *Th. ciliatum* and *Th. hemprichii* also show reasonable C_{AGA} values (5.25, 6.99 and 11.37g C/m², respectively), suggesting that while they are less dominant in biomass compared to *H. uninervis*, they still contribute meaningfully to carbon storage. *H. ovalis* contributes the least (0.02 ± 0.00g C/ m²), reflecting its low abundance and biomass. *H. uninervis* exhibited the highest carbon storage capacity among the studied seagrass species.

Temporal prediction of seagrasses coverage over the years (2007-2023)

The data presented in Fig. (2) and Table (4) indicate a clear trend in seagrass coverage over the years, with a total area of 269.07 ha recorded. In 2007, seagrass coverage was documented at 160.91 ha, representing 59.8% of the total studied area. However, by 2014, coverage sharply declined to 115.16 ha (42.8%), reflecting a reduction of 28.43% compared to 2007. This decline aligns with global trends in seagrass loss, often attributed to coastal development, pollution, and climate change **(Waycott *et al.*, 2009)**. In a positive turn, seagrass coverage rebounded to 171.13 ha (63.6%) by 2019, exceeding 2007 levels by 6.35%. By 2023, coverage further increased to 175.97 ha (65.4%), indicating a growth of 9.36% compared to 2007. The trends observed—initial decline followed by recovery and stabilization—are consistent with documented global patterns of seagrass loss and recovery **(Dunic *et al.*, 2021)**. The increase in coverage from 2014 to 2023 suggests that effective conservation efforts or natural regeneration may be influencing these positive outcomes.

Estimation carbon stock over the years (2007-2023)

Table (4) explored carbon stock dynamics reflect the changes in seagrass coverage. In 2007, the carbon stock was 203.57 tons, which declined to 145.70 tons (−28.43%) by 2014 due to reduced coverage. However, carbon stocks rebounded to 216.50 tons by 2019, surpassing 2007 levels by 6.35%. This upward trend continued into 2023, with carbon stocks reaching 222.63 tons, a 9.36% increase compared to 2007.

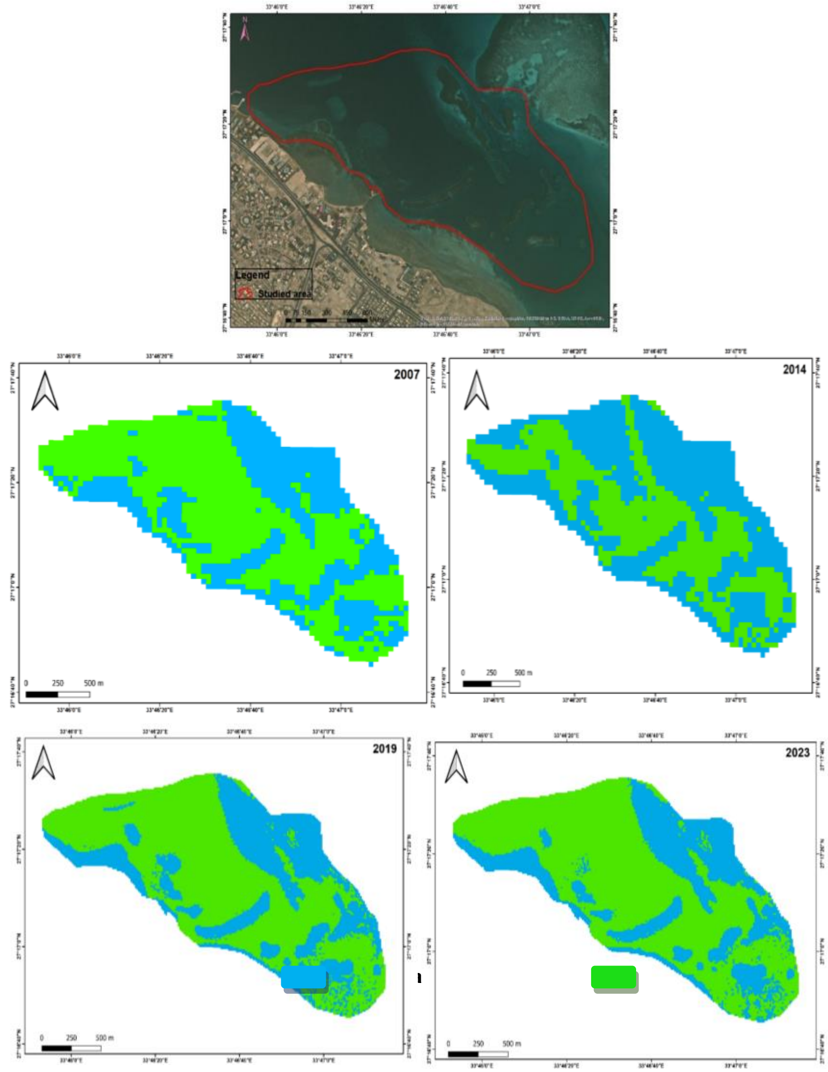

Fig 2. Temporal seagrass coverage over the years (2007-2023) in studied area

Table 4. Temporal prediction of seagrasses coverage and carbon stock (ton) over the years (2007-2023) in studied area NIOF

Total studied area (ha)	Years	coverage area of seagrasses(ha)	Ratio (%)	Carbon stock of seagrass (ton)	The change compared to 2007 (%)
269.073	2007	160.91	59.8	203.57	
	2014	115.16	42.8	145.7	-28.43
	2019	171.13	63.6	216.5	6.35
	2023	175.97	65.4	222.63	9.36

DISCUSSION

Floristic properties of the recorded species

Seagrasses play critical roles in marine ecosystems by providing essential services such as habitat for fish and invertebrates, facilitating nutrient cycling, and stabilizing sediments **(Duarte, 2002)**. The classification of these species within the Hydrocharitaceae and Cymodoceaceae families highlights the diversity and ecological adaptations present within seagrass ecosystems. The presence of multiple species in overlapping bioregions suggests potential ecological interactions and the capacity of these species to thrive under varying environmental conditions. All listed species forms a monospecific vegetation and they are perennial, indicating they live for multiple years and have established life cycles, which is crucial for stability and resilience in their ecosystems. Perennial species often contribute more significantly to habitat structure and ecosystem functions over time compared to annuals. The perennial nature of these species allows them to recover from disturbances more effectively than annuals, enhancing their importance in maintaining the health of coastal ecosystems **(Orth *et al.*, 2006)**. The bioregional codes (e.g., TA+M+TI-P for *Halophila stipulacea*) indicate the specific regions where these species thrive. TA (Tropical Atlantic), M (Mediterranean), TI (Tropical Indo-Pacific), and TSO (Tropical South-Western Ocean) suggest that these species are well-adapted to warm, shallow coastal waters across multiple biogeographic regions. The presence of species in overlapping bioregions indicates potential ecological interactions and the ability of these species to adapt to different environmental conditions. Moreover, the diverse bioregional distribution emphasizes the adaptability of seagrasses to changes in salinity and temperature, which is vital for their survival amid the challenges posed by climate change and anthropogenic pressures, including coastal development and pollution **(Waycott *et al.*, 2009)**. Understanding the distribution and ecological roles of these seagrass species is imperative for conservation efforts. Protecting these habitats not only enhance biodiversity and support fisheries but also mitigate climate change through carbon sequestration **(Fourqurean *et al.*, 2012)**. Effective conservation strategies should consider the specific ecological needs of each species and their habitats to maintain ecological balance.

Temporal seagrasses composition data over the years before 2019 from field studies in studied area NIOF

The persistence of *H. stipulacea, H. uninervis, H. ovalis,* and *Th. ciliatum* over multiple years reflects their resilience and adaptability to local environmental conditions. This stability aligns with the findings of **Madden *et al.* (2009)**, who highlighted the importance of a stable and diverse seagrass community as an indicator of ecosystem health and resilience. The recent appearance of *Th. hemprichii* in 2019 and 2021 may indicate either a recovery from previous ecological disturbances or a response to improved habitat conditions, such as reduced anthropogenic impacts. This trend suggests that the ecosystem is becoming more resilient and capable of supporting a wider range of species. The depth range observed indicates suitable habitat conditions, as seagrasses thrive in shallow, well-lit waters **(Jones *et al.*, 1987)**. The predominance of fine sand as a soil texture is conducive to seagrass growth, facilitating adequate drainage while retaining essential nutrients. The stability of sediment conditions is crucial for the anchorage and nutrient uptake of seagrass species **(Mellors *et al.*, 2002)**. The consistent presence of these seagrass species underscores their ecological importance, including providing critical habitat for marine organisms, stabilizing sediments, and facilitating nutrient cycling **(Creed *et al.*, 2023; Chen *et al.*, 2024)**. Furthermore, the presence of multiple species enhances biodiversity and ecological stability **(Hyman *et al.*, 2019)**. The stable depth range implies that the seagrass beds are well-adapted to their environment, ensuring sufficient light availability for photosynthesis. Shallow areas are known to be more productive, supporting diverse marine life **(Hatcher *et al.*, 1989)**. Variations in sediment type can influence species composition and distribution, with finer sediments generally supporting greater biomass **(Bennett, 2014)**. Understanding the dynamics of seagrasses is essential for assessing their resilience and response to environmental stressors **(Connolly *et al.*, 2018)**. Thus, the findings from this study contribute valuable insights for the conservation and management of seagrass ecosystems in the face of ongoing environmental changes.

Present studied results of seagrass shoot density, biomass and carbon stock (C_{AGA} /m^2) for studied species in the years (2019-2021) in studied area NIOF, Hurghada, Egypt

The assessment of shoot density and biomass across the five seagrass species reveals significant variability, reflecting their distinct ecological roles and contributions to the ecosystem. The dominance of *H. uninervis* not only contributes to overall seagrass cover but also enhances habitat complexity, providing refuge for various marine organisms **(Waycott *et al.*, 2009)**. The robust growth of *H. uninervis* aligns with global patterns where fast-growing species dominate in terms of biomass and shoot density. This species not only contributes significantly to the overall seagrasses cover but also has a notable capacity for carbon storage. These results were considerably higher compared to those from Umluj and Jazan in Saudi Arabia, as well as from Kuwait and Papua New Guinea **(Brouns, 1987; Al-Bader *et al.*, 2014; Qurban *et al.*, 2019)**. In contrast, the extremely low shoot density of *H. ovalis* suggests that environmental conditions may not be conducive to its growth in this area, or that it is outcompeted by other species. The observed shoot densities for *H. ovalis* are considerably lower than those recorded in regions such as Indonesia **(Nienhuis *et al.*, 1989)** and the Philippines **(Rollon *et al.*, 2001)**, underscoring the importance of species-specific assessments in understanding seagrass ecosystem dynamics.

The C_{AGA} values highlight each species' potential for carbon sequestration, with *H. uninervis* demonstrating the highest capacity. Its carbon storage value falls within the range reported for dominant monospecific seagrass meadows elsewhere **(Rahmawati & Kiswara, 2012)**, indicating the variability in carbon sequestration potential among seagrass species. This variability emphasizes the critical importance of understanding species-specific contributions to blue carbon dynamics. Given its high biomass and carbon stock, *H. uninervis* should be prioritized for restoration and conservation efforts, particularly in areas aimed at enhancing carbon sequestration. Continued monitoring and further research are necessary to evaluate the responses of these seagrass species to environmental stressors, such as climate change, nutrient loading, and habitat degradation. Understanding the interactions among seagrass species, their associated faunal communities, and the broader marine ecosystem will provide valuable insights into their functional roles and resilience strategies **(Duarte, 2002)**.

Temporal prediction of seagrasses coverage and carbon stock (ton) over the years (2007-2023)

However, by 2014, coverage sharply declined to 115.16 ha (42.8%), reflecting a reduction of 28.43% compared to 2007. This decline aligns with global trends in seagrass loss, often attributed to coastal development, pollution, and climate change **(Waycott *et al.*, 2009)**. In a positive turn, seagrass coverage rebounded to 171.13 ha (63.6%) by 2019, exceeding 2007 levels by 6.35%. By 2023, coverage further increased to 175.97 ha (65.4%), indicating a growth of 9.36% compared to 2007. The trends observed—initial decline followed by recovery and stabilization—are consistent with documented global patterns of seagrass loss and recovery **(Dunic *et al.*, 2021)**.

The recovery of seagrass coverage and carbon stocks is indicative of effective conservation strategies and highlights the resilience of seagrass ecosystems. The initial decline from 2007 to 2014 reflects global trends driven by coastal development and environmental stressors. However, the subsequent recovery suggests that targeted management and improved environmental conditions, such as reduced pollution and nutrient inputs, may be fostering a more stable ecosystem **(Short *et al.*, 2011)**. The increase in coverage from 2014 to 2023 suggests that effective conservation efforts or natural regeneration may be influencing these positive outcomes. While the stabilization in seagrass coverage by 2023 implies that the ecosystem may be reaching a new equilibrium, supported by local management initiatives. Protecting these habitats not only enhances biodiversity but also supports fisheries and mitigates climate change through carbon sequestration **(Fourqurean *et al.*, 2012; Epple *et al.*, 2016)**. In conclusion, while the data reflect past challenges, they also point toward the potential for recovery, aligning with findings that show the importance of protective measures for seagrass ecosystems **(Orth *et al.*, 2020; Hall *et al.*, 2021)**. This upward trend contrasts with global reports of continued seagrass decline, underscoring the importance of localized management strategies **(Swadling *et al.*, 2023).**

Carbon stock dynamics, seagrass meadows are critical blue carbon sinks, and their carbon stocks mirrored changes in coverage. In 2007, the carbon stock was 203.57 tons, declining to 145.70 tons (−28.43%) by 2014 due to reduced coverage. However, by 2019, carbon stocks rebounded to 216.50 tons, surpassing 2007 levels by 6.35%. This increase continued to 2023, with carbon stocks reaching 222.63 tons, a 9.36% rise compared to 2007. These findings align with studies emphasizing the resilience of seagrass ecosystems and their capacity to recover carbon sequestration functions following restoration **(Hejnowicz *et al.*, 2015; Gouldsmith &Cooper, 2022)**. The increasing carbon stock underscores the importance of seagrass conservation as part of climate change mitigation strategies. The observed recovery in seagrass coverage and carbon stocks contrasts with global trends, where seagrass meadows have declined at an annual rate of 1.5% since the 20th century **(Waycott *et al.*, 2009)**. However, localized recoveries have been documented in regions with effective management, such as the Mediterranean Sea (**Telesca *et al.*, 2015**) and Chesapeake Bay **(Orth *et al.*, 2020)**. The 9.36% increase in coverage and carbon stocks by 2023 in this study highlights the potential for seagrass recovery under favorable conditions, consistent with findings by **Unsworth *et al.* (2019)**, who reported similar recoveries in Southeast Asia following community-led conservation efforts. The carbon stock values in this study (145.70–222.63 tons) are comparable to those reported in other temperate and tropical seagrass ecosystems. For instance, **Fourqurean *et al.* (2012)** documented carbon stocks ranging from 140 to 250 tons in seagrass meadows across the Indo-Pacific region. The recovery of carbon stocks in this study underscores the importance of seagrass meadows in climate change mitigation, as highlighted by **Krause-Jensen *et al*. (2021)**, who estimated that seagrass ecosystems globally store up to 19.9 Pg (19.9 billion metric tons of carbon.) of organic carbon. In terms of conservation and climate change mitigation, the recovery of seagrass coverage and carbon stocks observed in this study demonstrates both the effectiveness of targeted conservation efforts and the resilience of seagrass ecosystems. However, continued monitoring is essential to address ongoing threats such as coastal development, eutrophication, and climate change. The findings also emphasize the role of seagrass meadows in achieving global climate goals, as their restoration can significantly enhance carbon sequestration and biodiversity (**McLeod *et al*., 2011**). Protecting and restoring seagrass habitats can enhance their capacity to sequester carbon while also providing essential ecosystem services **(Nordlund *et al*., 2024)**. Further research could explore specific restoration techniques or environmental policies that contributed to this positive trend. Additionally, f urther analysis could explore the underlying causes for the fluctuations and implications for marine habitats.

CONCLUSION

The floristic composition of the surveyed area reveals a diversity of seagrass species, including *Halophila stipulacea, Halophila ovalis, Thalassia hemprichii, Halodule uninervis,* and *Thalassodendron ciliatum*, each contributing uniquely to ecosystem stability and resilience. The presence of perennial species indicates established life cycles that enhance habitat complexity and ecological functions over time **(Waycott *et al*., 2009)**. Moreover, the presence of *Thalassia hemprichii* in 2019 and 2021 suggests potential ecological shifts linked to environmental changes or management actions and enhanced ecosystem health. Stability in seagrass depth range and soil texture indicates suitable habitat conditions, essential for their growth and productivity. The predominance of fine sands supports the nutrient retention and drainage necessary for seagrass survival **(Rehlmeyer *et al*., 2024)**. Moreover, the observed variations in shoot density and biomass among species suggest differential responses to environmental conditions, highlighting the importance of species selection in restoration and conservation efforts **(Jahnke *et al*., 2015)**. The analysis of seagrass coverage and ecological dynamics over the years reveals both challenges and promising trends for these vital ecosystems. The data indicate a significant decline in seagrass coverage from 2007 to 2014, dropping from 160.91 to 115.16 ha, reflecting a 28.43% decrease. This decline can likely be attributed to factors such as water quality degradation, coastal development, and climate change impacts **(Orth *et al*., 2010)**. However, from 2014 to 2023, a notable recovery occurred, with coverage increasing to 175.97 ha, representing an overall positive trend in seagrass health and ecosystem function. The coverage ratio increased from 59.8% in 2007 to 65.4% in 2023. In terms of carbon stock, an upward trend from 203.57 tons in 2007 to 222.63 tons in 2023 illustrates the significant role seagrasses play in carbon sequestration. The highest carbon storage potential is attributed to *Halodule uninervis*, suggesting its prioritization in conservation and restoration initiatives aimed at enhancing carbon capture **(Fourqurean *et al*., 2012)**. This underscores the resilience of these ecosystems and suggests that effective conservation efforts or improved environmental conditions may have facilitated this recovery **(Short *et al*., 2011)**. Such positive changes are critical, as seagrasses provide essential services, including habitat for marine life, nutrient cycling, and carbon sequestration, making them key players in coastal ecosystem health **(Fourqurean *et al*., 2012)**. Overall, while the data reflect past challenges, it also highlights the potential for seagrass recovery and resilience. Future research should focus on identifying specific drivers of seagrass dynamics and exploring effective restoration techniques. This knowledge will be vital for developing targeted conservation strategies that protect these critical habitats and enhance their ecological roles in the face of ongoing environmental pressures.

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