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Carbon retention in wetlands under different anthropogenic pressures: effects of reed mowing and pollution in the Burgas lake Ramsar site

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Abstract

Wetlands are acknowledged as important resources for carbon storage, yet their capacity to facilitate longterm carbon storage is extremely susceptible to human influence. Here, we evaluate the impacts of various management regimes on carbon retention at the Burgas lake RAMSAR site, Bulgaria - a wetland of international importance that also supports rich biodiversity. We conducted field soil analyses and satellite observations to assess unmanaged, occasionally mown, regularly managed and polluted wetland areas. Soil samples collected in July 2025, revealed clear contrasts: the unmanaged site contained the highest carbon and nitrogen levels, while mown and polluted sites showed reduced carbon retention and altered nutrient balances. Electrical conductivity was significantly elevated in the polluted zone, reflecting anthropogenic pressure. Remote sensing indicators, derived from Sentinel-2 (NDVI, NDRE, MSAI2, NBR, NDWI), showed vegetation productivity, chlorophyll content, soil background effects, moisture and structural disturbance. High positive correlations were noted as a result for the soil carbon, as an index with the vegetation indices and negative correlations with pH and moisture proxies. These results reveal how management and disturbance determine the carbon dynamics in wetlands, and show the benefit of combination of soil and remote sensing methods. The findings are the basis to guide research and implement evidence-based solutions for restoring and managing wetlands, and promoting the carbon sequestration ability of wetlands, without jeopardizing ecological soundness.

Key words: wetlands, carbon sequestration, ecosystem services, reed mowing, anthropogenic pressure, Burgas lake, RAMSAR site, soil nutrients

Introduction

Wetlands are among the best natural environments to store carbon over long periods of time. Not that they cover much of the planet's surface, but they are rich in carbon that's sitting in their soils and sediments, and they are crucial to tackling climate change.

Wetlands also have very high susceptibility to drainage, eutrophication, pollution, and the removal of direct biomass. These pressures may affect their carbon equilibrium, and even convert them from net sinks to sources of greenhouse gas emissions. Wetlands have also been paid increasing attention in European policy and scientific appraisals. Their contribution to climate neutrality goals is now widely acknowledged, and wetland protection and restoration is considered both a priority for biodiversity as well as carbon saving (ETC/ULS, 2021).

This dual act captures their special ability to provide ecosystem services, which incorporate both climate regulation and habitat provision to a wide range of organisms in a very diverse web of ecosystems. However, anthropogenic pressures can greatly alter carbon dynamics. Reed mowing significantly reduces biomass inputs from above ground to soils, while pollution alters nutrient balance and microbial metabolism - these both affect carbon sequestration potentials. On the other hand, poorly managed sites will tend to collect more organic carbon, and be more stable for long term carbon accumulation. There is a need to systematically assess both such divergent trajectories for the carbon sequestration potential to comprehend how both a modification and disturbance affect on the carbon storage capacity of the wetlands.

Many studies have already focused on the carbon dynamic in the wetlands, whether through soil analysis or satellite imagery, but only a limited number integrated the both approaches. Soil sampling provides direct proof of carbon content and nutrients in a given moment, whereas satellite data allow continuous monitoring of the vegetation and hydrological conditions in time and space. The importance of combining satellite-derived indicators with ground-based measurements for improving the accuracy and robustness of sustainability assessments has been emphasized in recent studies (Lobell et al., 2021). Sentinel-2's vegetation indexes (NDVI, NDRE, MSAVI2, NBR) and water index (NDWI), together with the radar metrics from Sentinel-1, secure strong proxies for detection of vegetation structure, humidity, and the level of disruption. The integration of those sets of data provides better knowledge on wetlands functioning as carbon reservoirs under different levels of anthropogenic pressure.

The present study focuses on the Ramsar site Burgas lake (19.95 km²) in Bulgaria – a wetland of international significance, which sustains nearly 300 bird species, and which is functioning under different management regimes. Along the shores of the lake extensive reedbeds (*Phragmites australis*) form large stands that represent a key structural and functional component of the wetland ecosystem. Through comparison of unmown, rarely mown, regularly mown and polluted zones, the study aims at assessing their capacity for carbon retention, and studying the links between the soil carbon and the indicators drawn from satellite data. It is expected that the results will form a base for a future scientifically grounded strategy for restoration and management, for improving the capacity of wetlands for carbon sequestration.

Literature review

Wetlands play a disproportionate role in the global carbon cycle. When preserved in good condition or restored, they provide substantial carbon storage and sequestration benefits at the continental scale. For example, the overall carbon stock capacity of wetlands in Europe is estimated to be between 12 and 31 Gt CO_2-eq, equivalent to 3-8 years of total EU greenhouse gas emissions. Healthy wetlands further sequester 24-144 Mt CO_2-eq.yr^{-1}, enough to offset 1-4% of EU total emissions (ETC/ULS, 2021). These figures provide a continental benchmark that underscores the importance of covering and restoring wetlands for climate neutrality targets.

Recent research has pointed out that the carbon dynamics of wetlands are highly sensitive to anthropogenic disturbances. Tidal and inland wetlands may tend to lose soil carbon under conditions of drainage, nutrient enrichment, or biomass removal (Maxwell et al., 2024). The above interventions change the hydrological system, and lower plant biomass inputs to soils and hasten the decomposition processes that can convert wetlands from carbon sinks to sources of CO_2 and CH_4. In contrast, unmanaged or minimally disturbed wetlands exhibit accumulation of increased content of organic matter, which reinforces their functioning as carbon reservoirs. Robust assessment of carbon sequestration as an evidence-laden process, relies in methodological and other studies on integrating multiple lines of evidence. For example, Mistry et al. (2024) compared radiometric techniques for estimating recent carbon sequestration rates in inland wetlands, and emphasized the need for combining soil, sediment, and remote sensing data, to capture both spatial variability and temporal variability. Remote sensing is a significant piece of the puzzle and advances such integrated strategies. Vegetation indices (using Sentinel-2), like NDVI, NDRE, MSAVI2, and NBR, yield insights on canopy productivity, chlorophyll content, soil background effects, and disturbance stress. NDWI and similar water indices are especially relevant to wetlands that are heavily influenced by carbon accumulation and preservation by hydrology. Optical data are enhanced by Sentinel-1 radar backscatter metrics based on detecting vegetation structure and mowing intensity. These satellite-derived indicators integrated with soil analysis create a complete scheme to assess how wetlands should function as carbon reservoirs under a range of management regimes.

Remote sensing plays a central role in advancing such integrated approaches. Vegetation indices derived from Sentinel-2, such as NDVI, NDRE, MSAVI2, and NBR, provide information on canopy productivity, chlorophyll content, soil background effects, and disturbance stress. Water indices such as NDWI are particularly relevant to wetlands, where hydrology strongly governs carbon accumulation and preservation. Sentinel-1 radar backscatter metrics complement optical data by detecting vegetation structure and mowing intensity. The integration of soil analysis with these satellite-derived indicators provides a comprehensive framework for evaluating how wetlands function as carbon reservoirs under different management regimes.

In the same time studies, warn that restoration of wetlands could not be the only solution. According to Tölgyesi et al. (2025), the carbon sequestration potential of restoration projects worldwide could not compensate for continued high carbon emissions. It highlights that restoration is still a crucial nature-based approach, but should be targeted at high carbon storage environments like wetlands.

Specifically, there continues to be a need for site-level research that quantifies how different anthropogenic pressures impact - carbon retention, informing effective restoration and management approaches. While deeper soil horizons can hold substential additional carbon pools and remain less well quantified in many wetlands (Maxwell et al., 2024; Cooray et al., 2024), the present study focuses specifically on the surface layer (0-20 cm), which is most sensitive to recent management interventions. Similarly, seasonal variations in soil organic carbon and nutrient flux also affect sequestration rates, but are not often characterized in one-time sampling campaigns (Kumar and Sharma, 2025). Remote sensing methods, though robust, possess limitations in cloud cover, mixed pixels, and the difficulty in separating vegetation and water signals in heterogenous wetlands (Abdelmajeed and Juszczak, 2024). Underlying, such limitations is the need for combined at-site investigations that integrate multiple soil sampling across depths but complement this with satellite-based monitoring of vegetation and hydrological indicators. In that context, these approaches are very pertinent, as there is a clear directive in particular in European policy frameworks (such as EU Green Deal and the LULUCF Regulation) for better carbon accounting practices both in wetlands and other types of land-use categories. Filling these methodological and policy gaps allows the local investigations to provide not only better science, but evidence-based restoration and management in accordance with the international commitments.

Previously unsolved aspects of the problem

Despite considerable progress in understanding wetland carbon dynamics, several important gaps remain unresolved in the literature. Many studies of wetlands carbon sinks focus on individual influencing factors such as vegetation type, hydrological regime, or nutrient status, but play relatively little attention to interactions among these factors. This creates uncertainty in estimates of carbon storage and sequestration (Li et al., 2024).

There is also a recognized limitation on the spacial and vertical coverage of soil organic carbon (SOC) data. Remote sensing studies tend to emphasize surface layers (e.g. 0-30 cm), while deeper soil horizons, which may contribute significantly to total carbon stocks, remain less well quantified (Sharma et al., 2022; Maxwell et al., 2024; Cooray et al., 2024). Addressing subsurface SOC requires dedicated sampling and methodological approaches and therefore lies beyond the scope of the present study, which focuses on the surface soil layer (0-20 cm). , Without reliable information on subsurface SOC or detailed field sampling down to subsurface depths, stock estimates can substantially underestimate sequestration potential (Sharma et al., 2022; Maxwell et al., 2024; Cooray et al., 2024).

Remote sensing approaches are constrained by limitations such as clouds, mixed pixels, and difficulties to distinguish water from vegetation background, especially in heterogenous wetlands (Abdelmajeed and Juszczak, 2024). Temporal resolution issues (i.e. fewer valid acquisitions during key periods) reduce the ability to capture seasonal dynamics, which are critical for carbon input (growth, biomass turnover) and soil respiration.

Many monitoring or storage models lack consistency in validation with localized soil carbon measurements. Reviews such as Practical Guide to Measuring Wetland Carbon Pools emphasize that soil sampling, including dry bulk density, soil depth, and carbon concentration remain essential, but is underused in remote sensing validation efforts (Bansal et al., 2023). Without strong ground-truth, remote predictors risk significant bias when generalized across zones with different management or disturbance regimes.

Lastly, but not by significance, there are somewhat fewer studies of management-induced disruptions (e.g. mowing, pollution, nutrient loading), for its effect on long-term carbon retention impacts of wetlands on the scale of vegetation structure and soil pools combined. Several authors had assessed vegetation response of soil carbon content, nutrient cycling, and remote sensing proxies at different management intensities remain under-researched (Li et al., 2024; Sharma et al., 2022). Recent studies show that changes in small and micro-wetlands, related to land-use dynamics and local management practices, can significantly influence ecosystem functioning and carbon processes, but these changes are often not well captured in regional assessments (Zhang et al., 2023).

Purpose and tasks of the study

The main purpose of this study is to determine the effectiveness of carbon saving and storage in wetland ecosystems under various kinds and levels of anthropogenic pressure, for the Burgas lake (Vaya) Ramsar site.

The study seeks to measure the interrelationships between ecosystem attributes, management approach and principal physicochemical parameters of wetland soils and to assess the extent to which vegetation productivity and satellite detection spectral variables can be valid proxies of soil carbon content and ecosystem integrity. Our study aims to connect field-to-land experiments and laboratory analysis with remote sensing in a holistic approach, by combining in situ measurements, laboratory analysis, and remote sensing to explore. These analyses, combined with global observation into a universal methodological model, to estimate carbon sequestration potential for the same-sized scales to understand trends in ecosystem functioning along spatial and temporal scales. To accomplish this aim, the following research tasks have been designed:

1) Characterization of the studied area:
- to describe the spatial configuration and environmental setting of the Burgas lake wetland system, including geomorphology, hydrology, vegetation and anthropogenic influences;
- to delineate representative zones with different levels of human intervention for comparative analysis - unmanaged, occasionally managed, regularly managed and polluted.
2) Soil sampling and laboratory analysis:
- to collect and analyze soil samples from the identified zones following standardized procedures for determining organic carbon (C), total nitrogen (N), available phosphorus (P2O5), pH and electrical conductivity (EC);
- to evaluate how these parameters vary among zones and how they reflect differences in management intensity and pollution impact.
3) Remote sensing data processing and index calculation:
- to obtain and process multi-temporal Sentinel-1 and Sentinel-2 satellite imagery (2018-2025) in the Google Earth Engine (GEE) environment;
- to derive vegetation and water indices (NDVI, NDWI, NDRE, MSAVI2, NBR) and compute zonal statistics for each study area;
- to analyze spatial and temporal trends in vegetation productivity and moisture conditions as indicators of wetland health.
4) Integration and statistical analysis:
- to combine soil and remote-sensing datasets into a comprehensive database linking field observations with spectral indicators;
- to apply appropriate statistical methods (ANOVA, Kruskal-Wallis, Spearman correlation) for identifying significant differences and relationships between soil carbon content, management type and remote-sensing indices.
5) Interpretation and evaluation of management effects:
- to assess the impact of mowing, pollution, and hydrological variability on carbon retention efficiency and nutrient balance;
- to identify the key factors controlling carbon sequestration in wetlands under anthropogenic stress;
- to provide recommendations for ecosystem restoration and adaptive management, aimed at enhancing carbon storage capacity and maintaining wetland resilience.

The expected scientific contributions are:
- development of an integrated methodological approach combining field ecology, soil science and remote-sensing for the assessment of carbon retention in wetlands;
- empirical evidence for the relationship between soil organic carbon and spectral indices (NDVI, NDRE, MSAVI2) as indicators of ecosystem state;
- a conceptual basis for applying multi-source data and statistical modelling in the long-term monitoring of wetland restoration effectiveness.

Methods

Study area and site selection

The study was conducted in the Burgas lake RAMSAR site, where the Ecopark "Vaya" is located, which represents the second largest natural lake in Bulgaria and an internationally important wetland.

Four sites with different management regimes were selected: (i) an unmanaged wetland with no human intervention for 11 years; (ii) an occasionally mown site; (iii) a regularly mown and intensively managed site within the ecopark, and (iv) a polluted site outside the ecopark.

The four investigated sites represent a gradient of anthropogenic pressure, ranging from natural to heavily impacted conditions. Their geographic coordinates, management regimes and ecological characteristics are summarized in Table 1. The geographical position and distribution of the four sampling zones within the Burgas lake RAMSAR area are illustrated in Figure 1.

Soil sampling and laboratory analysis

In July 2025, composite soil samples were collected from the top 0-20 cm soil layer at each site, supplemented with water samples, where available. In addition, morphological descriptions of soil horizons were recorded for representative profiles in unmanaged, ocassionally mown and regularly managed zones. The main morphological characteristics of the representative soil profiles are summarized in Table 1a. The uppermost horizons (0-10 cm to 0-20 cm) were characterized by dark colors, high organic matter content, and visible plant residues such as roots and undecomposed reed leaves. Subsurface horizons (down to 40-60 cm) showed denser, clay-rich textures, with gray to yellowish-gray colours, fewer root inclusions and clear evidence of compaction, while submerged layers often contained dense reed mats and partially decomposed organic material. The polluted site near Burgas lake was distinguished by the presence of biotic waste and altered substrate conditions.

Each soil sample was analyzed for organic carbon (C, %), total nitrogen (N, %), available phosphorus (P2O5, mg/100 g), pH, and electrical conductivity (EC, mS.cm-1). Standard laboratory protocols were applied: total nitrogen was determined by the Kjeldahl method, organic carbon by the Tyurin method, available phosphorus following the Penkov-Ivanov procedure, pH was measured potentiometrically, and electrical conductivity was measured conductometrically.

<u>*Remote sensing data and processing*</u>

To complement the field and laboratory information, multi-annual remote sensing data were analyzed to capture vegetation and hydrological dynamics of the Burgas lake wetland under different management regimes. All remote sensing processing was performed in the Google Earth Engine cloud environment (Gorelick et al., 2017), with access to time-series data from Sentinel missions and ancillary datasets such as ERA5 Muñoz-Sabater et al., 2021) and JRC Global Surface Water (Pekel et al., 2016). The analysis covered on July 2018-2025, to coincide with the timing of the field sampling.

Sentinel-2 optical indices: Level-2A atmospherically corrected images at 10 m resolution were used. To ensure consistency of the dataset, only scenes with <20% catalogue-level cloud cover were retained, after which remaining clouds and cirrus were masked using QA60 bands. For July 2025, this filtering procedure resulted in a set of 16 valid Sentinel-2 scenes contributing to the median composites. Vegetation and moisture indices were computed, including NDVI (Normalized Difference Vegetation index) as a proxy for vegetation productivity (Tucker, 1979), NDRE (Normalized Difference Red Edge) for canopy chlorophyll content (Gitelson and Merzlyak, 1994), MSAVI2 (Modified Soil-Adjusted Vegetation index) to reduce soil background effects (Huete, 1988), and NBR (Normalized Burn Ratio) as a stress/disturbance indicator. NDWI (Normalized Difference Water Index) was applied to estimate vegetation moisture and wetland hydrology (Gao, 1996). For each July from 2018 to 2025, median composites were produced, and zonal medians were extracted for each site polygon. These indices were subsequently integrated with the soil dataset to evaluate links between vegetation structure, moisture regime, and carbon content.

<u>*Contextual datasets*</u>

Sentinel-1 radar data, JRC Global surface Water occurrence, and ERA5-Land climatic variables were examined qualitatively, to support the interpretation of hydrological and climatic background, but quantitative analysis focuses on optical Sentinel-2 indices.

All spectral indices were clipped to the site polygons and summarized as zonal medians (scale = 10 m). This aggregation minimized pixel-level noise and aligned remote sensing outputs with the aerial footprint of the field sampling sites. The integration of soil and satellite-derived data provided a robust framework for evaluating wetland carbon retention under contrasting anthropogenic pressures. The overall workflow of data collection, processing and analysis is illustrated in Figure 2.

<u>*Statistical analysis*</u>

Soil and remote sensing datasets were integrated for joint analysis in R 4.5.1 (R Core Team, 2025) using the packages stat and vegan. One-way ANOVA was applied to test for differences between sites under the assumption of normality, while the non-parametric Kruskal-Wallis test was used as a robust alternative, given the small sample size and potential deviations from normal distribution.

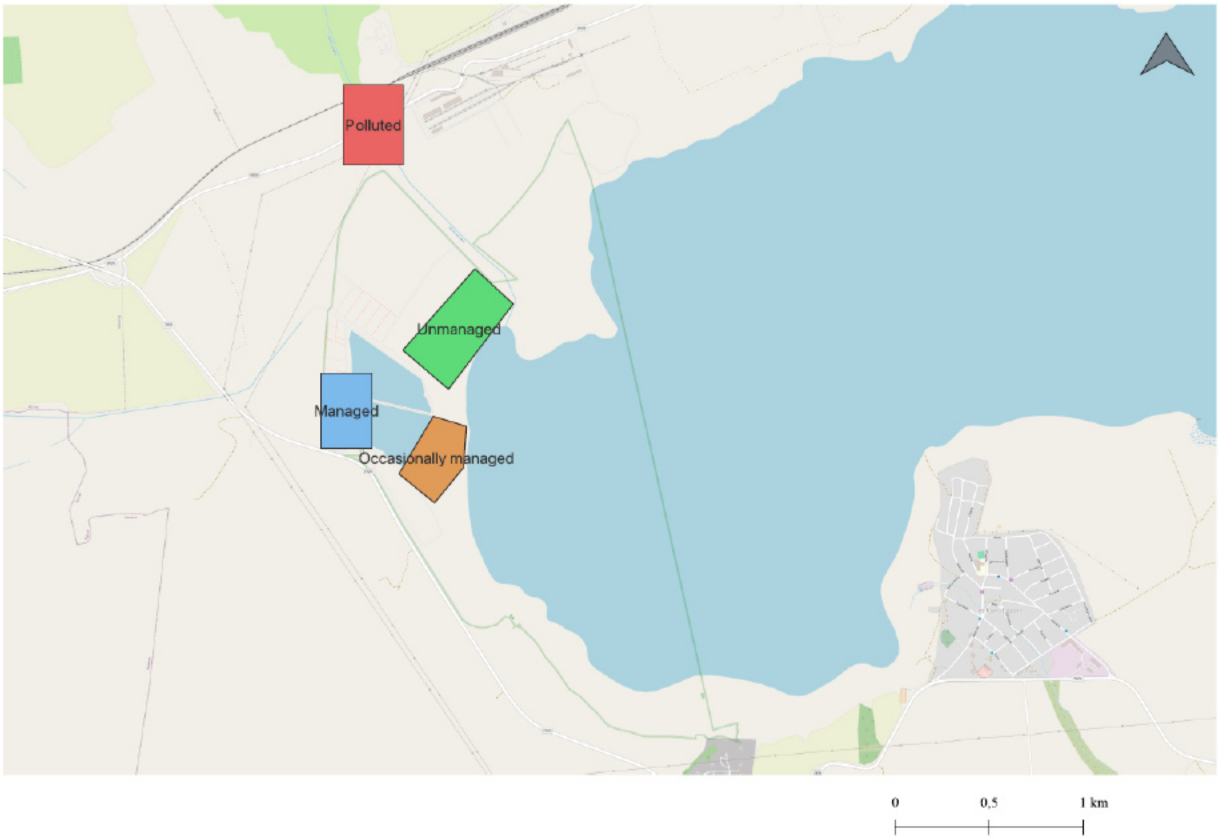

Fig. 1. Study zones

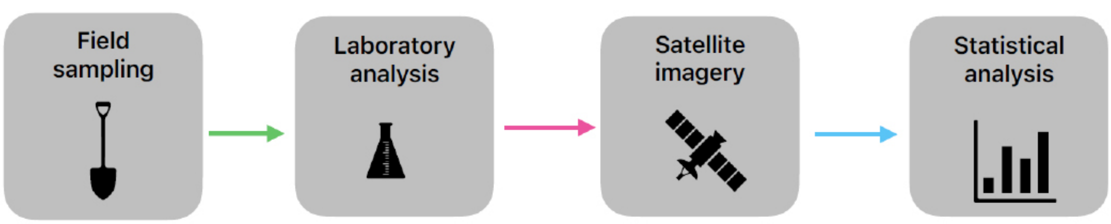

Fig. 2. Methodological workflow of the study

Spearman's rank correlations were calculated to explore relationships between (i) soil carbon and (ii) soil chemical properties (N, P, pH, EC), and (iii) remote sensing indices (NDVI, NDWI, NDRE, MSAVI2, NBR). Temporal dynamics of vegetation and moisture indices (2018-2025) were visualized to evaluate site-specific trends.

Results

Soil analysis revealed clear differences among the four wetland zones reflecting varying degrees of anthropogenic influence. The main results of the soil physicochemical analyses are summarized in Table 2.

The morphological observations confirmed clear structural differentiation among the four studied zones. The unmanaged area displayed well-developed soil horizons and a dark, clay-rich hydromorphic layer rich in organic inclusions and reed roots, typical for long-term carbon accumulation under stable anoxic conditions. In contrast,

Table 1. Coordinates and description of the study sites

Zone	Management regime	Coordinates (Lat, Lon)	Site characteristics
Unmanaged	No human intervention for the last 11 years	42.494726° N, 27.342954° E	Dense reedbeds dominated by Phragmites australis, high organic matter accumulation, stable hydrology, absence of mowing or disturbance.
Occasionally managed	Reed mowing carried out irregularly (every 2–3 years)	42.493428° N, 27.341967° E	Mixed reed and sedge vegetation with partially open water patches. Periodic biomass removal limits litter accumulation.
Managed	Regular mowing and intensive maintenance within Ecopark "Vaya"	42.491910° N, 27.338018° E	Reed area under constant anthropogenic presence (visitors, maintenance). Frequent mowing reduces standing biomass.
Polluted	Site outside Ecopark boundary affected by anthropogenic waste and runoff	42.505420° N, 27.336130° E	Degraded reed vegetation with high salinity and organic waste input. Altered soil structure and elevated electrical conductivity.

Table 1a. Morphological characteristics of representative soil profiles in the Burgas Lake wetland system

Zone	Horizon	Depth (cm)	Colour (Munsell)	Texture	Organic matter & roots	Structure & porosity	Notes / Interpretation
Unmanaged	1.1	0–10	Black (10YR 2/1)	Clayey	Rich in roots and undecomposed reed material	Porous, well-hydromorphic	Stable anoxic conditions; high organic C accumulation
	1.2	10–18	Dark brown (10YR 3/2)	Silty clay	Moderate roots	Compact, slight mineralization	Transition to mineral layer
	1.3	18+	Gray (2.5Y 6/1)	Clay	Few roots	Dense	Reduced biological activity
Occasionally mown	2.1	0–10 (underwater)	Brown (10YR 4/3)	Loamy	Few decomposing reed leaves	Compact	Periodic mowing; partial oxidation
Regularly managed	3.1	0–15	Black (10YR 2/1)	Clayey	Partially decomposed roots	Weakly porous	Moderate organic accumulation
	3.2	15–30	Grayish brown (10YR 5/2)	Clay	Sparse roots	Dense, dry cracks	Fluctuating water table
Polluted	4.1	0–15	Gray (5Y 5/1)	Silty clay with debris	Few organic residues	Very compact	Anthropogenic inclusions; limited infiltration

Table 2. Soil physicochemical properties by zone (0-20 cm layer, July 2025)

Zone	C (%)	N (%)	P_2O_5 (mg/100g)	pH	EC (μS/cm)
Unmanaged	8.59	0.78	7.06	7.82	423
Occasionally managed	2.01	0.23	0.76	8.30	892
Managed	2.50	0.17	13.03	7.95	383
Polluted	3.97	0.24	8.50	7.40	1.500

the regularly mown and intensively managed areas showed more compact surface layers with reduced porosity and signs of periodic aeration, indicating accelerated mineralization and partial oxidation of organic matter. The occasionally mown zone showed intermediate characteristics, with a moist black top horizon containing partially decomposed roots, but less distinct subsurface stratification. The polluted zone showed a drastically altered structure, containing biotic and anthropogenic debris and very high electrical conductivity values (>1500 mS.cm^{-1}), reflecting heavy contamination. These differences in soil morphology and chemistry demonstrate how management intensity and pollution collectively alter the hydrological regime, microbial activity, and overall carbon stabilization potential within the Burgas lake wetland system.

The unmanaged site, located within the protected reedbed of Ecopark Vaya, exhibited the highest organic carbon (8.6%) and nitrogen (0.78%) contents, as well as moderate electrical conductivity (≈ 423 μS.cm^{-1}). These results confirm the long-term accumulation of organic matter under minimal human disturbance.

In contrast, both occasionally managed and regularly managed sites had substantially lower carbon concentrations (2.0-2.5%) and nitrogen (0.17-0.23%), reflecting the consequences of recurrent reed mowing that removes above-ground biomass and restricts litter incorporation into the soil.

The polluted area, situated outside Ecopark Vaya, contained intermediate carbon levels (~ 4.00 %), but markedly higher electrical conductivity (≈ 1500 μS.cm^{-1}), confirming the presence of anthropogenic contamination and nutrient loading.

Soil pH values ranged between 7.4 and 8.3, remaining within the slightly alkaline range typical for calcareous wetland substrates.

Overall, the results suggest that management intensity and pollution jointly influence the nutrient balance and carbon retention capacity of the wetland soils.

To complement the soil data, vegetation productivity and moisture conditions were evaluated using Sentinel-2 imagery. The main values of the calculated vegetation and moisture indices (NDVI, NDRE, MSAVI2, NBR, NDWI) for each management zone are presented in Table 3. The Sentinel-2 derived indices confirmed pronounced spatial variability in vegetation structure and moisture conditions among the zones. The standardized (z-score) heatmap visualization provides a comparative overview of the relative magnitude of each spectral index across management regimes. Zones with higher values of vegetation productivity and chlorophyl indices (NDVI, NDRE, MSAVI) correspond to the unmanaged area, while the lowest values occur in polluted and regularly managed zones (Fig. 3).

NDVI and MSAVI2 values were highest in the unmanaged zone (>0.7), indicating dense and photometrically active reed canopy.

Lower values (0.45-0.55) were observed in the managed and polluted zones, consistent with reduced vegetation cover and possible stress effects.

The NDRE index (0.23-0.53) showed high sensitivity to canopy chlorophyll content and effectively differentiated between actively growing and mown reed patches.

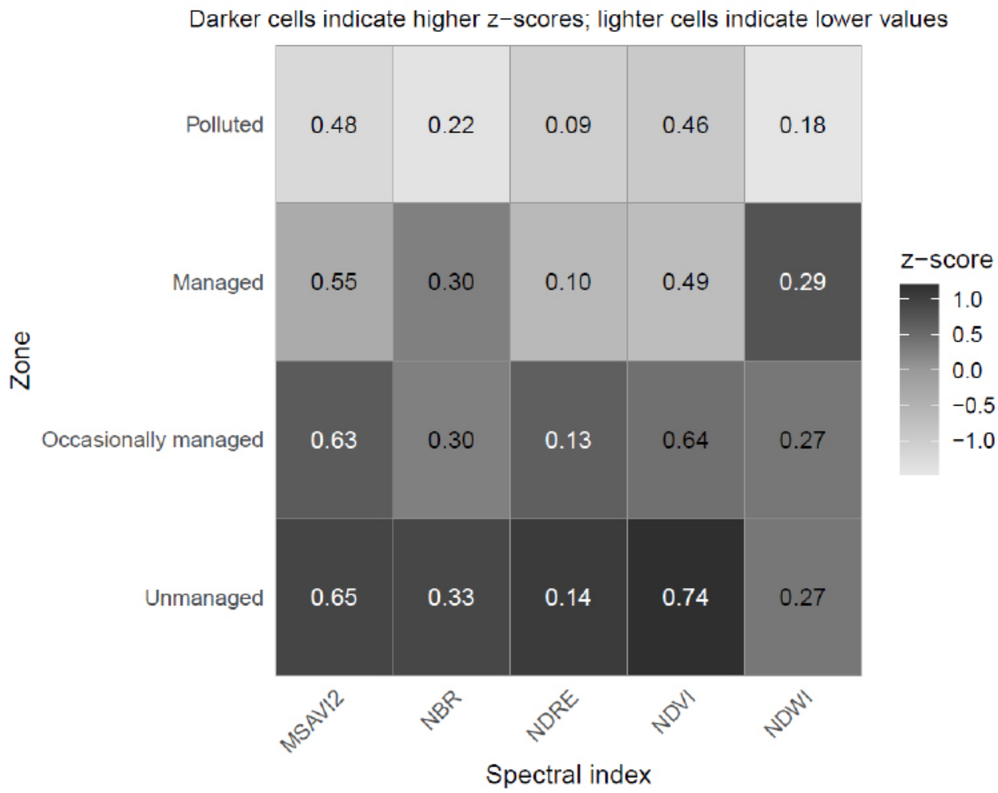

Fig. 3. Sentinel-2 indices by wetland management zone (grayscale version)

Negative NDWI values (-0.6 to -0.4) across all zones reflected dense emergent vegetation rather than open water, while NBR values (0.32-0.56) corresponded to variation in biomass condition and structural complexity.

The strength and direction of the relationships between soil physicochemical parameters and remote sensing indices are summarized in Table 4, which shows strong positive correlations between soil organic carbon and vegetation indices (NDVI, MSAVI2, NDRE). These spatial differences in spectral response aligns with field observations of reed density, coloration, and surface hydrology, confirming the utility of optical indices for mapping wetland vegetation conditions.

We found recurring connections among soil and satellite data integrated. The relationships between soil organic carbon (C%) and each of the Sentinel-2 indices are illustrated in Figure 4a-e, showing consistent positive trends for NDVI, NDRE and MSAVI2, while NBR exhibits a weaker correlation and NDWI a negative one. These patterns confirm the close link between vegetation productivity and carbon accumulation in the studied wetland zones. Spearman's rank correlation showed very high positive correlation between soil organic carbon and vegetation indices NDVI (0.86), MSAVI2 (0.83) and NDRE (0.78). Results from these studies show that areas with denser and healthier vegetation correspond to higher soil organic matter content and greater carbon storage potential. On the other hand, NDWI has a moderate negative correlation with carbon (-0.42), suggesting that a wetter or more saturated surface produces a slightly lower carbon concentration at the surface, due to slower litter decomposition and dilution by mineral sediment. NBR showed weak positive relationship (0.30), implying that this disturbance-related index captures biomass variations but is less sensitive to below-ground carbon.

Inter-soil parameter correlations also highlighted a strong coupling between carbon and nitrogen (Spearman's $\rho > 0.9$), reflecting their common origin from organic matter accumulation. In addition, a moderate inverse relationship was observed between soil organic carbon and pH ($\rho \approx -0.5$), indicating that higher carbon contents are associated with slightly lower pH values within the measured alkaline range (pH 7.4-8.3). This pattern is consistent with established patterns in wetland biogeochemistry, where increased inputs of organic matter and the formation of organic acids can lead to a local decrease in pH, while values remain within the physically plausible range for aqueous soil environment (Bansal et al., 2023; Sharma et al., 2022).

The heatmaps (Fig. 5) clearly visualize these relationships, illustrating that vegetation productivity indices (NDVI, NDRE, MSAVI2) are the most reliable proxies for soil carbon estimation in the Burgas lake wetland system.

Multi-annual Sentinel-2 data (2018-2025) revealed relatively stable NDVI and MSAVI2 trajectories in the unmanaged reedbed, indicating consistent vegetation productivity and hydrological stability over time. The interannual variation of vegetation productivity (NDVI) and moisture conditions (NDWI) during the 2018-2025 period is summarized in Table 5.

Managed and occasional mown areas, however, had higher interannual variability, correlated with the timing of reed cutting and recovery cycles. Years with higher precipitation (2020 and 2022) exhibit increased NDWI and decreased NDVI, suggesting temporary flooding or prolonged soil saturation. These trends show that vegetation productivity, hydrological variability, and management intensity interplay to set wetland carbon dynamics.

These processes can be effectively captured by remote sensing time series. The integrated analysis shows that anthropogenic pressure is indeed one of the factors, and the impact on the wetland's carbon retention can be direct. Unmanaged reedbeds are constant carbon sinks, maintaining dense vegetation and high organic matter accumulation. Reed mowing disrupts this balance by lowering biomass inputs and by speeding decomposition, which reduces soil carbon. Pollution also enhances electrical conductivity and changes the chemical environment, potentially limiting microbial activity and carbon sequestration efficiency.

By using both field and satellite data, this study provides quantitative proof that wetland management intensity and water regime jointly control

Table 3. Mean values of Sentinel-2 indices (July 2025)*

Zone	NDVI	NDWI	NDRE	MSAVI2	NBR
Unmanaged	0.74	0.27	0.14	0.65	0.33
Occasionally managed	0.64	0.27	0.13	0.63	0.30
Managed	0.49	0.29	0.10	0.55	0.30
Polluted	0.46	0.18	0.09	0.48	0.22

Table 4. Spearman correlations between soil properties and RS indices (2025)

Soil parameter	NDVI	NDWI	NDRE	MSAVI2	NBR
C (%)	0.86	-0.42	0.78	0.83	0.30
N (%)	0.81	-0.36	0.76	0.80	0.28
pH	-0.52	-0.18	-0.45	-0.39	-0.30
EC ($\mu S.cm^{-1}$)	-0.34	0.15	-0.28	-0.30	-0.44

Table 5. Temporal variation in NDVI and NDWI (2018–2025)

Year	Unmanaged NDVI	Managed NDVI	Polluted NDVI	Unmanaged NDWI	Managed NDWI	Polluted NDWI
2018	0.70	0.48	0.45	0.26	0.28	0.17
2019	0.73	0.51	0.46	0.27	0.29	0.18
2020	0.75	0.47	0.44	0.28	0.31	0.19
2021	0.74	0.50	0.46	0.27	0.29	0.18
2022	0.72	0.46	0.43	0.30	0.33	0.21
2023	0.73	0.49	0.44	0.27	0.30	0.20
2024	0.74	0.48	0.43	0.26	0.31	0.19
2025	0.74	0.49	0.46	0.27	0.29	0.18

Table 6. Summary of management effects on wetland soil and vegetation

Parameter	Unmanaged	Occasionally managed	Managed	Polluted
Soil carbon	↑↑	↓	↓	↓
Vegetation density	↑↑	↑	↓	↓
EC / salinity	→	↑	→	↑↑
Vegetation moisture (NDWI)	→	→	↑	↓
Overall carbon retention efficiency	High	Moderate	Low	Low

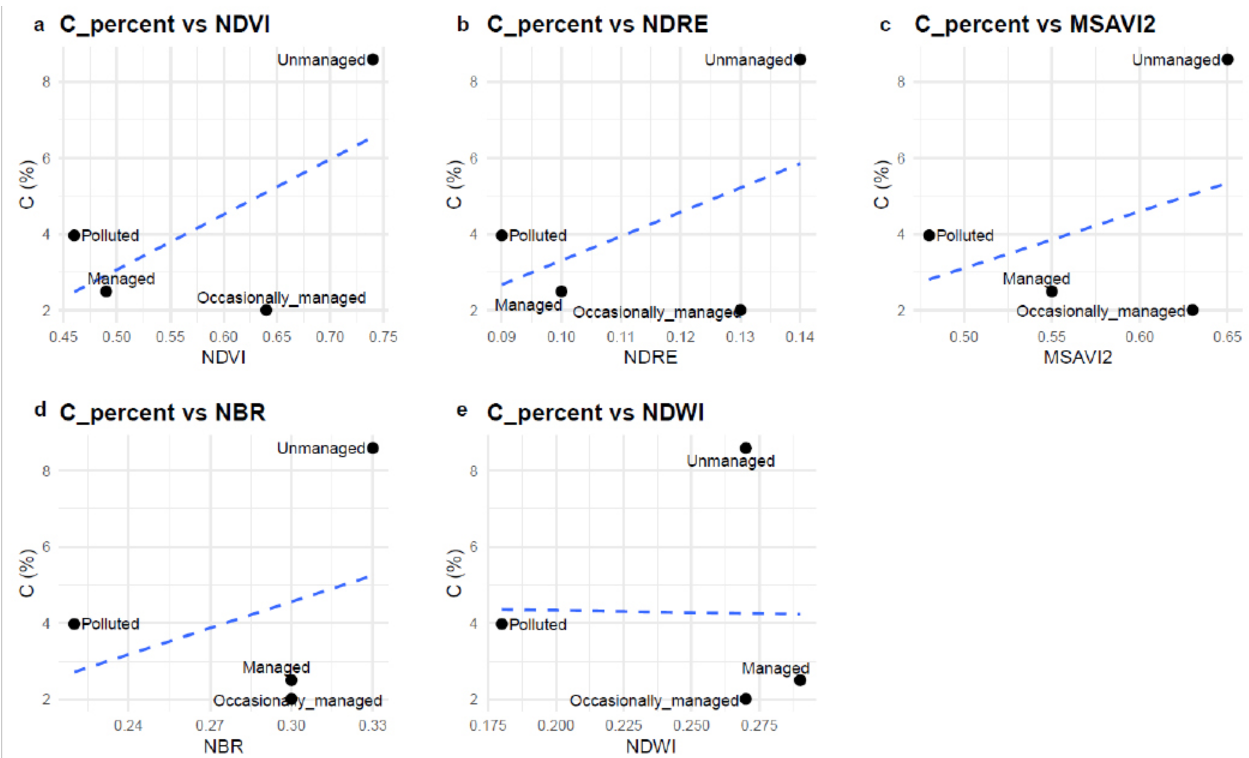

Fig. 4. Relationships between soil organic carbon (C %) and Sentinel−2 indices (NDVI, NDRE, MSAVI2, NBR, NDWI)

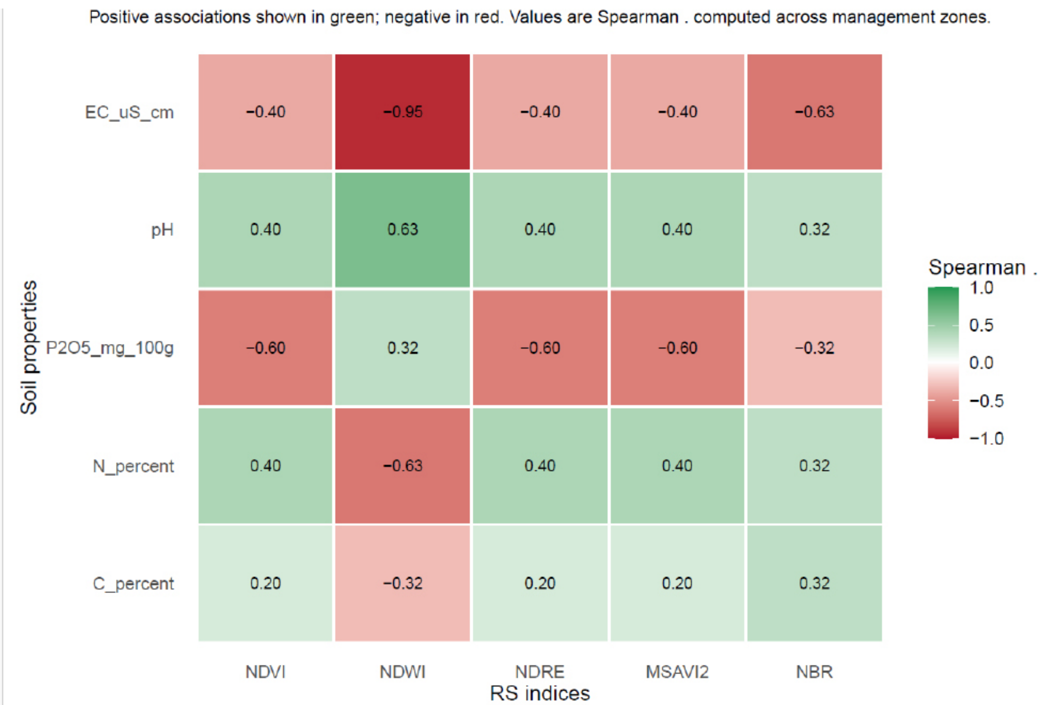

Fig. 5. Spearman correlations between soil properties and RS indices (matrix)

carbon retention. The approach demonstrates that using the combination of soil sampling and remote sensing indices is an efficient and generalizable instrument to track the status of ecosystem restoration and to assess the climate-mitigation performance of wetlands under different management regimes. A synthesis of the observed management -related effects on soil properties, vegetation structure and overall carbon retention efficiency is provided in Table 6.

Conclusion

One limitation of this study is the small number of sampled sites (n=4), making it a lower statistical power. Future studies will scale the sampling design to more sites and repeat measures to confirm the results and will combine the soil carbon measurements with the satellite-derived indices of several sampling campaigns to provide statistical relations.

Another limitation of the study was that only 0-30 cm depth soil sampling was performed. While this depth is common during carbon assessments and in line with IPCC Tier 1 recommendations, it does not account for deeper soil horizons that may contribute to a significant fraction of total carbon levels in wetlands. Recent global syntheses reveal that deeper horizons (30-100 cm) can hold 30-50% of total SOC, which suggests that measurements only at shallow depths are liable to underestimate the sequestration potential (Maxwell et al., 2024; Cooray et al., 2024). Seasonal variations of SOC in RAMSAR wetlands are recognized as significant and have been substantiated between pre- and post-monsoon seasons (Kumar and Sharma, 2025). These results reinforce the requirement of future research to expand both vertically (more deeply sift soil) and temporally (extending seasonal sampling campaigns across many sampling periods). By including such sizes, a deeper understanding of wetland carbon dynamics will be captured and the robustness of the site-level understanding will be enhanced.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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