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Blue Geochemistry: Sustainable Development in Libya Based on Blue Carbon

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ABSTRACT

The authors coined the term "blue geochemistry" in this article. Blue geochemistry is the study of blue carbon ecosystems. Consequently, one may consider blue geochemistry to be a branch of green geochemistry. Blue economy and blue carbon are related ideas that focused on the sustainable utilization of coastal and marine environments. Seagrasses, salt marshes, and mangroves are ecosystems that store and collect carbon, which is known as blue carbon. Meanwhile, the blue economy includes sustainable development and economic activities associated with the coasts and seas. This study's objective is to assess Libya's blue carbon using the BCDI and provide recommendations for the country's sustainable future development. Salt marshes and seagrasses are widespread in the Libyan coast, while mangroves cannot grow there naturally due to unsuitable conditions. These ecosystems are threatened by a variety of issues, including pollution, habitat degradation, and unsustainable coastal expansion. Libya consistently has low BCDI scores due to poor management and preservation of blue carbon ecosystems, and serious climate change problems.

1. INTRODUCTION

The sustainable use of ocean resources for job development, economic growth, and better livelihoods while maintaining the health of marine ecosystems is known as the blue economy. It highlights the significance of striking a balance between environmental sustainability and economic development and includes all ocean-related economic activities (e.g., Rodríguez-Rodríguez *et al.,* 2016; Katila *et al.,* 2019; Niner *et al.,* 2022; Guedri *et al.,* 2025).

The field of green geochemistry, also known as sustainable geochemistry, is a relatively young one. It is a scientific idea aimed at increasing the effectiveness of using natural resources to satisfy human demands for chemical goods and services. The relationship between humans, the environment, and manmade systems is the main emphasis of green geochemistry. It aims to understand the issues that humanity will face in the future and to assist in finding solutions. More specifically, it seeks to identify ways to preserve the integrity of life support systems globally. Such sustainable development tackles a variety of issues, including pollution, biodiversity loss, climate change, and, for instance, the deterioration of land and water. In fact, direct action to preserve, safeguard, and improve natural resources is necessary for sustainability. Topics related to green geochemistry include: (1) Sustainable raw materials; (2) Blue carbon; (3) Green hydrogen; (4) Enhanced weathering; (5) Ocean afforestation; (6) Landfill geochemistry; (7) Nuclear waste recycling; and (8) Green infrastructure (Shaltami, 2022). The term "blue geochemistry" was created by the authors in this article. The study of blue carbon ecosystems is the focus of blue geochemistry. Therefore, blue geochemistry can be regarded as a subfield of green geochemistry. Mangroves, salt marshes, and seagrasses are examples of coastal and marine ecosystems that absorb and store carbon, which is known as "blue carbon." The carbon that these ecosystems store in their plants and, more significantly, in the wet soils underneath them is extremely effective. In order to mitigate climate change, this stored carbon is taken out of the atmosphere and ocean. Carbon dioxide is stored in the biomass and sediments of blue carbon ecosystems after being absorbed from the atmosphere and ocean. Because the blue carbon ecosystems eliminate carbon dioxide from the atmosphere, they are therefore essential for reducing the effects of climate change (e.g., Thomas, 2014; Ahmed *et al.,* 2017; Lovelock and Reef, 2020; Grey *et al.,* 2023; Benani *et al.,* 2025). Unfortunately, human activities like pollution, climate change, and coastal expansion are posing an increasing danger to these ecosystems. These dangers have the potential to cause these ecosystems to deteriorate or even collapse, which would release stored carbon back into the atmosphere and accelerate climate change. Blue carbon ecosystems must be preserved and restored in order to continue sequestering carbon and reducing the effects of climate change. Benefits include preserving wildlife and preventing erosion along coasts. Consequently, blue carbon ecosystems are essential to reaching the Sustainable Development Goals (SDGs). Fig. 1 shows blue carbon conceptual diagram.

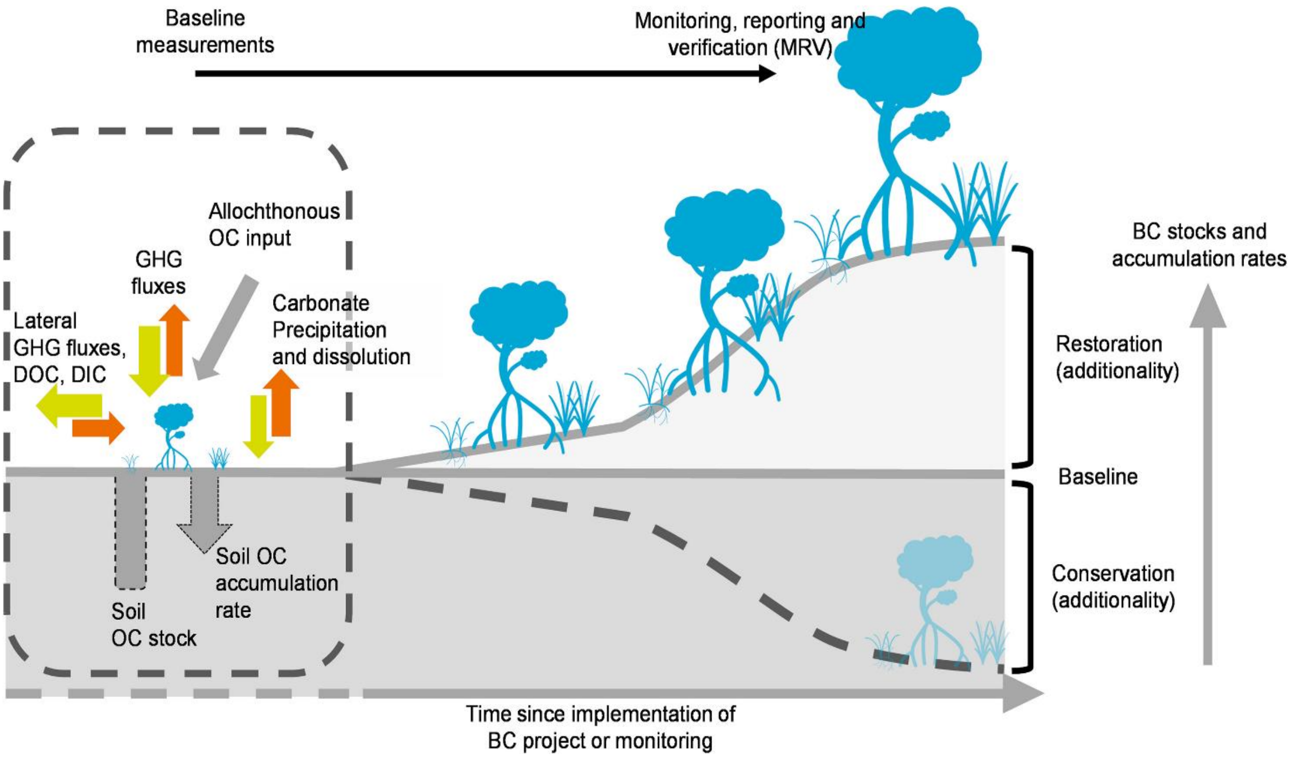

Fig. 1: Blue carbon (BC) conceptual diagram showing baseline data and methods for evaluating the climatic benefits of conservation and restoration efforts (after Dahl *et al.,* 2025).

The Blue Carbon Initiative (BCI) was created in collaboration with Conservation International (CI) and the Union for Conservation of Nature (IUCN) (Thomas, 2014; Jiao *et al.,* 2018). Following the publication of the 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventory: Wetlands, blue carbon was formally and progressively accepted as a solution to climate change (United Nations Environment Programme, 2020).The global carbon store of coastal wetlands was estimated to be between 10447 and 25066 Mt (Howard *et al.,* 2017). Feng *et al.* (2023) established the blue carbon development index (BCDI). The BCDI evaluates the long-term sustainable development level of blue carbon in 136 coastal countries by integrating three subsystems (Fig. 2) and investigating the linkages among subsystems. The performance of blue carbon ecosystem protection and restoration, as well as the ability of socioeconomic interventions to develop blue carbon under the effects of human activity and global climate change, are all included in the BCDI's sustainable development level. The viability of international collaboration to boost carbon sequestration and the financial advantages of blue carbon was also examined using a cooperation model. The findings guide future policy-making and international cooperation by offering a glimpse of the spatial and temporal sustainable growth of blue carbon as well as a plan for achieving ecological and economic benefits through collaboration (Feng *et al.,* 2023).

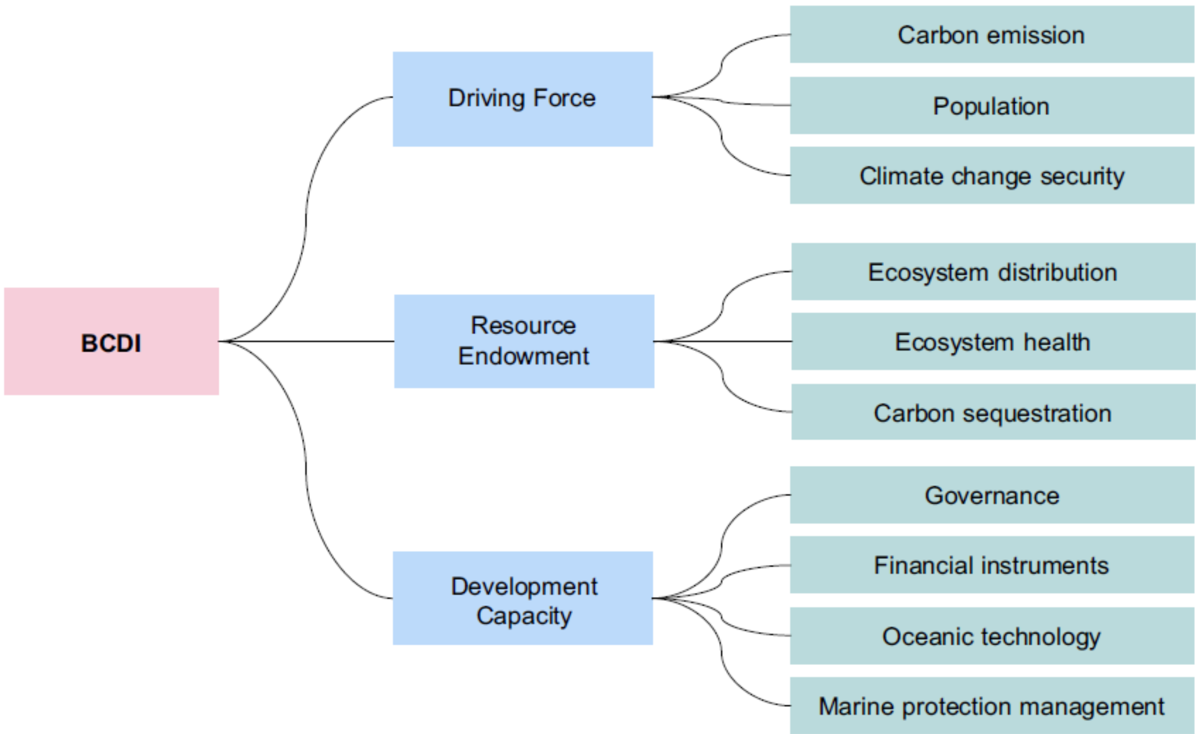

Fig. 2: The BCDI framework (after Feng *et al.,* 2023).

The annual percentage change in CO_2 emissions for 2023 is shown in Fig. 3. Although the oil and gas industry in Libya contributes significantly to carbon emissions, blue carbon ecosystems have the potential to help reduce carbon emissions and promote climate resilience. The purpose of this study is to evaluate Libya's blue carbon based on the BCDI and offer suggestions for the nation's future sustainable development.

2. METHOD

The methods can be summarized as follows:

(1) Field trips to some of the blue carbon ecosystems in Libya to determine the impact of human activity on these ecosystems.

(2) Assessment of blue carbon in Libya using the BCDI score ($I_{BC} = \sum w_k * I_k$, where I_{BC} is the BCDI score and w_k is the weight of the various subsystems. I_k and I_{BC} vary from 0 to 1, with a greater number signifying better performance. The worldwide score for each year is considered to be the average grade of all countries (Feng *et al.,* 2023)).

3. ETHIC APPROVAL

This work proposes the conservation of blue carbon ecosystems in Libya as an important step towards sustainable development in the country. Data taken from references are cited.

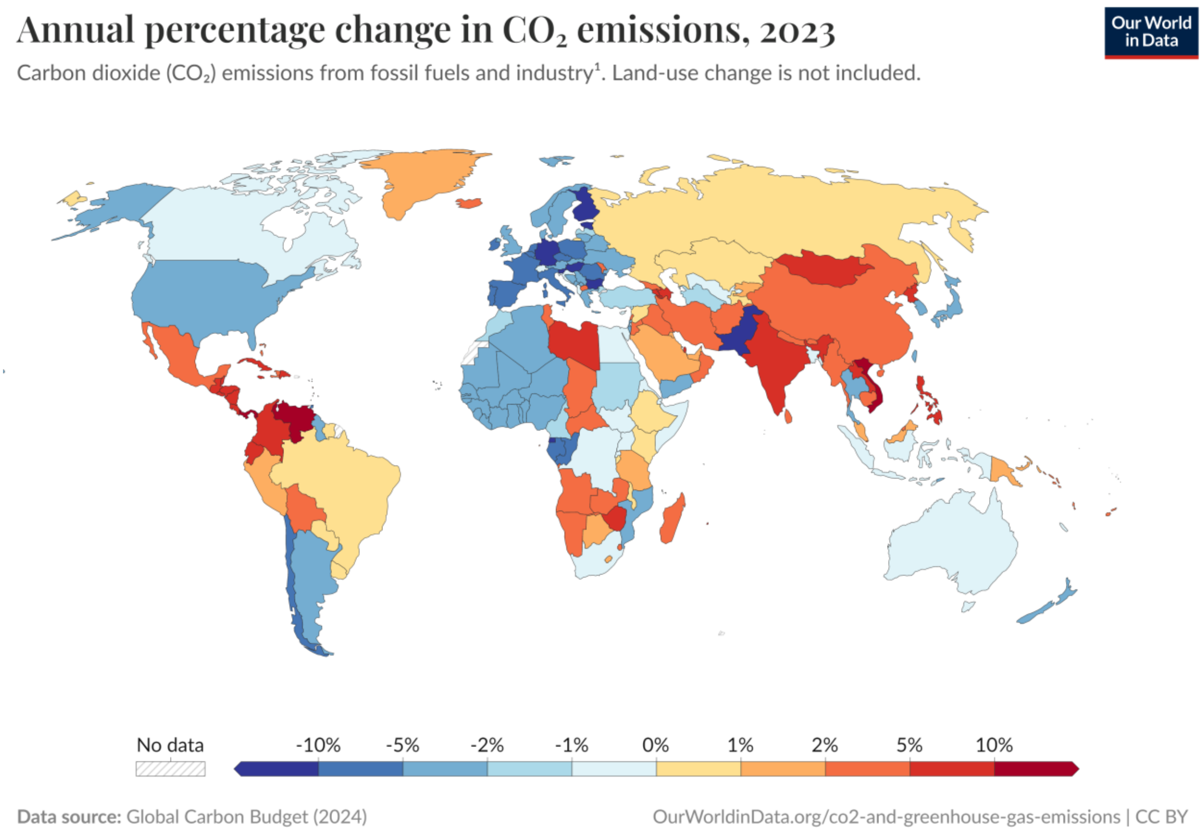

Fig. 3: Annual percentage change in CO_2 emissions for 2023 (after Ritchie and Roser, 2024).

4. Results and Discussion

The coastline of Libya is approximately 1900 kilometers long. Important blue carbon ecosystems, including salt marshes (or sabkhas, Fig. 4), and seagrasses (Fig. 5), are scattered around the coast. Numerous factors, such as pollution, habitat degradation, and unsustainable coastal expansion, pose a threat to these ecosystems (e.g., Shaltami *et al.,* 2017, 2020, 2021).


Fig. 4: Salt marsh in Al-Thamah area, Benghazi city, NE Libya.

Fig. 5: Seagrasses in Al-Sabri area, Benghazi city, NE Libya.

Tropical and subtropical climates, which are located between 25°N and 25°S, are ideal for mangrove growth. The Mediterranean coastal areas located at higher latitudes, such as Libya, are not suitable for the growth of mangroves. However, there are attempts to cultivate mangroves in some coastal areas of Libya. There are many wetlands, including salt marshes, along Libya's coastline (Fig. 6) Flat, low-lying places that flood during rainy winters and generate saline ponds and pools that drain in the summer, leaving behind a heavy layer of salt, are what define these salt marshes. Seagrasses along Libya's coast are mostly made up of three main species: *Posidonia oceanica* (e.g., Almasri and Kafu, 2021), *Cymodocea nodosa* (e.g., Pergent *et al.,* 2002) and *Halophila stipulacea* (e.g., Winters *et al.,* 2025).

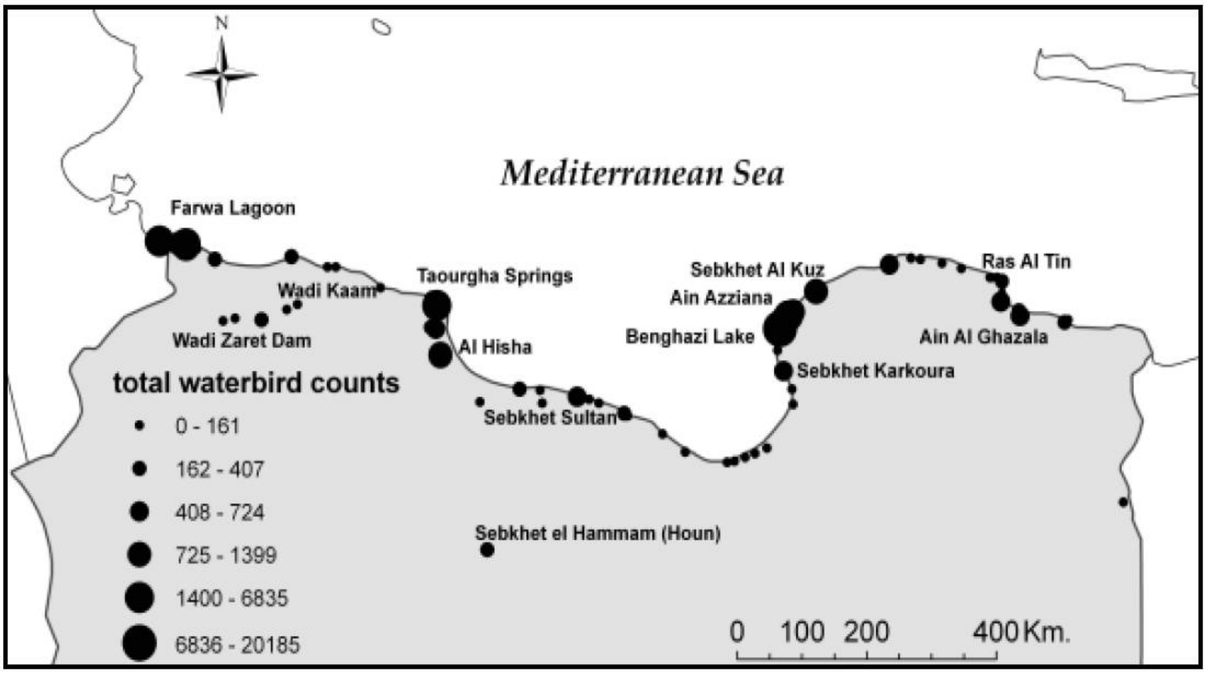

Fig. 6: Libyan wetlands that were surveyed in 2005 and 2006 (after Smart et al., 2006).

Many countries' BCDI scores have significantly improved over the past 20 years (Fig. 7). Obviously, Libya is in the green zone. The BCDI scores of Libya are consistently low. The country suffers from deficiencies in the conservation and management of blue carbon ecosystems, as well as significant climate change challenges.

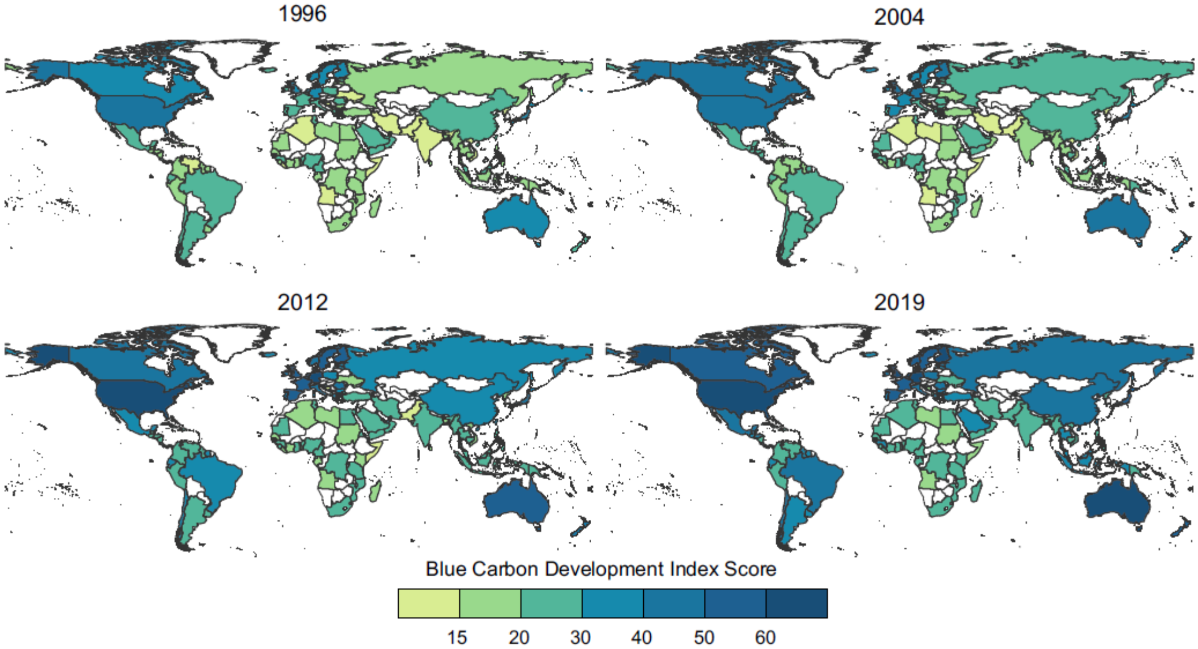

Fig. 7: BCDI score from1996 to 2019 (after Feng *et al.,* 2023).

5. Conclusion and Recommendation

In this work, the term "blue geochemistry" was first used by the authors. Blue carbon ecosystems are the subject of blue geochemistry. As a result, blue geochemistry can be thought of as a subfield of green geochemistry. Blue carbon and blue economy are related concepts that emphasize the sustainable use of marine and coastal areas. Mangroves, salt marshes, and seagrasses are examples of ecosystems that store and absorb carbon, or "blue carbon." On the other hand, sustainable development and business ventures related to the waters and coasts are included in the blue economy. The Libyan coast is dotted with salt marshes and seagrasses, but the conditions are not conducive to the natural growth of mangroves. These habitats are endangered by a range of factors, including pollution, habitat degradation, and unsustainable coastal expansion. Inadequate management and conservation of the blue carbon ecosystems in Libya, along with severe climate change issues, are the main reasons for Libya's continued low BCDI scores. The following are the authors' recommendations for promoting blue carbon: (1) In order to facilitate landscape-level carbon accounting on coastal areas, create a database of blue carbon storage, sequestration, and emission components; (2) Create pilot projects that show how blue carbon policies and initiatives can be implemented, and then develop lessons learned from these initiatives; (3) Include the benefits of blue carbon in existing and future ecosystem service models and descriptions to more accurately reflect the full spectrum of benefits provided by these ecosystems; (4) Assuming that worldwide figures are typical of a particular study region is never going to be as reliable as using site-specific data; (5) It is advised to use remote sensing methods to help with sampling design and estimate scaling in order to improve the representation of blue carbon data across regions of interest; and (6) Since modeled estimates contain numerous inputs that may have multiplicative errors, it is best practice to use quantitative analyses to evaluate the confidence in blue carbon estimates at every scale of assessment.

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