The Economic Benefit of Coastal Blue Carbon Stocks in a Moroccan Lagoon Ecosystem: a Case Study at Moulay Bousselham Lagoon

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Received: 13 October 2021 / Accepted: 14 January 2022 / Published online: 3 February 2022
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Abstract
Land degradation is a problem which affects large areas of land and the ecological services provided by coastal wetlands. Coastal ecosystems offer significant benefits for humans and the environment, including services like coastal blue carbon sequestration (CBCS), the economic value of which merits further study. The aim of this paper is to estimate the economic value of coastal blue carbon in Moulay Bousselham lagoon (MBL), Morocco, by analysing the changes in carbon storage that have taken place over 49 years in response to changes in land use and cover (LULC). To achieve this, high resolution orthophotos were used to map LULC changes and investigate the flow of cumulative LULC transformation in the MBL over the period 1971-2020. InVEST was then used to model the quantity and economic value of the CBCS service provided by coastal ecosystems. The results indicate that there were 94 types of LULC transformation over the period 1971-2020, most of them involving the conversion of wet lawn and juncus meadow into cultivated land and the extension of non-wetland areas, especially coastal dunes and built-up areas, at the expense of wetland habitats. These conversions have to some extent affected the capacity of coastal habitats to sequester and store CO2, which reached 1.47 Mt C of CBCS in 2020. In addition, the monetary value of CBCS was subject to gains of between US$ 371,053 and 3,803,295 per year, and losses of between US$ 10,127 and 103,806 per year, according to recent estimates by the European Emission Allowances (EUA) social cost of carbon (SCC) and CO2. This study reveals that revenues from CBCS service can accelerate the implementation of wetland rehabilitation strategies, which have a positive impact on climate regulation.

Keywords Ecosystem services · Global climate regulation · Blue carbon · Economic value · InVEST model · LULC changes

Introduction
Coastal ecosystems are essential for maintaining human well-being and global biodiversity. These ecosystems provide many benefits and services that contribute to regulatory functions such as erosion protection, hydrological regimes, flood risk reduction and water purification (Khomalli et al. 2020; Mouttaki et al. 2021; Saintilan et al. 2018; Sutton-Grier and Sandifer 2019). In addition to these services, coastal wetlands also contribute to climate regulation by sequestering and storing carbon captured from the atmosphere and ocean (Chmura 2013; Herr et al. 2017; Howard et al. 2014), aka coastal blue carbon.

Blue carbon is carbon stored in the biomass and sediments of tidal marshes, mangroves and seagrass beds. These coastal ecosystems sequester more carbon than terrestrial ecosystems (McLeod et al. 2011). Despite their important
role in carbon sequestration, coastal ecosystems are increasingly affected by climate change factors such as rainfall and temperature, and human activities including population growth, environmental pollution and LULC changes (Lovelock and Reef 2020; Ward 2020). The loss of coverage for these ecosystems means that the stored carbon is being released, and LULC changes and other disturbances to these systems are diminishing their potential to store more carbon in the future (Pendleton et al. 2012). In Morocco, the main estuarine wetlands have been protected by the Ramsar Convention on Wetlands of International Importance, but LULC changes are threatening the coastal ecosystems and they are becoming a source of carbon emission.

Where these wetlands are pressured by land-use, the sediments are exposed to the atmosphere or water, causing carbon stored in the sediments to bind with oxygen from the air to form CO$_2$ and other greenhouse gases (GHGs), which are released into the atmosphere and ocean (Donato et al. 2011; Fourqurean et al. 2012; Howard et al. 2014). These activities lead not only to CO$_2$ emissions, but also to losses in biodiversity and essential ecosystem services.

For this study we used the Integrated Valuation of Ecosystem Services and Tradeoffs (InVEST) model, an open-source tool available at www.naturalcapitalproject.org, to quantify the value of the CBCS service provided by coastal ecosystems by analysing changes in carbon storage over time in response to LULC changes. This model has been used in many previous studies, including an evaluation of the role of coastal habitats in providing protection (Arkema et al. 2013), predicting the amount of carbon stored and sequestered over a coastal zone (Sharp et al. 2014), assessment of the potential LUCC effects on ecosystem service provision (Clerici et al. 2019; Maanan et al. 2019), an evaluation of coastal vulnerability (Sathiya Bama et al. 2020), and estimation of the economic value of carbon sequestration and storage in coastal habitat areas (Ait Kacem et al. 2021). The present case study was conducted in the MBL in northwest Morocco and a detailed account of blue carbon over the period 1971-2020 was made, to assess the potential effects of LULC changes on the spatial and temporal dynamics of the CBCS. The InVEST model was used to analyse disturbances to coastal ecosystems caused by climate change and anthropogenic activities (Harley et al. 2006). Analysing these disturbances is important in order to prioritise strategies of mitigation and adaptation to climate change based on conservation and management of these ecosystem services. Several coastal management strategies (Duarte et al. 2013b; Karim et al. 2019; Sutton-Grier and Sandifer 2019; Wu et al. 2020) have been developed on a global scale for the conservation (restoration and protection) of coastal ecosystems, in response article 4.1(d) of the United Nations Framework Convention on Climate Change (United Nations Framework Convention 1992). Converting these strategies into policies and funding mechanisms that are still under development can be a powerful tool for effective coastal management.

The aims of this paper are therefore: (1) to compile an accurate map of the historic and current distribution of coastal ecosystems; (2) to monitor LULC changes over five decades (49 years); (3) to quantify the carbon being sequestered and stored by coastal wetlands as result of changes in LULC; (4) to estimate the monetary value of the CBCS provided by coastal ecosystems.

Materials and Methods

Study Area

Moulay Bousselham lagoon, also known as Merja Zerga, is a Ramsar wetland (Ayadi et al. 2014) located on the northern coast of Morocco at the north-western of the edge of the Gharb plain (longitude: 6°16′32″ W, latitude: 34°50′57″ N; (Fig. 1). The town of Moulay Bousselham has a population of 26,600 (RGPH. 2014). The total area of MBL is approximately 6100 ha; it contains two lagoons (merjas): Merja Kahla in the north-east, a shallow lagoon of 300 ha, and Merja Zerga in the south, a deeper lagoon of 2700 ha. The elevation of MBL varies between −6 and 20 m. The general climate is sub-humid Mediterranean with temperate winters influenced by the Atlantic Ocean. The temperature ranges between 9°C and 30°C, and precipitation between 300 and 1000 mm depending on the season. The soil in the study area is sandy and of varying texture. The soil on the Merja’s western bank is sandy, and that on the continental margins (north and east) is clay-conglomerate. The occasionally flooded areas at the site are of fine sand rich in organic matter, while the Nador canal and the Drader Wadi are bordered by alluvial soils (Bureau de la Convention de Ramsar 2004). The hydrological regime of the MBL is mainly subject to the tidal rhythm. At low neap tide, only the channels and downstream sections of the Nador canal and the Drader Wadi are submerged; at high spring tide, the entire mudflat is submerged (Qninba et al. 2006).

The wetland habitats identified at the site currently represent only 52% of the overall surface area, with a predominance of mudflat-and-sandpit, halophilic meadows, wet lawns and estuarine aquatic beds, while cultivated land, coastal dunes and shrub-and-forest occupy the non-wetland area (Olengoba Ibara et al. 2015). The main types of activity in the study area are agriculture, fishing and animal breeding.

LULC Changes and Cumulative Transformation

To prepare for the LULC mapping, three mosaics of orthophotos dated 1971, 2010 and 2020 were obtained from the...
National Agency of Land Conservation of the Cadastre and Cartography (ANCFC), with spatial resolutions of 1.5 × 1.5 m, 1.3 × 1.3 m and 0.6 × 0.6 m respectively, and comprising 10, 17 and 6 orthophotos respectively. Figure 1 shows a georeferenced mosaic of orthophotos of the MBL in 2020. Based on these mosaics of orthophotos, a detailed cartogram of the lagoon was produced each year using the ArcGIS software spatial analysis methods (Fig. 2). The LULC was classified into eleven major types (Fig. 3) and validated by field missions and previous studies (Ait Kacem et al. 2019; Olengoba Ibara et al. 2015; Qinibba et al. 2006).

Next, we used geoprocessing methods to determine LULC transformation in the MBL over two periods (1971-2010 and 2010-2020) and their cumulative conversions in the coastal wetland using LULC maps from 1971, 2010 and 2020. Finally, a chord diagram was used to facilitate visual analysis and track the LULC cumulative transformation distinctly (Fig. 2). In this study, the Power BI software was used to create transformation flows across LULC types, based on the cumulative transition matrix of LULC types. The eleven colours in the outer circle correspond to eleven LULC types. The inter-circular bands indicate the flow area converted from the initial LULC type to the final type.

### Modelling Coastal Blue Carbon Storage

#### InVEST Model

The InVEST model was used to quantify the carbon storage provided by coastal ecosystems in response to LULC changes and estimate its economic value over the last 49 years. InVEST models the carbon cycle using a bookkeeping-type approach (Houghton 2003), totalling the carbon stored in four carbon reservoirs: above-ground and below-ground biomass (AGB and BGB, respectively), litter biomass (LB) and soil organic carbon (SOC). It also models the rate of annual carbon accumulation in sediment and biomass (Liang et al. 2017). The model
involves two steps: CBC pre-processor and main CBC model (Fig. 2). The pre-processor tool creates a transition matrix which is the result of LULC changes in the periods studied. The main CBC model calculates carbon stock and sequestration based on the transition and carbon input data.
Carbon Data

The InVEST model requires biophysical data including carbon storage and accumulation rates, soil and biomass disturbance rates, and carbon decay rates. The carbon storage (Table 1; Fig. 4) and accumulation rates (Table 2) of each LULC type are defined by the Intergovernmental Panel on Climate Change’s (IPCC) database and detailed values from recent blue carbon studies. The specific data from these studies was used because they are comparable with our study area, being based on the same habitat types. The biomass and soil disturbance rates are the percentages of carbon lost as a result of LULC changes. These percentages are specific to vegetation types and are classified by three categories.
of impact: high, medium and low. In our case, we used the percentages of disturbance provided by the Natural Capital Project (Sharp et al. 2014). The carbon decay rate parameter is based on vegetation disturbance-specific to a 7.5 year carbon release rate and is based on a global literature review (Sharp et al. 2014).

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**Table 1** Carbon model input for above-ground and below-ground biomass, litter biomass and soil organic carbon by LULC types

| No | LULC types | (AGB & BGB) (Mg ha⁻¹) | LB (Mg ha⁻¹) | SOC (Mg ha⁻¹) | References |
|----|------------|------------------------|-------------|---------------|------------|
| 1  | Cultivated land (High activity) | 7.3 | 1 | 110 | IPCC |
| 2  | Cultivated land (Low activity) | 7.3 | 1 | 70 | IPCC |
| 3  | Cultivated land (Sandy soils) | 7.3 | 1 | 25 | IPCC |
| 4  | Estuarine aquatic bed | 0.62 | 0 | 87.93 | (Röhr et al. 2018) |
| 5  | Juncus meadow | 32 | 1.1 | 15.69 | (Sousa et al. 2017) |
| 6  | Mudflat | – | 0 | 143 | (Phang et al. 2015) |
| 7  | Salicornia meadow | 15.3⁽ᵃ⁾ | 1 | 97.5⁽ᵇ⁾ | (a) (Laffoley and Grimsditch 2009) (b) (Schile et al. 2017) |
| 8  | Shrub and forest | 41 | 1 | 88 | IPCC |
| 9  | Spartina meadow | 8.66 | 1 | 85 | (Curado et al. 2013) |
| 10 | Wet lawn | 13.5 | 1 | 88 | IPCC |

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**Fig. 4** Coastal blue carbon ecosystems storage graph. (1) Cultivated land (high activity), (2) cultivated land (low activity), (3) cultivated land (sandy soils), (4) estuarine aquatic bed, (5) juncus meadow, (6) mudflat, (7) salicornia meadow, (8) shrub and forest, (9) spartina meadow, (10) wet lawn.
CBC Pre-Processor Tool

The CBC pre-processor tool used the LULC input maps (1971, 2010 and 2020) and LULC lookup table to map LULC classes to their values in a raster, and to identify whether an LULC class is a coastal blue carbon habitat. It compared the LULC input maps pixel by pixel to identify the set of transitions produced between LULC classes (Table 3). The cells of the ‘Accumulation’ matrix indicated that an LULC class with carbon storage potential persisted between 1971 and 2020. The ‘Disturbance’ matrix indicated that an LULC class with carbon storage potential was changed from a vegetated LULC class to a non-vegetated LULC class. The “None” matrix indicated that the transition between LULC types did not occur on any of the LULC maps. The tool generated a carbon pool table for LULC classes, a carbon pool transition variables table, and an LULC transition effect table.

Main CBC Tool

After running the model using the above data, the main CBC tool produced an output folder containing raster carbon maps, namely the carbon stocks in 1971, 2010 and 2020, as well as carbon accumulation, emission and sequestration over the period 1971 to 2020. The net sequestration of carbon $N_{p,t}$ in year $t$ in the pool $p$, whether positive (for accumulation of carbon) or negative (for emission), equals:

$$N_{p,t} = S_{p,t} + S_{p,t-1}$$  \hspace{1cm} (1)

where $S_{p,t}$ refers to the carbon stocks in the pool $p$ for the year $t$, which is calculated by:

$$S_{p,t} = S_{pSOC,t} + S_{pAGB,t} + S_{pBGB,t} + S_{pLB,t}$$  \hspace{1cm} (2)

The carbon stock maps show the total combined stock in the four reservoirs for each year. The accumulation map shows the areas that gained carbon for the period 1971 to 2020, while the emission map shows the areas that experienced a decrease in carbon storage. The sequestration maps show the net value ($\pm$) between the accumulation and emission maps.

Economic Valuation of CBCS

For the purpose of encouraging economic decision-makers to invest more in clean energy or low-carbon technologies and less in GHG-emitting technologies, some countries have decided to give CO$_2$ emissions an economic value per tonne (I4 2019). 2020 market prices for carbon were taken into consideration in anticipation of future carbon pricing in Morocco and to estimate the current economic value of the
CBCS service provided by the MBL wetland, according to two scales: the social cost of carbon (SCC) adopted by the United States and Canada, with prices ranging from $12 to more than $123 per tonne of CO₂ (Government US 2015), and the European Emission Allowances (EUA) price for CO₂ at €25 per tonne (www.markets.businessinsider.com/commodities/CO2-european-emission-allowances 2020).

Results

LULC Changes and Cumulative Transformation Analysis

In Fig. 5 and Table 4, the mudflat-and-sandpit zone and cultivated land are identified as the largest areas of LULC habitat in the MBL in 1971-2020.

The area of wet lawn decreased by 80% between 1971 and 2020, showing a dramatic decline in the first period (1971-2010) and remaining mostly stable in the second period (2010-2020). The Salicornia meadow area decreased in 1971–2010 but increased over the subsequent period. The built-up area continuously expanded in the whole period 1971–2020.

To facilitate visual analysis of the cumulative transformation between LULC types in each period, we used a chord diagram. The eleven colours of the diagram (Fig. 5) correspond to eleven LULC types. The chords within the circle indicate how the flow area converted from the initial LULC types to the final ones. The essential transition in the first period was a change of 420 ha from wet lawn to cultivated land, followed by a change of 290 ha from Salicornia meadow to mudflat-and-sandpit. In the second period, most of the mudflat-and-sandpit transition (about 460 ha) was mainly into Salicornia meadow, estuarine aquatic bed, juncus meadow and spartina meadow. To summarise, 94 types of LULC transformation occurred in the period 1971-2020.

The extensive wetland losses were marked by the conversion of about 394 ha of wet lawn and 175 ha of juncus meadow into cultivated land.

Estimated Carbon Stocks in Different LULC

The results of this study, carried out on coastal habitats that store carbon (Table 4), show that the amount of carbon stock recorded in 1971 totalled 0.60 Mt C (Megatons of Carbon) for an area of 5535 ha. By 2010, this quantity had risen to 1.77 Mt C for a continually decreasing area.
### Table 4  LULC change area and CBCS statistics

| InVEST types             | Area (ha) | CBC stocks (Mt C) | Total CBC sequestration |
|--------------------------|-----------|-------------------|-------------------------|
|                          | 1971      | 2010              | 2020                    | 1971-2020                   |
|                          | ha        | %                 | ha                      | %                          | (Mt C) | %                           |
| Cultivated land          | 1610      | 29,08             | 1905                    | 35,99                      | 1935   | 36,79                        | 0,17 | 0,48 | 0,58 | 0,42 | 28,43 |
| Estuarine aquatic bed    | 286       | 5,17              | 256                     | 4,84                       | 262    | 4,98                        | 0,03 | 0,06 | 0,07 | 0,05 | 3,33  |
| Juncus meadow            | 587       | 10,60             | 604                     | 11,41                      | 627    | 11,92                       | 0,02 | 0,39 | 0,44 | 0,42 | 28,28 |
| Mudflat                  | 1642      | 29,66             | 1712                    | 32,34                      | 1366   | 25,97                       | 0,23 | 0,46 | 0,44 | 0,21 | 14,11 |
| Salicornia meadow        | 417       | 7,53              | 129                     | 2,44                       | 346    | 6,58                        | 0,05 | 0,11 | 0,23 | 0,19 | 12,58 |
| Shrub and forest         | 309       | 5,58              | 338                     | 6,39                       | 317    | 6,03                        | 0,04 | 0,15 | 0,15 | 0,11 | 7,77  |
| Spartina meadow          | 60        | 1,08              | 215                     | 4,06                       | 282    | 5,36                        | 0,01 | 0,10 | 0,13 | 0,12 | 8,32  |
| Wet lawn                 | 625       | 11,29             | 134                     | 2,53                       | 124    | 2,36                        | 0,06 | 0,02 | 0,02 | -0,04 | -2,81 |
| Total* (ha)              | 5536      | 100               | 5293                    | 100                        | 5259   | 100                         | 0,60 | 1,77 | 2,08 | 1,47 | 100   |
| Total (Mt C)             |           |                   |                         |                            | 0,60   | 1,77                         | 2,08 | 1,47 | 100 |

*The areas of no vegetation zones were excluded from our analysis because our aim was to assess the CBCS from vegetation’s LULC.
This increase in carbon stock is due in particular to development of the cultivated area. Despite the presence of changes in LULC, carbon continues to be sequestered naturally. In 2020, 2.07 Mt C were sequestered in an area of 5259 ha.

The results show that cultivated land had the highest amount of sequestered carbon in 2020 with 0.58 Mt C, followed by mudflat-and-sandpit with 0.44 Mt C and juncus meadow with 0.43 Mt C, while wet lawn had the lowest amount with 0.02 Mt C. This increase in carbon stock at the cultivated land level compared to other coastal habitats (Table 4) is due to the intensity of cropland use, the nature of the soil (black soils rich in organic matter) and the development of irrigation systems affecting carbon storage in the form of soil organic carbon (M. Maanan et al. 2019).

In terms of carbon emissions, the large estimated loss of −0.04 Mt C (Table 4) is due to the loss of 80% (501 ha) of wet lawn to built-up area, followed by the conversion of cultivated land, juncus meadow, Salicornia meadow and shrub-and-forest to built-up area and coastal dunes (Table 3, Fig. 5). The majority of these LULC changes occurred in the coastal dunes and the expanding built-up areas of Moulay Bousselham town and some rural villages (Fig. 3). Total carbon sequestration is estimated at 1.47 Mt C between the years 1971 and 2020, with carbon gains of 0.42 Mt C, 0.41 Mt C and 0.21 Mt C respectively for cultivated land, juncus meadow and mudflat-and-sandpit (Table 4).

**Economic Valuation of Carbon Stocks**

Of the wide range of estimates of the market price of carbon, five were used in this study for accounting the value of CBCS services in MBL coastal ecosystems (1,515,134 t of carbon over approximately 5300 ha): US$ 12, 25, 42, 62 and 123 per tonne of C (Table 4).

Table 5 shows the approximate estimated value of revenues from CBCS in the period 1971-2020 as being the equivalent gain of US$ 18,181,608 (US$371,053.22 per year) at a discounted rate of 5%, and US$ 186,361,482 (US$3,803,295.55 per year) at a discounted rate of 3% (95th percentile), both at the SCC price, and US$45,832,804 (US$935,363.34 per year) at the EUA price. The estimated economic loss from CBCS ranged from US$496,248 (US$10,127.51 per year) to US$5,086,542 (US$103,806.98 per year) at SCC prices, and US$1,250,959 (US$25,529.77 per year) at the EUA price.

**Validation of Results**

Because land use and cover change data are among the main inputs used for assessing the spatial and temporal dynamics of CBCS, this may affect the accuracy of the results obtained in this study. LULC changes were mapped using high-resolution orthophotos. In our evaluation of the correlation between the InVEST model simulated outputs and the LULC transformation in all types of habitat, we used ArcGIS software for validation. The validation results show that the CBCS simulation was correctly modelled. In the present-day MBL, CBCS is positively correlated with the LULC pixel, which continued to accumulate carbon between 1971 and 2020, and negatively correlated with the LULC pixel, which changed from a vegetated to a non-vegetated LULC class (Fig. 6).

| Carbon Cost | CBCS service loss in tonnes of C (1971-2020) | CBCS service gain in tonnes of C (1971-2020) |
|-------------|---------------------------------------------|---------------------------------------------|
|             | Economic value of total loss by (US$)       | Economic value of annual loss by (US$/y)    | Economic value of total gain by (US$) | Economic value of annual gain by (US$/y) |
| SCC prices/tCO₂ eq | 5%: US$12 | −496,248 | −10,127,51 | 18,181,608 | 371,053,22 |
|              | 3%: US$42 | −1,736,868 | −35,446,29 | 63,635,628 | 1,298,686,29 |
|              | 2.5%: US$62 | −2,563,948 | −52,325,47 | 93,938,308 | 1,917,108,33 |
|              | 3% (95th %): US$123 | −5,086,542 | −103,806,98 | 186,361,482 | 3,803,295,55 |
| CO₂ European Emission Allowances/tCO₂ eq | € 25 | −1,250,959 | −25,529,77 | 45,832,804 | 935,363,34 |

(a) SCC prices/tCO₂ eq

(b) CO₂ European Emission Allowances/tCO₂ eq

(5) Current US social cost of carbon estimates, for 2020 in $ per tonne of CO₂. The US defines four values for the SCC. These are a high-impact figure (95th percentile value for a 3% discount rate) and average values for three discount rates of 2.5%, 3% and 5% (Government US 2015). (6) The market price per tonne of carbon in European countries. (www.markets.businessinsider.com/commodities/CO₂-european-emission-allowances 2020)
In addition, the use of detailed carbon values of soil and above-ground and below-ground biomass in our research, which were derived from similar findings of previous studies (Tables 1 and 2), suggests that our CBCS estimate could be a good representation of actual CBCS in the study area.

**Discussion**

The aim of this paper is to present the methodology and results relating to economic valuation of the carbon sequestration service provided by the MBL for Morocco.
The first section of the study shows that non-wetland area, especially coastal dunes, cultivated land and built-up areas, increased over the study period (1971-2020). This is coherent with numerous LULC studies carried out in Morocco (Maanan et al. 2014; Simonneaux et al. 2015) and other global studies (Scharsich et al. 2017; Zhang et al. 2017). However, some wetland areas have declined since 1971, as demonstrated by the regression of wet lawns, natural habitats and the external margins of mudflats. This regression is also motivated by hydrological and/or anthropogenic factors. Hydrological factors include the decrease of fresh water in the MBL due to the proliferation of collection and pumping points in the Nador canal and the Drader Wadi for agricultural needs, and over-exploitation of groundwater, which gradually causes the outer margins of wetland habitats, particularly wet lawn, to transform into bare land. Anthropogenic factors include the impact of cutting down vegetation and overgrazing on wet lawns and meadows, as well as pollution of the water and sediments at the site by hydrocarbons and certain heavy metals discharged by the highway sanitation system directly into the MBL (Maanan et al. 2013).

This study also examines whether any disturbance of wetland LULC has caused a negative impact on blue carbon storage, and is consistent with previous studies of the modifications of carbon stocks by LULC changes (Clerici et al. 2019; Li et al. 2018; Xiong et al. 2014; Yim et al. 2018). The expansion of cultivated land and urban areas had a slight influence on carbon storage in our study area, as this change in LULC has mainly affected wet lawns and the edges of unused land (which store less carbon).

The reduction in potential CBCS capacity is also caused by the conversion of LULC types with greater carbon storage capacities to types with lower carbon storage capacities. However, the overuse of plant protection products in agriculture, which contributes to contamination of the water and sediments of the lagoon, has slowed down the growth of some natural vegetation that lives in fresh water, diminishing the dynamics of carbon storage, especially for juncus and spartina meadows, in the process. The continued overuse of plant protection products risks destroying a much greater quantity of these natural habitats.

The third and final section of this study reveals that the economic value of blue carbon sequestration and storage in wetlands such as MBL is very attractive. In view of their extremely important role in carbon storage and sequestration rates, blue carbon ecosystems have been included in the Nationally Determined Contributions (NDCs) for climate change mitigation (Herr et al. 2017; Lovelock and Reef 2020). Countries with wetlands, especially developing countries, can benefit from even greater revenues if other ecosystem services provided by wetlands, such as recreation and tourism, food production, genetic resources, biological control and nutrient cycling are taken into account (Badamfirooz and Mousazadeh 2019). These revenues could be used for projects dedicated to the rehabilitation and protection of wetlands, as these coastal ecosystems are increasingly at risk of degradation.

The number of marine or coastal wetlands of international importance worldwide has increased continuously since the Ramsar Convention came into effect in 1975, recording a total of 992 sites with a total area of about 75 million hectares in 2021. Morocco has also used the designation of marine protected areas as a tool to conserve marine and coastal ecosystems. There are currently 21 protected marine or coastal wetlands in the country, covering approximately 174,267 ha (https://rnis.ramsar.org/). Morocco can also increase the efficiency of conserving protected wetlands, and even increase their number, with international climate financing from developed countries to encourage developing countries to reduce their greenhouse gas (GHG) emissions. In addition, the country’s investment in wetland development projects could strengthen its position on the Climate Change Performance Index (CCPI) to meet the commitments required by the 2030 Agenda (www.unfoundation.org) for the United Nations Sustainable Development Goals (SDGs), specifically goal 13 (Climate Action) through carbon sequestration and storage, and goal 15 (Life on Land) by halting biodiversity loss and halting and reversing land degradation. In terms of scientific integrity, it is also important to note that this study has some limitations:

- It uses estimates of carbon stock and accumulation from a global database (IPCC) and published data from similar studies. Using empirical data on carbon cycle dynamics for the habitat types in the study area would certainly reduce the time required and improve the results of the study.
- It does not account for variability in carbon stock across LULC types.
- It assumes that carbon is stored and accumulated linearly over time between transitions.
- It assumes that some human activities which may degrade coastal ecosystems do not disrupt carbon in sediments.
- The temporal resolution provided, which depends on the availability of high spatial resolution orthophotos, was quite coarse, and this study therefore overlooks intermediate changes in the years fixed (1971, 2010 and 2020) by analysing changes in these years only over a 49-year period.

Our study demonstrates that even with the limited information available, simulated carbon storage could be an adequate representation of actual carbon storage in the study area. In this sense, there is a need to strengthen research in this field with additional studies.
Conclusion

This paper investigates the value of blue carbon on the Atlantic coast of Morocco, based on LULC analysis. It demonstrates the economic importance of the CBCS service and the opportunity for countries to benefit from climate change funding and reinforce their efforts in coastal ecosystem management. The major outcomes of this study are therefore: (1) the mapping of the historic and current distribution of coastal ecosystems achieved with a high resolution; (2) the monitoring of LULC changes over five decades (49 years) demonstrating a decrease of 8.83% in wetland habitat areas in the MBL since 1971, marked by the conversion of wet lawn and juncus meadow to cultivated land, and the increase of some non-wetland areas, especially coastal dunes and built-up areas, at the expense of wetland habitats; (3) despite the presence of changes in LULC, carbon continues to be sequestered naturally. Due to 1.47 Mt C of CBCS from the natural growth of coastal habitats, carbon storage reached 2.07 Mt C in 2020; (4) the monetary value of the CBCS provided by coastal ecosystems was estimated to be an equivalent gain of US$45,832,804 at the EUA price. Finally, it is useful to recall from this study that the scheduled or already-listed coastal ecosystems was estimated to be an equivalent gain of US$45,832,804 at the EUA price. Finally, it is useful to recall from this study that the scheduled or already-listed coastal ecosystems was estimated to be an equivalent gain of US$45,832,804 at the EUA price. Finally, it is useful to recall from this study that the scheduled or already-listed coastal ecosystems was estimated to be an equivalent gain of US$45,832,804 at the EUA price.

Acknowledgements The authors gratefully acknowledge the contributions of Marinus L. Otte (Editor-in-chief, Wetlands) and two anonymous reviewers for their scientific suggestions and constructive comments. The authors thank Catherine Enwright who kindly corrected and improved the English of the manuscript. We also acknowledge the support of the National Agency of Land Conservation of the Cadastre and Cartography.

Availability of Data and Material All data generated or analysed during this study are included in this published article and its supplementary information files.

Code Availability Not applicable.

Authors’ Contributions All authors contributed to the study conception. HAK, YB, MeM, YK and SE were responsible for preparation of materials, data collection and analysis. HAK, HR, MM and MeM verified the analytical methods. HAK wrote the first draft of the manuscript and all authors commented on previous versions of it. All authors discussed the results and approved the final manuscript.

Funding The authors received no financial support for the research, authorship, and/or publication of this article.

Declarations

Conflicts of Interest/Competing Interests The authors declare that they have no conflict of interest and no competing interests.

Ethics Approval Not applicable.

Consent for Publication Not applicable.

Consent for Publication Not applicable.

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