ECONOMIC VALUATION OF COASTAL BLUE CARBON STOCK'S DYNAMICS. AN STUDY IN NW SPAIN USING LAND COVER TRANSITIONS AND INVEST

David Herves-Pardavila, Maria Loureiro

Abstract: Economic valuation of ecosystem services stands as a critical element in comprehending the benefits derived from natural capital and guiding policymakers worldwide. Among these services, the regulation of CO_2 fluxes is paramount for climate adaptation and mitigation, prominently observable within Coastal Blue Carbon habitats as salt marshes. We conducted a case study of sea-level rise impacts on Galician (NW Spain) salt marshes and their carbon pools from present day to 2050. First, we compute the physical damage from flooding, using a rule-based model to identify land cover transitions. Secondly, Coastal Blue Carbon model of InVEST software is deployed to quantify impacts on carbon sequestration and apply economic valuation through the social cost of carbon. Our results indicate that the consequences of sea-level rise are limited when compared with other processes as erosion, which need to be better understood and modelled. 11 tons of CO_2 would be emitted to the atmosphere by 2050 due to sea-level rise, with damages valuated in 37 thousand €. Our approximation is useful for including the monetization of regulating services for cost-benefit analysis and coastal protection.

Keywords: Galicia, Ecosystem Services, Sea-Level Rise, Blue Carbon, Salt Marshes, Simplified Marsh Response Model, Sea Level Affecting Marshes Model, InVEST, Social Cost of Carbon, SLAMM.

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Referee List (DOI 10.36253/fup_referee_list)
FUP Best Practice in Scholarly Publishing (DOI 10.36253/fup_best_practice)

David Herves-Pardavila, Maria Loureiro, *Economic valuation of coastal blue carbon stock's dynamics. An study in NW Spain using land cover transitions and InVEST*, pp. 385-396, DOI: 10.36253/979-12-215-0556-6.35

Introduction

The absorption of greenhouse gases emissions can alleviate the impacts of climate change. According to Wilson (2012), 44 % of all emissions are sequestered in the atmosphere, 26 % in terrestrial ecosystems, and 30 % in oceans and coastal habitats. The carbon (C) absorbed in coastal areas is referred to as Blue Carbon (Minx, 2018), with approximately 70 % found in coastal vegetated zones (Nelleman, 2009) (referred to as Coastal Blue Carbon or CBC hereafter).

CBC encompasses C stored in the biomass, sediments, and litter of tidal marshes, mangroves, and seagrass beds. The sequestration capacity of these habitats is reported to be 10 (Mcleod, 2011) to 50 (Ma, 2019) times greater on a per area basis than forest and twice as effective at storing capacities (Murray, 2011). This significant disparity can be attributed to two main factors:

1) Sediment deposition, which grows vertically without saturation, absorbs C through regular tidal flooding (Fagherazzi, 2012).
2) The anaerobic nature of their soils, where the majority of C is located (Murray, 2011), substantially reduces loss to the atmosphere through oxidation.

Coastal ecosystems face vulnerability from both land use and climate change (Hopkinson, 2012; Nahlik, 2016). Recently, a substantial portion of these areas has been converted to agricultural and industrial use (Boorman, 1999). Current estimates state that 30÷40 % of tidal marshes and sea grasses (Pachauri, 2007) and 100 % of mangroves (Duke, 2007) could be lost by the end of the century. Moreover, they are particularly sensitive to natural threats such as sea-level rise (SLR) due to their low elevations. Flooding and the consequent disruption of these zones not only imply the release of C stored over the past 100 to 1000 years (Sapkota, Y., & White, J. R., 2019; Parkinson, 1994) due to mineralization to CO_2 gas (Pendleton, 2012), but also the destruction of the potential for future sequestration. Current predictions estimate an annual release between 0,15 and 1,02 billion tons of C (Pendleton, 2012). The flooding process consists of two effects: the deposition of sediments (accretion) and SLR. If the former matches the latter, marshes may increase or maintain their extension. However, the latest SLR rates suggest that this equilibrium could be reversed (Kirwan, 2013), leading to a reduction in their surface. Nevertheless, this loss could potentially be counterbalanced, to some extent, by the migration to new suitable plains if coastal squeeze is limited.

Our area of research is the San Simon Bay in the coast of Galicia, a region situated in the northwest of Spain. The Galician coast, stretching over 1500 km, primarily features salt marshes as the core CBC habitat. Our study is, therefore, confined to this type of wetland. Our objectives are twofold: firstly, to predict future physical impacts of flooding induced by rises in the mean sea-level using rule-based models as the Simplified Marsh Response Model (SMRM) (Inácio, 2022) and Sea Level Affecting Marshes Model (SLAMM) (Warren Pinacle Consulting, 2016). Secondly, changes in land use computed by those models work as inputs for the CBC model of InVEST (Natural Capital Project, 2024), that quantifies the gas regulation by simulating CO_2 absorption or emissions. Thirdly, InVEST also valuates the damage to this ecosystem service using the Social Cost of Carbon (SCC). SCC is a measure of the loses induced to society for each new ton of CO_2 emitted into the atmosphere (Environmental Protection Agency, 2023). An economic valuation is crucial as it permits the implementation of cost-benefit analysis and generating incentives for their conservation (Lovelock, 2020).

InVEST is one of the most common tools for the integrated valuation of Ecosystem Services (ES). The CBC module has been previously implemented to assess the consequences of climate change on C reservoirs. Kadaveguru *et al*. (2022) quantified mangrove ES in Odisha (India) based on plausible future scenarios, leveraging surveys and expert knowledge from stakeholders in the region. Kotagama *et al.* (2023) assesses net sequestration and the valuation of CBC ES in Sri Lanka under several SLR scenarios. de Paula Costa *et al.* (2022) and Mortitsch *et al*. (2021) analysed C sequestration and the monetary value of mangroves and tidal salt marshes in Australia, considering different management scenarios. SLAMM was implemented by Tanner *et al.* (2023) to examine the consequences of 1m of SLR in Long Island, New York, for a 1m SLR scenario. After that, the CBC model of InVEST was implemented, including a sensitivity analysis considering three different C accumulation rates. Finding the effects of SLR are not as important as the uncertainty introduced in the model by the accumulation rates. Another application of SLAMM (Richmond, 2015) under a 1 m SLR scenario and several restoration and management regimes were developed in Port Susan Bay (US). It was found that restoration efforts are essential to maintain the ability to function as C sinks.

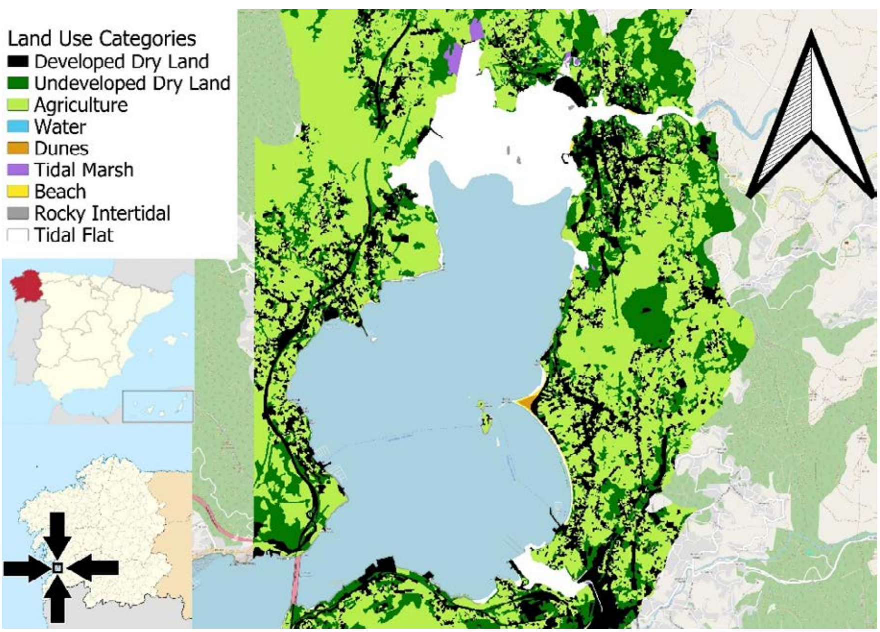

Figure 1 – Land Cover classifications of San Simon Bay. The location of this marine inlet in Galicia and the region of Galicia itself within Spain is also depicted.

Materials and Methods

SMRM, an open-source, rule-based model calculates salt marsh evolution under SLR. Developed by Inácio *et al.* (2022), it was applied in a southern Portugal case study and compared with SLAMM results. SMRM evaluates the evolution of three wetland types: tidal flat, low marsh, and high marsh. Tidal flats include land below the Mean High Water Neap (MHWN). Low marshes are between MHWN and Mean High Water (MHW), while high marshes are between MHW and Mean High Water Spring (MHWS). Terrain above MHWS is considered non-inter-tidal, classified as terrestrial land cover, and is outside SMRM's scope. Each year, SMRM accounts for sea-level rise, which lowers raster elevations and increases MHWN, MHW, and MHWS. It also factors in accretion rates increasing elevations. The interaction of these effects determines whether marsh surfaces decrease in lowland areas or increase by migrating to more suitable terrain.

SLAMM is another rule-based model requiring elevation and land cover files. If the years of these files do not match, elevations are adjusted using historical rates of global and local SLR. Elevation is the most critical parameter, as the lower elevation range of a class determines when it is inundated too frequently and thus (fractionally) converted to a different land cover. An elevation analysis tool checks if SLAMM's conceptual model fits the area of interest by comparing the assumed minimum elevation for each wetland class with the real elevations of input data. Besides flooding, we can simulate three other responses to sea-level rise: saturation of dry land (1), leading to wetland migration to adjacent uplands, accretion (2) of sediments increasing wetland elevation, and erosion (3).

Elevations were derived from a 2 m resolution digital terrain model raster provided by the Spanish National Geographical Institute (Centro Nacional de Información Geográfica - CNIG, 2024), referenced to the Spanish geographical datum. To map current salt marshes and other land uses in the area of interest, we used the 2011 cartography from the *Plan de Ordenamento do Litoral* (Dirección Xeral de Sostenibilidade e Paisaxe - Consellería de Medio Ambiente, Territorio e Infraestruturas, Xunta de Galicia, 2011), designed for urban planning and integrated assessment of the Galician coast.

Tidal data was sourced from *Puertos del Estado* (Puertos del Estado, 2023), the state-owned Spanish Port System, which manages real-time, predictive, and historical oceanographic data for several ports in Galicia. We downloaded data from the oceanographic station Vigo2 during years 1992-2012, located 13 km from the bay's centre. We computed MHWN, MHW, MHWS, mean sea-level (MSL), great diurnal tidal range (GDTR), and salt elevation (height inundated once every 30 days). SMRM uses the first three parameters, SLAMM uses GDTR and salt elevation, and both models use MSL. All measurements taken at the port of Vigo are shown in Table 1.

Table 1 – Tidal parameters. From left to right: Mean High Water Neap, Mean High Water, Mean High Water Spring, Mean Sea Level, Salt Elevation and Great Diurnal Tidal Range. All of them are expressed in meters with respect to Spain's vertical datum and obtained from Puertos del Estado (2023).

MHWN	MHW	MHWS	MSL	Salt Elev.	GDTR
0,77 ± 0,13	1,08 ± 0,04	1,33 ± 0,13	-0,1	1,9	2,45

Sea-level rise scenarios are defined by the IPCC Sixth Report (Fox-Kemper, 2021. We focus on two scenarios: SSP2-4.5 and SSP4-8.5. SSP2-4.5 deviates mildly from a 'no-additional-climate-policy' reference scenario, predicting a best-estimate warming of about 2.7ºC by the late 21st century relative to 1850-1900. SSP4-8.5 represents a high reference scenario without additional climate policy. Data is accessed via the IPCC AR6 Sea Level Projection Tool, providing projections for the nearby port of Vigo. SMRM requires inputs for SLR velocity (mm $year^{-1}$) and acceleration (mm $year^{-2}$), obtained by regressing the projections using a second-order polynomial function on a decennial time series (Table 2).

Table 2 – Sea-level Rise estimates (m) in the port of Vigo from IPCC Sixth Report (Fox-Kemper, 2021).

Scenario	2020	2030	2040	2050
SSP2-4.5	0,07	0,12	0,17	0,24
SSP5-8.5	0,07	0,12	0,19	0,26

The final set of inputs relates to marsh erosion, accretion, and saturation. Erosion is used only in SLAMM. Lacking field measurements, we used the default values of 2 m $year^{-1}$ for marshes and 0.5 m $year^{-1}$ for tidal flats. The accretion rate for marshes is used by both models and was computed by averaging results from a bibliographic review. We identified four studies measuring sedimentation using different techniques. These studies took place in the inter-tidal zone of the bay, close to the marsh ecosystems shown in purple in Figure 1 (Alvarez-Iglesias P. Q.-A., 2007; Pérez-Arlucea, 2024; Álvarez Iglesias, 2016; Alvarez-Iglesias P. &., 2009). We obtained values of 5.5 ± 1.1 mm $year^{-1}$ for tidal flats, 2.3 ± 0.9 mm $year^{-1}$ for low marshes, and 1.9 ± 0.8 mm $year^{-1}$ for high marshes. In SMRM, the definition of low and high marshes is determined by MHWN, MHW, and MHWS within the initial marsh mapping zone. In SLAMM, the user defines the type of marshes in the land cover input raster. Comparing our initial marsh elevations with SLAMM's minimum and maximum elevations for each type of marsh, we concluded that tidal marsh was the most accurate type, assigning it an accretion rate of 2.3 ± 0.9 mm $year^{-1}$.

After each model run, future marsh cover provides a preliminary estimation, which tends to be an overestimation since elevation relative to tidal heights is not the only criterion for marsh existence. To refine the actual cover computation, we incorporated the following rules: retain only newly created marsh cells that intersect with marsh cells from the previous time step (1) and assume marsh migration cannot occur towards land cover types labelled as "artificial" or "rocks."

The Coastal Blue Carbon model of InVEST® is a spatially explicit tool that calculates stocks, emissions, accumulation, net sequestration, and the net present value of CBC ES. InVEST uses a simplified representation of the C cycle and relies on various inputs. The model considers four distinct pools: above-ground biomass, below-ground biomass, soil, and litter. Following Murray (2011), which indicates that 95 to 99 % of C stocks in salt marshes are concentrated in the first three meters of soil, our analysis focuses solely on this pool, disregarding the other three.

The inputs for the CBC model of InVEST consist of a time series of raster maps containing land use and land cover information. We utilize results obtained from SMRM or SLAMM, where land polygons are rasterized and categorized into nine groups: tidal flat, marsh, beach and dune, forest, scrub, cropland, water, rocks, and artificial. Notably, the marsh category is the only relevant CBC habitat for InVEST.

To simulate the C cycle, the following parameters must be supplied to InVEST: initial stocks, accumulation rates, half-life, and the proportion of C released to the atmosphere when marshes transform into tidal flats due to ocean flooding. Since our interest lies in the future accumulation or releases rather than current stocks, all initial stocks are set to zero. This decision is motivated by the idea that stand-alone environmental values (such as current C stock) do not aid the policymaking process of choosing several socioeconomic development options (Costanza, 1997). Enhancing sequestration is considered a positive flow of ES, while a decrease is seen as a negative flow or disservice. It is the potential service and disservice that is valued here (Beaumont, 2014).

Accumulation rates pose a challenge to measure due to their site-specific nature, often varying within the same marsh at different scales. In-field measurements are preferred over literature estimates. We consulted colleagues from the Biological Oceanography group of the University of Vigo (Biological Oceanography Group, 2024), who estimated an average accumulation for the whole bay of 125 g C m^{-2} $year^{-1}$. On the contrary, the half-life of C remains constant across studies and soil types, converging to a value of 7,5 years (Kacem, 2021; Kadaverugu, 2022; Tanner, 2023). Additionally, the percentage of C released by marshes when converted to tidal flats, based on studies we reviewed (Adams, 2012; Carnero-Bravo, 2018; Howe, 2009; Macreadie, 2015), is estimated at 42 % of the stock.

Economic valuation of CBC ecosystems is conducted in InVEST by defining a Net Present Value (NPV) of future stored CO_2. For each cell i in the model:

$$NPV_i = \sum_t \frac{p_t(S_{it} - S_{it-1})}{(1+d)^t} \qquad 1$$

where t ranges from zero to the number of years of the InVEST simulation. In this case, our initial mapping of the marshes dates to 2011 and lasts until 2050, totaling 39 years. P_t is a price vector indicating the cost of an emitted ton of CO_2e, and S_{it} represents C stock in cell i at year t. The discount rate d accounts for society's preferences, assigning a higher value to benefits or losses closer in time compared to those in a long-time horizon. For our analysis, we set d to 0,025, a value consistent with other studies utilizing InVEST to assess CBC ES (Kacem, 2021; Tanner, 2023) and aligning with the proposed discount rates of the United States' Environmental Protection Agency (EPA) for evaluating the SCC (Environmental Protection Agency, 2022). The price vector was also retrieved from this last source.

Results

Our initial step involves validating the models by comparing our initial mapping of the marshes with the adjustments made by the models regarding elevations and local tide levels, which make the initial area to differ from input area. According to the *Plan de Ordenamento do Litoral*, our source of land cover, the marsh extent was reported to be 14,4 hectares. However, SMRM underestimated this extent by assuming only 7 hectares before commencing the simulation. In contrast, SLAMM adjusted marsh extent to 16,2 hectares. Based on these comparisons, we decided to proceed with SLAMM simulations exclusively.

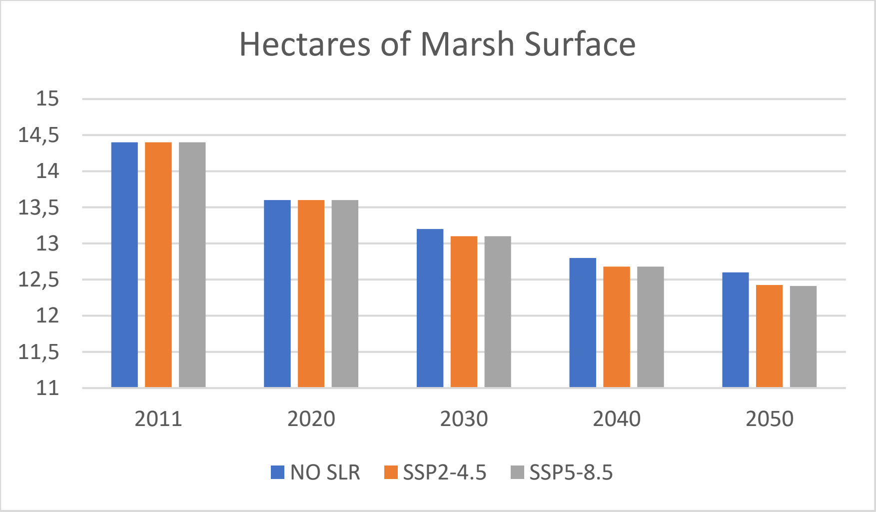

Figure 2 – SLAMM's predictions on the effects of sea-level rise on the marshes of the area of interest.

The future estimated marsh surface predicted by SLAMM is illustrated in Figure 2. Even in the baseline scenario with SLR set to zero, natural erosion is projected to decrease marsh surface. By the years 2040 and 2050, the influence become apparent, albeit limited. For instance, in the final year of the time series (2050) and in the baseline scenario, erosion has reduced the extent from 14,4 to 12,6 hectares. Under SSP2-4.5 and SSP5-8.5 scenarios, the reduction decreases further to 12,43 and 12,41 hectares, respectively.

New land use maps for the years 2020, 2030, 2040, and 2050 are rasterized and utilized as inputs for InVEST CBC. Cells where marsh has been lost and converted to tidal flats now emit a quantity of previously determined C based on its half-life. Cells with saturation of dry lands (now converted to marsh) begin absorbing carbon at a rate determined by the C accumulation rate. The results are displayed in Table 3, presenting net sequestration, emissions, and economic valuation. Overall, all three scenarios demonstrate a net sequestration of over 2300 tons by 2050. Using the SCC, this absorption equates to more than 7 million euros of benefits associated with removing this C from the earth's natural cycle, serving as a measure of the value of this ecosystem. The impact of climate change is limited to 2,4 and 2,5 emitted tons for SSP2-4.5 and SSP5-8.5, respectively, translating to 37 thousand euros in costs derived from the increase of CO_2 in the atmosphere.

Table 3 – Results of InVEST CBC model. Net Sequestration and emissions of CO_2e and Net Present Value computed using equation 1.

Scenario	Net Sequestration (10^6 kg CO_2e)	C emissions (10^6 kg CO_2e)	NPV (10^6 €)
Baseline	2378	31,3	7,157
SSP2-4.5	2368	33,7	7,119
SSP5-8.5	2367	33,8	7,118

Discussion

We compared two models for computing the impact of sea-level rise on marshes. Both models simulate the balance between flooding and natural vertical growth of marshes due to accretion (deposition of sediments). Additionally, both models utilize elevations as their main input. A key difference is that SMRM only needs to know which cells in the elevation raster are initially considered marsh ecosystems, whereas SLAMM requires a full land cover map and additional biophysical parameters. SLAMM's elevation analysis allows the user to verify if the range of elevations of the marshes aligns well with the conceptual framework of the model. In contrast, for SMRM, this verification must be done by the user themselves. We found that SLAMM only overestimates the initial cover of marshes by 12,5 %. However, SMRM underestimates it by 48,6 %. This contradicts what SMRM's developers found in a case study in Portugal (Inácio, 2022), where the area after initial adjustments remained almost the same in both models. SLAMM has been widely used for this topic, unlike SMRM, which is employed for the first time in this paper after its publication.

We have published the results for SLAMM simulations, revealing a limited effect of SLR when compared to erosion, which is present in the baseline scenario. Given that erosion is the parameter affecting the marshes the most, future improvements of our study should be guided towards collaboration with ecologists for in-field measurements of horizontal erosion. This information is valuable for local public authorities and policy frameworks such as Reducing Emissions form Deforestation and Forest Degradation (REED+) project for forest carbon offset (Herr, 2012). Blue Carbon offset programs have been worldwide applicated as well. For example, the Methodology for Tidal Wetlands and Seagrass Restoration v1.0, (Emmer, 2015) approved by Verra (Verra, 2009) (former Verified Carbon Standard (VCS)). We aim to share this and further results to the competent authorities of Galicia in the form of GIS visor, leading to the implementation of mitigation policies in our region. Besides, we hope our work encourages other researchers in the field of CBC ES to use the not-so-known SMRM in other countries and to apply InVEST on larger scales.

Moreover, forthcoming research efforts are intended to implement modern portfolio theory applied to coastal protection under sea-level rise scenarios. This approach allows us to account for uncertainty in the supply of ES (Runting, 2018).

Conclusions

Our study merges in-field local measurements with open data. This combination is necessary as marsh ecosystems and their biophysical parameters are subject to great variability and in-situ observations are a must. Sea-level rise projections, land use and elevation, which can be found in the form of open data referring to regions/countries, work well when applied to regional scales. The Sea Level Affecting Marshes Model was preferred to Simplified Marsh Response Model, revealing limited variability with respect to a baseline (no SLR) scenario until 2050. As well as a minimal difference between the climate change scenarios considered. For SSP2-4.5 and SSP5-8.5 scenarios, InVEST Coastal Blue Carbon model computed a storage of 11 tons less CO_2e than the baseline scenario due to SLR in the marshes of San Simon Bay. According to the most recent Social Cost of Carbon estimates. By 2050, CO_2 emissions would be equivalent 37 thousand € on economic damages to society.

Acknowledgements

The authors want to thank Emilio Manuel Fernández Suárez and Gonzalo Méndez Martínez from University of Vigo for their expertise and valuable support concerning the use of biophysical parameters regulating carbon capture and accretion rates in the inter-tidal ecosystems of San Simon's Bay.

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