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UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

FACULTADES DE CIENCIAS QUÍMICAS, INGENIERÍA Y MEDICINA

PROGRAMA MULTIDISCIPLINARIO DE POSGRADO EN CIENCIAS AMBIENTALES

AND

TH KÖLN - UNIVERSITY OF APPLIED SCIENCES

FACULTY SPATIAL DEVELOPMENT AND INFRASTRUCTURE SYSTEMS

INSTITUTE FOR TECHNOLOGY AND RESOURCES MANAGEMENT IN THE TROPICS AND SUBTROPICS

THESIS TO OBTAIN THE DEGREE OF

MAESTRÍA EN CIENCIAS AMBIENTALES

DEGREE AWARDED BY UNIVERSIDAD AUTÓNOMA DE SAN LUIS POTOSÍ

AND

MASTER OF SCIENCE

NATURAL RESOURCES MANAGEMENT AND DEVELOPMENT

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ASSESSMENT OF POTENTIAL BLUE CARBON RESERVOIRS IN THE GULF OF GUAYAQUIL, ECUADOR

PRESENTS:

SAID ISRAEL LIGER ALDÁS

CO-DIRECTOR OF THESIS ITT
PROF. DR. UDO NEHREN
CO-DIRECTOR OF THESIS PMPCA
DR. ÁLVARO GERARDO PALACIO APONTE
ASSESSOR
PH.D. ALBA KATHERINE CALLES PROCEL

COLOGNE, GERMANY AUGUST 2023

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COLOGNE, GERMANY AUGUST 2023

PROYECTO FINANCIADO POR:

STRENGTHENING THE CLIMATE CHANGE, ECOSYSTEMS, AND LIVELIHOOD NEXUS IN COASTAL ZONES OF ECUADOR THROUGH TRANSDISCIPLINARY RESEARCH AND INNOVATIVE TEACHING (CELICE)

DEUSTSCHER AKADEMISCHER AUSTAUSCH DIENST (DAAD)

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CON EL APOYO DE:

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LA MAESTRÍA EN CIENCIAS AMBIENTALES RECIBE APOYO A TRAVÉS DEL PROGRAMA NACIONAL DE POSGRADOS (PNPC - CONACYT)

Erklärung / *Declaración*

Name / *Nombre*: Said Israel Liger Aldás

Matrikel-Nr. / *N° de matrícula*: 11151880 **(TH Köln),** 348497 **(UASLP)**

E-Mail: said_92liger@hotmail.com

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Abstract of the Thesis

ASSESSMENT OF POTENTIAL BLUE CARBON RESERVOIRS IN THE GULF OF GUAYAQUIL, ECUADOR

SAID ISRAEL LIGER ALDÁS, 2023

Mangrove forests have been studied broadly in the recent three decades for their outstanding ability to sequester carbon in the beneath soil and other beneficial ecosystem services. Endeavors to conserve and regenerate mangrove cover are still increasing worldwide as a mechanism to include them in NDCs and carbon markets. Therefore, decision-makers in the private and public sectors require identify possible areas for conservation and restoration prior to blue carbon project investment. Thus, an integral assessment of potential mangrove carbon reservoirs in a landscape scale, considering environmental and socioeconomic factors was performed. This study was aimed to determine areas with the highest blue carbon sequestration potential in the Gulf of Guayaquil through the construction of a Blue Carbon Potential Index (BCPI) based on Spatial Multicriteria Analysis (SMCA). A narrative integrative literature review was employed to select indicators of mangrove carbon sequestration gains and losses. These indicators were pondered following the Analytical Hierarchy Process (AHP) with the judgments of two experts and reclassified in four potential categories based on their thresholds. Since no consensus was achieved in the indicator importance hierarchization, a comparative of equal weighting method and AHP weighting was implemented. The linear combination rule was used to integrate these factors into a unique-scaled index supported by a geographic Information System (GIS). The results showed that 15.82% and 16.21% of the study area belonged to high and moderate potential of blue carbon sequestration respectively. Moreover, no significant differences were found between the two weighting methods applied. The BCPI provides a comprehensive understanding of spatial distribution of blue carbon potential reservoirs and grants a quantification of this potential to prioritize conservation and restoration areas.

Keywords: Blue carbon, mangroves, spatial multicriteria analysis, blue carbon potential index, GIS.

RESUMEN DE LA TESIS

EVALUACIÓN DE RESERVORIOS POTENCIALES DE CARBONO AZUL EN EL GOLFO DE GUAYAQUIL, ECUADOR

SAID ISRAEL LIGER ALDÁS, 2023

Los manglares se han estudiado ampliamente en las tres últimas décadas por su extraordinaria capacidad para secuestrar carbono en el subsuelo y otros servicios ecosistémicos beneficiosos. Los esfuerzos por conservar y regenerar la cobertura de manglares siguen incrementando mundialmente como mecanismo para incluirlos en las NDC y los mercados de carbono. Por lo tanto, los responsables de la toma de decisiones en los sectores público y privado requieren identificar posibles áreas para la conservación y restauración previo a la inversión en proyectos de carbono azul. Por ello, se realizó una evaluación integral de potenciales reservorios de carbono en manglares a escala de paisaje, considerando factores ambientales y socioeconómicos. Este estudio tuvo como objetivo determinar las áreas con mayor potencial de secuestro de carbono azul en el Golfo de Guayaquil a través de la construcción de un Índice de Potencial de Carbono Azul (BCPI) basado en el Análisis Espacial Multicriterio (AEMC). Se empleó una revisión bibliográfica narrativa integradora para seleccionar los indicadores de las ganancias y pérdidas en el secuestro de carbono de los ecosistemas de manglar. Estos indicadores se ponderaron siguiendo el Proceso Analítico Jerárquico (PAJ) con los juicios de dos expertos y se reclasificaron en cuatro categorías potenciales basadas en sus umbrales. Dado que no se alcanzó un consenso en la jerarquización de la importancia de los indicadores, se realizó una comparativa entre el índice con ponderación igual y el índice con ponderación a través de PAJ. Se utilizó la regla de combinación lineal para integrar estos factores en un único índice escalado apoyado en un SIG. Los resultados mostraron que el 15,82% y el 16,21% del área de estudio pertenecían a un potencial alto y moderado de secuestro de carbono azul, respectivamente. Además, no se encontraron diferencias significativas entre los dos métodos de ponderación aplicados. El BCPI proporciona una comprensión y cuantificación de la distribución espacial de los reservorios potenciales de carbono azul para priorizar las áreas de conservación y restauración.

Palabras clave: carbono azul, manglares, análisis especial multicriterio, índice de potencial de carbono azul, SIG.

“- ¡Los manglares son como nosotroj mejmoj!

Sí, aunque todos ellos lo dudaran, los pobres mangles veían, oían, hablan y sentían. Cada hachazo les hacía palidecer de dolor como a cualquier hombre. Se quejaban. Protestaban. Hubieran deseado emprender una loca huida. Pero estaban maniatados a las islas. Y, además, su lenguaje no era comprendido por los mangleros.”

Don Goyo - Aguilera Malta, (1933).

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Abbreviations

AUSCM	Sustainable Use and Custody Agreements for Fragile Marine and Coastal Ecosystems (SUCAs)
AGB	Above ground biomass
BGB	Below ground biomass
CI	Clumpiness Index
CR	Consistency Ratio
CODA	Organic environmental code
DIC	Dissolved inorganic carbon
DOC	Dissolved organic carbon
POC	Particulate organic carbon
ENCC	National Climate Change Strategy
FIM	Factor Interaction Method
GHG	Greenhouse gases.
LOI	Loss-on-ignition method.
LULC	Land use and land cover
LULCC	Land use and land cover change.
NDC	National determined contributions
NDVI	Normalized difference vegetation index
NIR	Near-infrared
MAG	Ministry of Agriculture and Livestock
MAE	Ministry of the Environment
MCA	Multicriteria Analysis
MPS	Mean Patch Size
SIGTierras	The National System of Information and Management of Rural Land and Technological Infrastructure
SLR	Sea level rise
SMCA	Spatial Multicriteria Analysis
SOC	Soil organic carbon
SRTM	Shuttle Radar Topography Mission
TOC	Total organic carbon

1. INTRODUCTION

The common objective of the Paris Agreement (2015) is not to exceed a 1.5 °C increase in the global average temperature, so climate change mitigation strategies are needed to reduce CO_2 emissions. In 50 years of world conventions addressing environmental problems in search of sustainability, it has only been possible to set goals that are still far from being met, where efforts to comply with these commitments are insufficient (Sobrido Prieto, 2017).

From this arises a possible solution to reduce CO_2 concentrations in the air by capturing and storing carbon in the less dynamic pool of carbon cycle, the land which in turn has a turnover time of millions of years (Chapin, Matson and Vitousek, 2011). Different approaches have been proposed for this achievement, such as reforestation and soil carbon sequestration, where wetlands stand out (Ruseva *et al.*, 2020). Coastal wetlands, especially mangroves, are remarkable at integrating carbon storage in living biomass, decomposing biomass, and their substratum.

The role of mangrove forests in the formation of carbon sinks has been globally observed due to their greater capacity for carbon sequestration than many terrestrial ecosystems (Donato *et al.*, 2011). It is known that mangroves are capable to store globally about 4.19 million tons of CO_2 of which 70.65% is stored in the soil, 19.57% in above-ground biomass, and 9.78% in belowground biomass (Hamilton & Friess, 2018). Considering their litter yield per year, these high amounts of organic matter and underlying sediments form carbon sinks as well as natural water filters (FCEA, A.C. & GIZ, 2017).

Even so, mangrove carbon pools are highly affected by land use and land cover change (LULCC) with conversions into aquaculture ponds, agriculture fields, pastures, and logging heading the list. The former is the main cause of biomass loss whilst the second is the largest cause of carbon soil loss (Sasmito *et al.*, 2019). Moreover, mangroves are one of the most threatened ecosystems in the world because between 1982 and 2002 about 35% of its land cover was lost; which is equal to 3.8×10^{14} g C of biomass released (Cebrian, 2002; Polidoro *et al.*, 2010), without taking into account the soil organic carbon (SOC). Indeed, when these wetlands are cleared and their suboxic soil layer is removed, the CO_2 stored for hundreds or even thousands of years is released back into the ocean and eventually into the atmosphere (Mcleod et al., 2011; Alongi & Mukhopadhyay, 2015). Recent studies indicate that between 2000 and 2016, 2.1% of this type of coastal wetland was lost, of which 62% is attributable to anthropogenic activities (Goldberg et al., 2020).

Besides carbon sequestration, Ecuadorian mangroves contribute to coastal productivity, and coastal protection (Morocho *et al.*, 2022), and are considered as biodiversity hotspots (López, 2021). Ecuador's coastal wetlands were lost by LULCC, mainly due to the advent of shrimp aquaculture until 2014 (Hamilton, 2020). For example, in Guayas Estuary 16% of the mangrove forest was lost by the increase of shrimp farms in the period 1985 to 2014 (Hamilton, 2020), mainly due to the uncontrolled urban expansion of Trinitaria Island and shrimp ponds (Cedeño, 2010). The Gulf of Guayaquil is the largest estuarine system on the South Pacific coast and represents 81% of Continental Ecuador's mangroves (The Clearing-House Mechanism of the Convention on Biological Diversity, 2017). Despite this loss, a remote sensing survey performed in the Gulf of Guayaquil from 2015 to 2020 inferred an increase in this ecosystem assuming a natural regeneration and reforestation by local endeavors (Calla, 2022).

Although successful incentive programs have been implemented in Ecuador (e.g., the Socio-Manglar program), there is still a need to consolidate legal and planning instruments. For example, the National Climate Change Strategy (ENCC by its acronym in Spanish) in the mitigation line argues in its main objective is to increase the carbon sinks in strategic sectors (MAE, 2012), but the National Mitigation Plan has not been launched yet. To achieve such an ambitious objective, an a priori unbiased assessment of natural resources is required to provide a reference framework for the improvement of blue carbon management in the country.
Nonetheless, likely, local actors, national policies, and global priorities concerned about climate change provide an opportunity to replenish the mangroves cover within Ecuador's estuaries (Hamilton, 2020). This relatively recent mangrove recovery period should be accompanied by blue carbon projects to encourage the conservation and rehabilitation of such a valuable ecosystem. Therefore, some

scholars agree that coastal wetlands endeavors may consider the suitable location of the project (Primavera and Esteban, 2008), the complexity and uncertainty of socioecological systems (Schönig, 2014), the nature recovery capacity, and the needs of nearby human settlements (Zimmer, 2021).

More attention should be paid to coastal wetlands as strategic ecosystems in adaptation to climate change. In this context, the need to evaluate the feasibility of the Gulf of Guayaquil as an extraordinary carbon sink will provide a first approximation of its potential, before the precise methods of in situ assessment. Building on that, this proposal pretends to provide a tailored spatial framework in the Gulf of Guayaquil(GoG) to identify blue carbon conservation and restoration opportunities.

1.1. Justification

The interest in these fragile ecosystems lies in the possibility of counteracting and offsetting Ecuador's carbon emissions in the frame of the Paris Agreements. For example, Tanner et al. (2019) determined that the carbon soil of Galapagos mangroves represent 15% of Ecuador's annual national carbon emissions in 2016, considering 3,690 hectares of a pristine ecosystem (Moity, Delgado and Salinas-de-León, 2019). Consequently, the potential of the 121,000 hectares of mangroves in the Gulf of Guayaquil (The Clearing-House Mechanism of the Convention on Biological Diversity, 2017), should not be underestimated as a carbon reservoir despite the constant anthropic disturbance.

Having said that, decision-makers demand concise, efficient, and accurate information to ensure the best investment of resources for blue carbon projects. In that sense, mapping, and modeling of blue carbon ecosystem services have been proven as a powerful tool to enhance authorities' management and achieve sustainable solutions for ecosystems; like prioritizing restoration, conservation areas, and adaptive actions to climate change for NDC (Maes *et al.*, 2012; Wedding *et al.*, 2021).

Therefore, specific studies are needed to assess the potential of mangroves as carbon reservoirs and develop a tailored methodology for identifying possible areas for intervention in a portion of the most productive bioregion in terms of carbon sequestration in Ecuador, the GoG. It is intended to provide a detailed spatial framework methodology for identifying blue carbon conservation and restoration opportunities, considering biophysical and socioeconomic indicators previous to in situ assessments.

1.2. Objectives

1.2.1. Main Objective

To determine areas with the best carbon sequestration potential in the Gulf of Guayaquil through Spatial Multicriteria Analysis (SMCA).

1.2.2. Specific Objectives

- To classify the study area through a set of biophysical and socioeconomic indicators depicting carbon sequestration potential.

- To determine the blue carbon potential index by weighting biophysical and socioeconomic indicators through spatial analysis of the coastal landscape using a Geographic Information System.

- To identify high-potential areas for blue carbon sequestration in the Gulf of Guayaquil.

2. REFERENTIAL FRAMEWORK

2.1. The Carbon Cycle

According to Chapin et al. (2011), the main carbon pools involved in the carbon cycle are the atmosphere, the soils, the plant biomass, the ocean, and superficial sediments. The smallest but most dynamic carbon pool is atmospheric carbon dioxide (CO_2). This gas has a mean residence time of five years in the atmosphere and its mobility is mainly caused by the photosynthetic activity and the respiration process (Chapin, Matson and Vitousek, 2011). Thus, these biotic processes constitute the engine that drives the carbon global cycle in the different temporal scales, from seconds to millennia (Ciais *et al.*, 2014). From the perspective of the biogeochemical cycle budget, the carbon loss of the soil by respiration is slightly less than the carbon sequestration by the vegetation (CO_2 deposition and nitrogen contained in the fertilization). The land carbon is eroded and transported through the rivers, where half is released into the atmosphere, a fraction is buried in freshwater sediments, and the rest ends in the oceans as dissolved inorganic carbon (DIC), dissolved organic carbon (DOC), and particulate organic carbon (POC) (Tranvik *et al.*, 2009). Likewise, the net carbon brought back to the atmosphere from the ocean is less than the input of carbon to this coarse pool. Marine primary production is approximately the same as in the lithosphere. Around 80% of carbon from marine primary production is released to the atmosphere by respiration and the rest is transported to the deep ocean in form the of feces, dead organisms, and sediments(Chapin, Matson and Vitousek, 2011). Most of this carbon is translated to ocean surface water by ocean upwelling and poor amounts are deposited in sediments. These terrestrial and oceanic carbon pools are equivalent to less of the half carbon released into the atmosphere (Gallardo and Merino, 2007).

In contrast, anthropogenic activities cause a net carbon flux to the atmosphere through the burning of fossil fuels, cement production, and land use change which account the 80% of the radiative forcing by the main three GHG (CO_2, CH_4, and N_2O) (Ciais *et al.*, 2014). This flux is equivalent to 14% of heterotrophic soil respiration and 15% of the carbon cycle by terrestrial or marine productivity, making it the third largest controlled biological flux of carbon to the atmosphere (Chapin, Matson and Vitousek, 2011). Therefore, the increase in atmospheric carbon dioxide since the Anthropocene (Late 18th century) has produced alterations in the carbon cycle (Raupach and Canadell, 2010), that in turn have caused the increase in the average temperature of the planet (Canadell *et al.*, 2021). Thus, different ways to store carbon in more stable pools have been proposed, and one of them is carbon sequestration by ecosystems which has proven to be effective in decreasing CO_2 emissions (Fang *et al.*, 2014; Gattuso *et al.*, 2018).

2.2. Mangrove's Blue Carbon Sequestration

On average, mangroves are highly productive intertidal forests with the strategic characteristics of maximizing carbon assimilation, maintaining water and nutrient efficiency, and minimizing transpiration. These physiological mechanisms increase the rate of CO_2 uptake and respiration, despite living in saltwater-saturated soils (Alongi and Mukhopadhyay, 2015). In other words, the input of organic carbon from primary productivity and adjacent marine and riparian ecosystems exceeds the losses of carbon through respiration, decomposition, and export by tidal flow, which makes these ecosystems store surplus organic carbon in their soils successfully for millennia if they are not disturbed (Mcleod *et al.*, 2011; Santos-Andrade *et al.*, 2021).

In addition, they also have an advantage in the exchange of solutes and organic and inorganic particles contained in the ocean, unlike terrestrial forests. This process generally contributes to sediment formation and carbon accumulation in its four distinctive reservoirs: living aboveground biomass, living belowground biomass (root system), decomposing dead biomass (dead roots, litter, and allochthonous organic matter), and the underlying soil (Alongi, 2012). However, viewed on a short time scale, while a portion of mangrove biomass is buried, the majority is eventually removed, destroyed, or exported by tidal action (Alongi and Mukhopadhyay, 2015). Alongi (2020) estimated the amount of carbon fluxes and pools of mangrove forests of the world in Tg C per year as illustrated in Figure 1. In this carbon budget, the greatest carbon pool is the soil, whilst the major negative carbon flux after the canopy respiration is carbon mineralization that in turn supplies the oceans in the form of DIC and DOC.

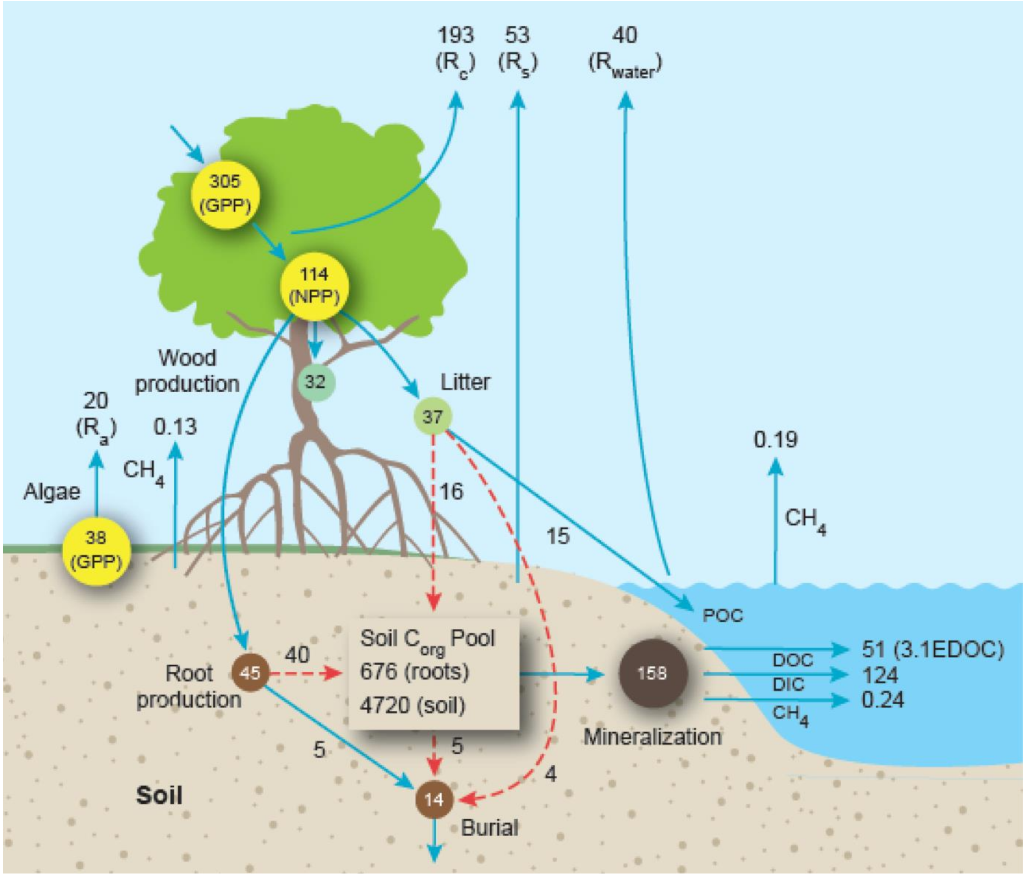

Figure 1. Carbon mass balance in Mangrove Forests (Tg C yr^{-1}). GPP = gross primary production; NPP = net primary production; Ra = algal respiration; R_C = canopy respiration; R_S = soil respiration at soil surface; R_{WATER} = waterway respiration; POC = particulate organic matter; DIC = dissolved inorganic carbon; DOC = dissolved organic carbon; EDOC = exchangeable dissolved organic carbon. Source: (Alongi, 2020).

The accumulation of carbon in the soil is arranged in layers of peat, which in turn depends on litter production, roots, branch fall, rate of decomposition of recalcitrant material, tidal frequency, and magnitude, the activity of micro and macro organisms (algae and benthos), mangrove composition, humidity, and temperature (Andreetta *et al.*, 2014; Alongi, 2018). Anaerobic conditions in mangrove soils facilitate an enzymatic blocking mechanism of phenol oxidases that allows the accumulation of phenolic compounds that in turn inhibit the decomposition of organic matter, spawning the formation of peat in mangrove soils (Saraswati *et al.*, 2016).

2.3. The Blue Carbon in Ecuador

In continental Ecuador, blue carbon ecosystems are reduced to mangrove forests, which a current area of 146,165.74 hectares (MAG, 2020). These wetlands are abundant along the coastline, particularly in the Gulf of Guayaquil and Esmeraldas province. Despite their importance, blue carbon ecosystems in Ecuador face a range of threats, including deforestation, degradation, and pollution. Over the past few decades, significant areas of mangroves have been destroyed due to shrimp farming, agricultural encroachment, and coastal cities development among other human activities (IUCN and CI Ecuador, 2016).

In an attempt to tackle these threats, several initiatives have been implemented in favor of mangroves. In this aspect is remarkable the general objective of the mitigation line of the ENCC states "…to increase carbon sink in strategic sectors.". Moreover, this strategy provides mainstream insights for the National Mitigation Plan (PLANMICC by its acronym in Spanish) to reduce GHG and for the sequestration and storage of carbon (MAE, 2012). At the time of writing, this plan had not been issued but is foreseen for specific blue carbon projects based on the first Ecuadorian NDC. Rather in the more recent National Biodiversity Strategy, mangroves are given due importance, with the intention to create partnerships of co-responsibility among the state and communities, and an included goal to restore 500 million hectares of forests and increase the protected cover by 1.8 million hectares by 2017 (MAE, 2016).

One of the most important initiatives is the National Action Plan for the Conservation of Mangroves of Continental Ecuador (PAN-Manglares Ecuador). It seeks to strengthen policies and programs for protection, recovery, and sustainable use of mangroves in Ecuador through workshops and dialogue in the coastal provinces. Moreover, it contributes to the improvement of the quality of life of the ancestral and traditional users who depend directly on the natural resources of this ecosystem" (Carvajal and Santillán, 2019).

Among the efforts for the conservation of these wetland ecosystems, the need for management plans for Sustainable Use and Custody Agreements for Fragile Marine and Coastal Ecosystems (AUSCM by its acronym in Spanish) was established within the regulation of the organic environmental code (CODA by its acronym in Spanish) regulations (Presidencia de la República del Ecuador, 2019). As the name indicates, these are environmental management instruments to define a sustainable use of the ecosystems that seek the custody and protection of the ecosystems by their direct beneficiaries. It is known that, as of August 2019, about 237 mangrove reforestation plans have been approved (Sánchez, 2019), which are linked to the Management Plans for AUSCMs as a concession regulated by the national environmental authority (MAE). This kind of conservation status comprises 68,161.60 hectares of mangrove with 52 recognized civil associations (Carvajal and Santillán, 2019).

In addition, the Socio Manglar Program provides financial incentives to landowners and communities who commit to conserving their mangrove forest, meanwhile, they can harness the fishery resources of the area with a previous AUSCM signed. Specifically, the incentive offered is an annual monetary nature, ranging from USD 7,000 to 15,000 per year, depending on the hectares of mangrove under custody and conditional on compliance with the management plan (MAE, 2017).

The National Blue Carbon Policy Assessment in Ecuador (IUCN and CI Ecuador, 2016) highlights several gaps and opportunities to enhance the blue carbon policy in the country. Simplifying the process of accessing Socio Manglar, extending its effective period, and including a mechanism for reforesting abandoned and illegal shrimp ponds may help to increase the conservation and restoration of these coastal wetlands. Adding a carbon component to the program as a complementary tool for mitigation assessment and leveraging international funding is also needed. The establishment of a REDD+ framework in Ecuador adds uncertainty regarding project-based crediting in the future, and it is crucial that the government completes its REDD+ mechanism on the ground as soon as possible. Finally, the article highlights the need for a cross-cutting approach to managing mangroves and fostering a more synergistic implementation of various international agreements.

2.4. Spatial Analysis and Models in GIS

Spatial analysis consists of a set of techniques and models that explicitly addresses spatial patterns and the processes involved (Berry & Marble, 1968 as cited in Malczewski & Rinner, 2015; Turner & Gardner, 2015). Models viewed from the perspective of decision analysis are distinguished between statistical models and mathematical models; both are considered for spatial analysis. There are two main axes in mathematical modeling within Geographic Information Systems (GIS);

simulation, which is a method to perform experiments based on models of real-world spatial systems (Langlois, 2013 as cited in Malczewski & Rinner, 2015); and optimization, which aims to find the best solution to established spatial decision or management problems (Faiz and Krichen, 2012). The difference between the two lies in their starting point, since simulation starts from an action that affects the entire system, while optimization starts from the establishment of system objectives and specifies the actions that satisfy those objectives (Malczewski and Rinner, 2015).

In turn, these modeling axes are broken down into four distinct approaches for addressing decision problems: normative, descriptive, prescriptive, and constructive. Normative models are based on rationality as a guide for decision-making and provide a formal representation of the spatial system that determines an optimal course of action. On the other hand, descriptive models aim to describe and explain the actual decision-making behavior of agents. In contrast, prescriptive models seek improvement in the decision-making process by combining the theoretical foundation of the normative approach with the empirical findings of descriptive theory. Prescriptive models focus on the internal knowledge of the decision-making process rather than on the underlying axioms of normative modeling (Malczewski, 2011). This knowledge comes from understanding why a particular solution is recommended over another (Jankowski and Stasik, 1997), and therefore spatial prescriptive decision models can be supported by combining the use of GIS with Multi-Criteria Analysis (MCA). Even MCA models can be considered normative, descriptive, prescriptive, or constructive depending on the manner how employed to address the decision problem (Malczewski and Rinner, 2015).

2.5. Spatial Multicriteria Analysis & GIS

Multicriteria Analysis (MCA) is a method for decision-making based on explicitly formulated criteria through the systematic exploration of the advantages and disadvantages of different alternatives; unveiling their dependency relationship (Geneletti, 2019). MCA provides a methodology to steer decision-makers through a process of clarifying evaluation criteria and defining values that are relevant to the decision situation (Malczewski and Rinner, 2015).

The main stages of MCA processes are problem structuring and decision context, analysis, and the decision (Geneletti, 2019). The first stage includes the definition of the objectives of the decision process, the identification of possible alternatives to achieve them, and the explicit formulation of criteria to evaluate how each alternative contributes to achieving those objectives. The analysis stage consists of the evaluation of the criteria, their weighting, and their sensitivity analysis (Munda, 2012). In summary, criteria evaluation consists of quantifying the performance of each criterion against each of the previously defined alternative criteria. Weighting refers to the quantified preferences among the possible outcomes for the criteria from the perspective of decision-makers and/or stakeholders. Aggregation of the criteria involves the application of a decision rule that combines the output of the criteria evaluation and their weighting to assess the performance of each alternative. Finally, sensitivity analysis explores the relationships between the output and the inputs of the process; and tests the robustness of the results considering the uncertainty factors related to the previous steps (Delgado and Sendra, 2004).

Remarkably, the weighting process requires consultation with stakeholders involved in the decision process. The select group provides judgments and perceptions about the levels of importance of the criteria in question, which are then converted into weights through various techniques. Among the most common methods are Delphi surveys, the exchange method, the swing method, the hierarchical analytical process, the random method, extreme weights, and expected value (Geneletti & Ferretti, 2015; as cited in Geneletti, 2019)

GIS techniques and procedures play an important role in MCA because they offer unique functions for the storage, management, analysis, and visualization of geospatial data (Malczewski and Rinner, 2015). The integration of GIS and MCA constitutes a powerful analysis tool since it offers the possibility to intervene in complex spatial analysis processes such as the allocation and location of activities, keeping in mind various criteria and multiple objectives. Thus, it allows determining the optimal location of some environmental phenomenon through the selection of spatial alternatives in a short time (Borderías and Cañas, 2014).

The criteria used in the process can be factors; which represent in their arrangement of cells digital values corresponding to the evaluated phenomenon on a homogeneous scale (relief, temperature, nutrients, etc.); and limiting criteria; which reflect the surface of the territory limited to the establishment of an activity considered through Boolean images (distribution of mangroves, flood zones, conservation areas, etc.). Borderías & Cañas (2014), propose the following steps for the multi-criteria spatial evaluation from the approach of spatial analysis procedures supported in GIS:

Each of the representative variables of a criterion is arranged in tessellations or square spatial grids or raster format. Most of the time, these layers come from remote sensing processes.

- The reclassification and normalization of the layers involves the preparation of the analysis criteria for their subsequent integration, according to a uniform scale of established categories.

- The integration of the different layers is performed by algebraic calculation and logical and/or mathematical superposition of the different layers of information (multiplication by a scalar, addition, subtraction, etc.).

- The values of the resulting layer can be reclassified to obtain a final thematic map of the evaluation of the territorial suitability in the establishment of the considered activity.

3. STUDY AREA: Gulf of Guayaquil

3.1. Background studies

Global estimations of Mangrove Forest's pools at a global scale were first studied by Donato et al., (2011). He inferred the overall Indo-Pacific mangroves carbon storage accounting for AGB, BGB, dead biomass, and carbon in the soil, resulting in 1,023 Mg C ha^{-1} ± 88 s.e.m. This author also claimed that the AGB pool in that region is 159 Mg C ha^{-1} on average and regarding soil carbon content it oscillates from 49% to 98% of the total Mangrove carbon storage. This understanding is supported by Alongi & Mukhopadhyay (2015), highlighting that mangroves are the most productive coastal ecosystems storing about 956 Mg C ha^{-1}.

Jardine y Siikamäki (2014) determined the global mangrove carbon reservoir in the soil is about 5.00 ± 0,94 Pg and 80,5% of this carbon is allocated in twenty different countries. Nevertheless, Ouyang & Lee (2020) claimed that this carbon pool is 1.93 Pg and that the overall carbon stock in mangrove forests is 3.7-6.2 Pg, given their statistical assessment over the conversion factor, which is used to estimate organic carbon by the loss-on-ignition method (LOI) is over-estimated.

Likewise, Hamilton & Friess (2018) have established that mangroves have the capacity to globally sequester approximately 4.19 million tons of CO_2. Out of this total, around 70.65% is stored in the soil, 19.57% is stored in AGB, and 9.78% is stored in BGB. However, a more recent study by Kauffman et al. (2020) estimated globally the total ecosystem carbon stock is about 11.7 Pg C where 86.32% corresponds to belowground carbon stock. This difference in global carbon stock could be rooted in the soil depth measured or the method employed, where the most broadly used protocol to measure, monitor, and report was established by Kauffman & Donato (2012)

Twilley et al. (2018) have provided valuable insight into the carbon dynamics by stating how coastal morphology explains the variability of carbon sequestration by these wetlands at different global landscapes, specifically measuring SOC. This parameter significantly ranged from 14.9 mg cm^{-3} in river-dominated soils, 53.9 mg cm^{-3} in carbonate environmental settings, to 60.1 mg cm^{-3} in arheic settings.

A comparison of valuation models in continental Ecuadorian mangroves was conducted to assess the carbon sequestration service under three different future scenarios to 2032. The results indicate that 154,24 ha of mangrove can sequestrate over 23 Mt over 20 years, under the assumption that the mangrove area will not decrease, and with a full recovery of the mangrove area in reach 34 Mt (Burgess, Qin and Li, 2015). The unique carbon stock sampling research in the GoG was conducted by Merecí-Guamán et al. (2021). The authors concluded a TOC of 320.9 ± 20.8 Mg ha−1 to 1 m soil depth and 452.8 ± 28.3 Mg ha−1 to 2 m soil depth for medium-statured mangroves and 419.4 ± 55 and 537.6 ± 72.3 Mg C ha−1 for the same respective soil depths.

Regarding previous studies involving the use of SMCA for mangroves, it is worth mentioning that in Vietnam it was employed to identify suitable zones for mangrove breeding and shrimp farming (Nguyen *et al.*, 2022). In Indonesian mangroves, AHP was utilized as a decision-making methodology to assign ecological intervention approach for different zones in combination with NDVI diagnosis (Singgalen and Manongga, 2022). Another interesting research addressed the impact of microplastics in mangrove forests.

3.2. General Description

The Gulf of Guayaquil is part of the exoreic basin of the Guayas River, fed by freshwater from 20 rivers, including the Daule and Babahoyo rivers, and is located on a 200 km platform on the 81°W meridian and 120 km (Figure 2) including Puná Island (Pesantes, 1983). It is positioned as the largest estuarine system on the Pacific coast of South America and is subdivided into three sub-estuaries with diffuse boundaries: the Guayas estuary, mainly influenced by the Guayas River; the long western Salado estuary, which lacks local freshwater sources, and receives most of the wastewater from the city of Guayaquil; and the eastern Churute estuary, with the Churute and Taura Rivers as freshwater sources (Twilley et al., 2001).

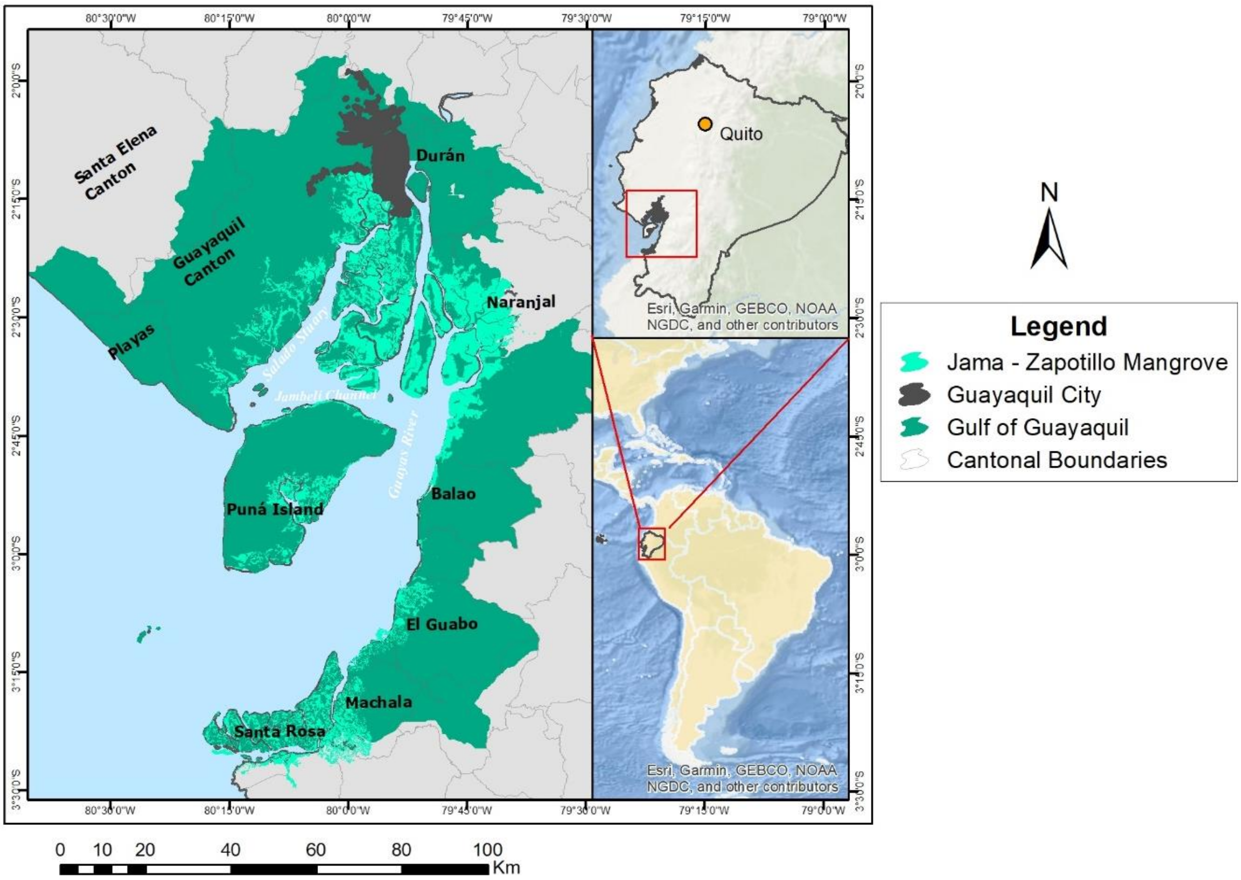

Figure 2. The Gulf of Guayaquil.
Source: National Information System (2014). Own elaboration

The depth of the waters of Guayas estuary is known to be approximately 183 m, and it gradually loses depth until it reaches 18 m; contrary to the Morro Channel (north of Puná Island) and Jambelí Channel (south of Puná Island) whose sea bottoms reach 56 m and 22 m, respectively (Stevenson, 1981).

Two defined functional seasons occur in the Gulf of Guayaquil. The warm rainy season (January to May), with more than 95% of the annual precipitation; and a cooler drier season (June to December) with less than 2% of the annual precipitation (Figure 3). In the rainy season, the region is influenced by the tropical Panama Current; while in the dry season it is influenced by a subtropical saline current from Peru (Cucalón, 1989; as cited in Schönig, 2014). With mean annual temperatures varying between 24°C to 27°C, the potential annual evaporation rate is 1300 mm (Twilley *et al.*, 2001).

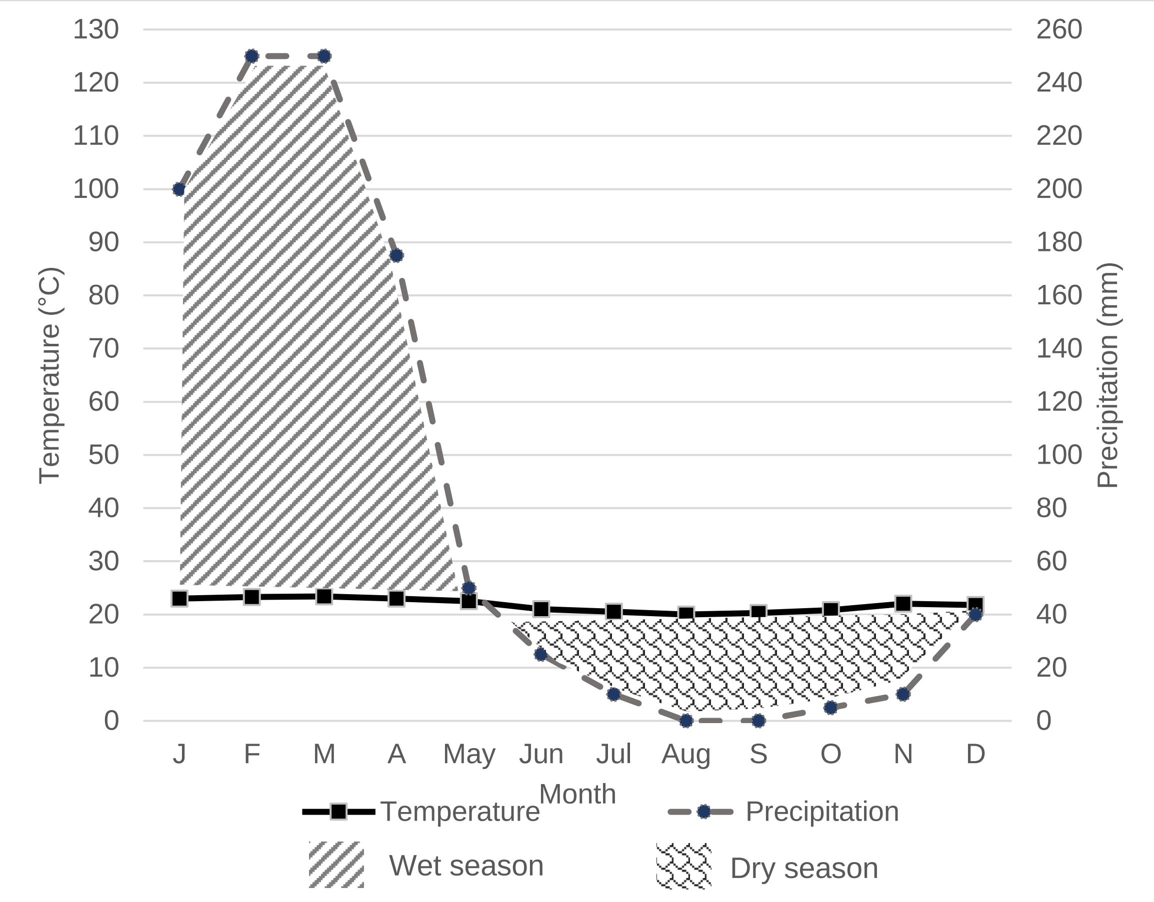

Figure 3. Climograph of Guayaquil INOCAR station (1948 -2008). Source: INOCAR, (2008).

The Gulf of Guayaquil harbors various ecosystems, with the mangrove forests being the most abundant, closely followed by the lowland deciduous forest. According to Solis (1961), the botanical association of the mangroves is of the consocieta type, which means that 98 to 100% of its elements correspond to the dominant genus *Rhizophora*, which are associated with other species of mangroves, which in turn are systematically of different gender and family. In this regard, Twilley et al. (2001) argue that *Rhizophora harisonii* is considered the most abundant in the gulf, followed by *Rhizophora racemose*. Furthermore, *Avicennia germinans, Laguncularia racemose, and Conocarpus erectus* are also present in smaller quantities in sites of less floodable intertidal zones (Twilley et al., 2001) and disturbed sites (Schönig, 2014).

Mangrove forests are one of the most productive ecosystems, which provide commodities and services for humans (Carugati *et al.*, 2018) on local, urban, and regional scales (Kovacs, 1999; Lee *et al.*, 2014). Firstly, they are useful as spawning and nursery grounds for marine species, thus they are related to industrial and artisanal fisheries. Therefore, among their provisioning services, livelihood and food supply for local communities (crabs, shells, mussels, oysters, etc.), timber and non-timber forest resources, and great diversity of biological resources are included (Poveda and Avilés, 2018). In addition, their regulation services also embrace hazard mitigation as a barrier against storm surges and hurricanes, depleting the impact of erosion on coastal lines (Barbier, Acreman and Knowler, 1997).

For all forest types, including mangroves, biomass calculation is used to infer living carbon storage. Mangrove biomass among all species is proportional to solar energy at each mangrove location; therefore, latitude can be used to explain most of the variability of biomass in mangrove forests in different zones. This explains why the tallest *Rhizophora* trees in the world are found crossing the equator within northern Ecuador (Hamilton and Lovette, 2015). Indeed, red mangrove (*Rhizophora spp*.) trees up to 50 m have been recorded on Puná Island, that are currently no longer reported in the equatorial Pacific (Eggers, 1892; as cited in MAE et al., 2014).

Hamilton & Friess (2018) estimated that Ecuador's mangrove forests contain 55,566,461 tons of carbon or 1.33% of the global mangrove carbon stock in 2012; a percentage that the same author discusses its underestimation, due to the dominance at the national level of *Rhizophora mangle* which has the highest aerial biomass. In addition, taking into account that for the evaluation of carbon sequestration, 69% of the biomass of mangrove forests comes from the soil, it is inferred that Ecuador would occupy the sixth place of the largest mangrove carbon sinks in the world with the most current data (Hamilton, 2020).

In this regard, the project “Strengthening the Climate Change, ecosystems, and livelihood nexus in coastal zones of Ecuador through transdisciplinary research and innovative teaching” (CELICE) aims to encourage transdisciplinary research on the matter of sustainable socio-ecological development in the Gulf of Guayaquil. Specifically, CELICE aims the intensification of transdisciplinary research and the promotion of students and young scientist to contribute to solutions of problems in the GoG (Objectives of CELICE project a and c). Therein, the present research is framed within the CELICE project, specifically in the central Guayas Estuary and Salado Estuary, in the central northern region of the Gulf of Guayaquil (Figure 4).

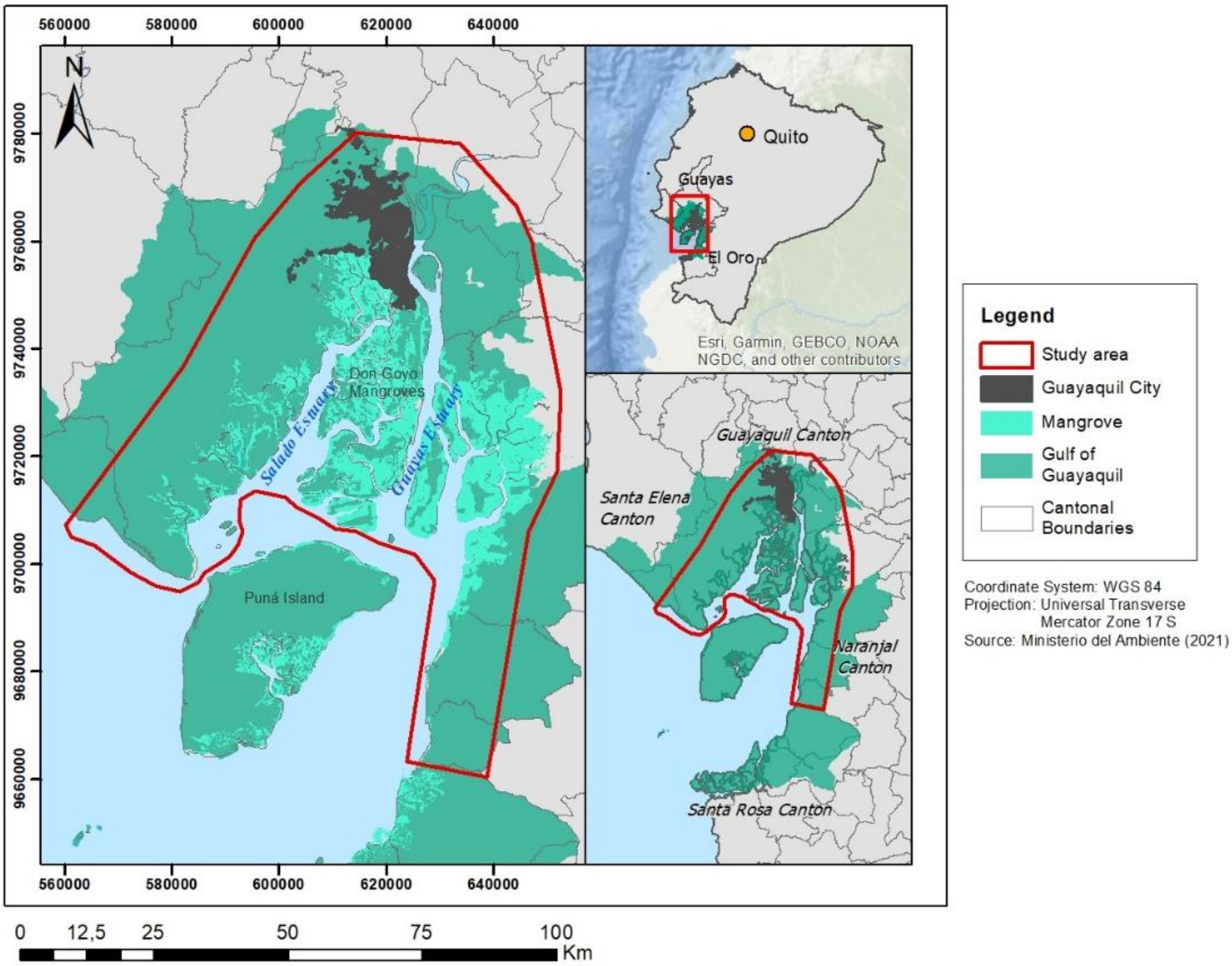

Figure 4. Study Area.
Source: National Information System (2014). Own Elaboration.

4. METHODOLOGY

The assessment of blue carbon reservoirs in the Gulf of Guayaquil follows the spatial assessment framework of Rogers et al. (2019), although it incorporates tailored indicators to the study area and the weighting of these indicators, attempting to reduce the subjectivity of their contribution. The present quantitative research based on an exploratory case study aims to follow Multicriteria Analysis (MCA) combined with Geographic Information Systems, to achieve the proposed objectives as shown in Figure 5.

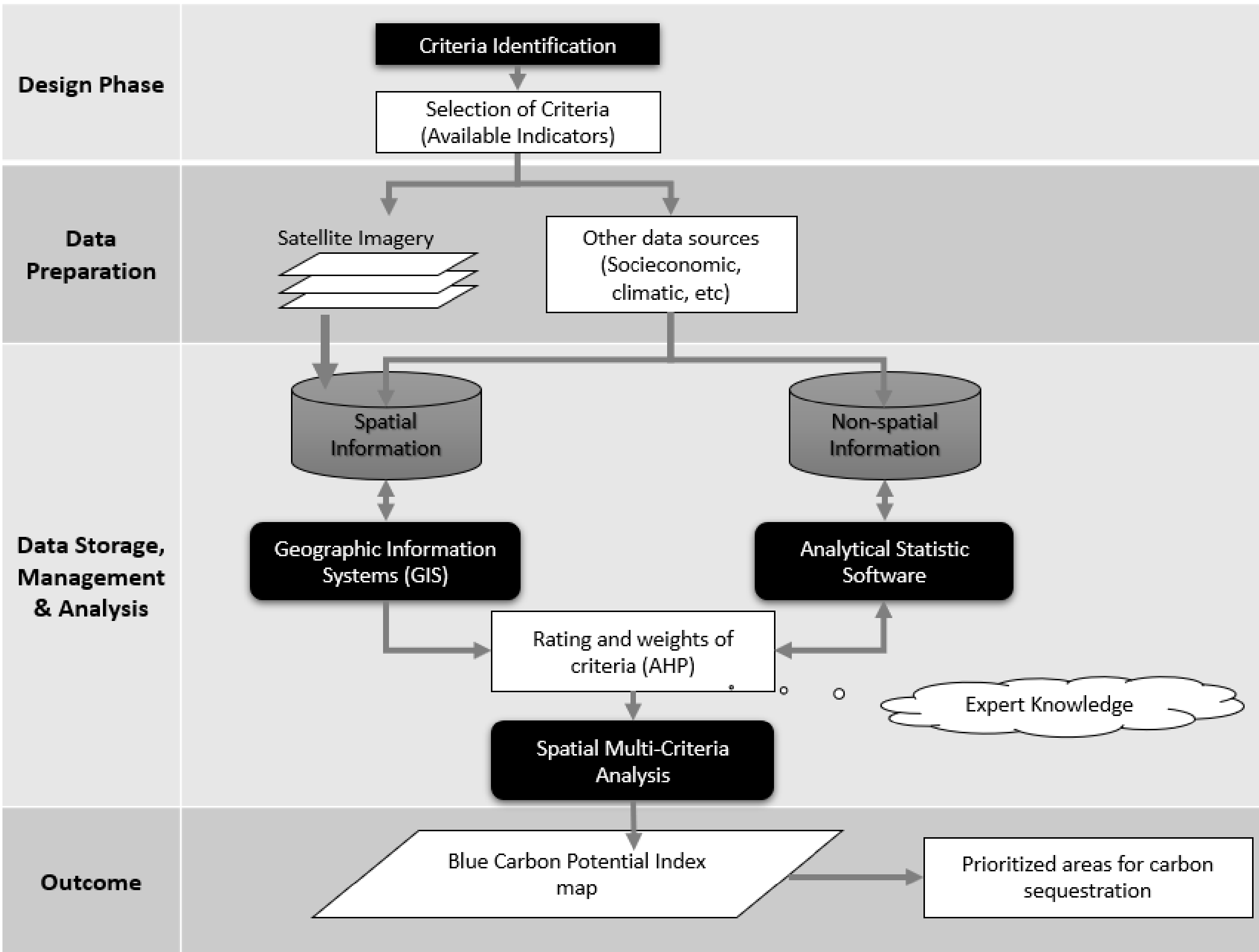

Figure 5. Methodological scheme for the determination of the blue carbon potential index. Adapted from Omo-Irabor et al. (2011).

4.1. Design Phase

MCA is a method for decision-making based on explicitly formulated criteria through the systematic exploration of the advantages and disadvantages of the different alternatives; and the unveiling of their dependency relationship (Geneletti, 2019). The first phase aims to establish a shared understanding of the decision context and problem structure; to this end, a literature review on the functioning of the carbon sequestration process and the criteria involved in the generation, storage, and permanence of blue carbon pools was conducted.

4.1.1. Literature review: Drivers of gains and losses in mangrove carbon sequestration

This step sought to identify mainly the drivers of carbon loss, as well as the drivers of carbon sequestration service by mangroves to provide an understanding of them as a complex system. A literature review was conducted to identify studies related to human activities that decrease the amount of carbon sequestered by mangroves and proxies of factors that enhance carbon sequestration in a natural environment perse. This narrative integrative review was focused to compile the main ideas in mangrove carbon sequestration matter.

The search of incomes for this review was performed from March 2nd to May 4th, 2023, including articles comparing anthropogenic disturbance to mangrove reservoirs in the entire globe. The online databases used were Science Direct, ResearchGate, Springer Link, Nature, and Wiley; limited to journal articles in English. Boolean queries were used, made up of the following keywords: “Blue carbon stocks AND mangrove AND disturbance”; “Blue carbon stocks AND mangrove AND LULCC”; “carbon storage AND mangrove AND biodiversity”; “carbon sequestration AND mangrove AND remote sensing”; “carbon sequestration AND mangrove AND GIS”; “Blue carbon stocks AND mangrove AND carbon gain”; “carbon burial AND mangrove AND driver”. The selection of the publications is better explained in Figure 6.

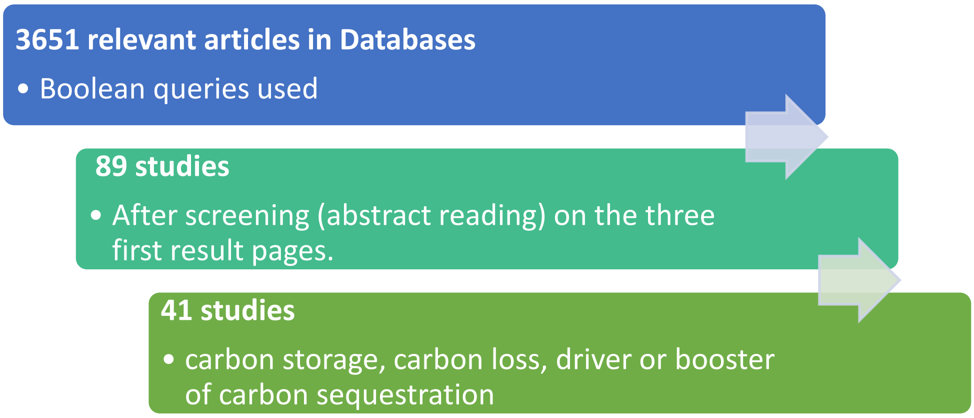

Figure 6. Literature selection process

The eligibility criteria for screening include those studies which evaluate quantitatively the carbon account (or loss) by comparing two sites with different environmental conditions. Moreover, descriptions of underlying processes of carbon uptaking, burial, and permanence were taken into consideration. The search included publications describing anthropic disturbances and amounts of change in carbon stocks.

After reading each of the studies, relevant data such as the authors, the publication date, keywords, country of the study case, scale addressed, and positive or negative driver of mangrove carbon sequestration were systematized in a summary table.

4.1.2. Indicators selection

The selection of the criteria was performed according to the identified drivers of carbon sequestration in the literature review in addition to the available datasets of the national institutions, academics, or NGOs. Moreover, suitable indicators were those with higher scales than 1: 25 000 and the most updated date. The selected criteria are depicted in Table 1.

Table 1. Potential blue carbon reservoir assessment indicators.

CATEGORY	INDICATOR	Source and Year	Technique and Software	Resolution /scale
Biophysical / Environmental	Geomorphology	(IEE, 2011b)	Geoprocessing and Classification of vector layers. ArcMap 10.8.	1: 25 000
	Above Ground Biomass of mangroves	(Simard *et al.*, 2019)	Reclassification of the raster data set. ArcMap 10.8.	30 m / pixel
	Mangrove canopy maximum height	(Simard *et al.*, 2019)	Reclassification of the raster data set. ArcMap 10.8.	30 m / pixel
	NDVI	PSScene (Planet Team, 2022)	Map algebra with raster calculator. ArcMap 10.8.	3 m / pixel
Socioeconomic	Protection and conservation categories.	(MAE, 2022)	Geoprocessing and Classification of vector layers.	1: 25 000
	Population pressure	(INEC, 2010)	Geoprocessing and Classification of vector layers.	1: 25 000
	Land use and land cover	(MAG, 2020)	Geoprocessing and Classification of vector layers.	1: 25 000
	Mangrove Fragmentation	(MAG, 2020)	Landscape pattern analysis with Fragstats	1: 25 000

Source: Own elaboration.

4.2. Data Preparation Phase

The required spatial information was extracted with their relevant attributes and then clipped to the extent of the study area. Non-spatial information was converted into spatial layers in GIS format with coordinates within the datasets or basic pre-existing cartography (Fragmentation). The layers for each criterion were exported to choropleth maps in raster format and reclassified setting four levels of high, moderate, low, and null blue carbon potential. This process is called standardization, which is imperative in the assessment to perform a comparison among the criteria and indicators which in turn usually are measured in different scales and units. Once the different layers (criteria) have been obtained, they are normalized as required for better comprehension.

4.3. Data Storage, management, and analysis Phase

This phase included the creation of the geographic database, which allowed the storage and management of different thematic coverages. Geographic databases allow linking the georeferenced spatial information with thematic information, which is steered to spatially represent each of the selected criteria.

4.3.1. Analytic Hierarchy Process

It is a weighting indicators method based on the comparison of pairs of indicators and the judgment of their relative importance through a numeric scale. It consists of four main steps.

Structure the problem is the first step that implies organizing hierarchically several levels of criteria, which may disaggregate into sub-criteria and in the lowest level, alternatives are located. Then, decision makers perform paired comparisons of alternatives concerning given criteria at a superior level. These paired judgments are given in the 1-9 integer scale shown in Table 2 and then arranged in called comparison matrix (A) as shown in equation 1.

Table 2. The Fundamental Scale.

Intensity of Importance	Definition	Explanation
1	Equal importance	Two activities contribute equally to the objective
2	Weak	
3	Moderate importance	Experience and judgment slightly favor one activity over another
4	Moderate plus	
5	Strong importance	Experience and judgment strongly favor one activity over another
6	Strong plus	
7	Very strong or demonstrated importance	An activity is favored very strongly over another; its dominance demonstrated in practice
8	Very, very strong	
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
Reciprocals of above	If activity i has one of the above nonzero numbers assigned to it when compared with activity j, then j has the reciprocal value when compared with i	A reasonable assumption

Intensity of Importance	Definition	Explanation
Rationals	Ratios arising from the scale	If consistency were to be forced by obtaining n numerical values to span the matrix

Source: (Saaty, 1994)

$$A = (a_{ij})_{n\times n}\begin{bmatrix}1 & a_{12} & a_{13} & \cdots & a_{1n}\\ \vdots & 1 & a_{23} & \cdots & a_{2n}\\ & \vdots & 1 & & \vdots\\ \vdots & 1/a_{ij} & \vdots & \ddots & \vdots\\ & \cdots & & & 1\end{bmatrix} \quad (1)$$

When executing pair-wise comparison, an element could be considered less favorable than another, then judgment is a fraction. Moreover, when comparing one element with itself, the comparison must score 1. Since this matrix is reciprocal, half of the matrix is only required.

Then, the solution of the principal eigen vector of the matrix provides the weights of the compared criteria. To obtain w_i the vector, the most common method employed is the mean of the row that consists of the following three steps (Ishizaka and Labib, 2011):

1) Sum the elements of each column j: $\sum_{i=1}^{n} a_{ij} \quad \forall i,j$ (2)
2) Divide each value by its column sum: $a'_{ij} = \frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad \forall i,j$ (3)
3) Mean of row i: $w_i = \frac{\sum_{j=1}^{n} a'_{ij}}{n}$ (4)

According to Ishizaka & Labib (2011), Saaty (1980), justifies the principal w_i eigenvector as the desired priorities vector supported by the perturbation theory as shown in equation 5.

$$Aw = \lambda_{max} w \quad (5)$$

Where λ is the maximal eigen value. This process is used as well to obtain the weights in the levels below (sub-criteria, alternatives), but it is important to highlight that the weights in inferior levels are proportional to the weights of the superior levels (mathematically this is obtained by the matrix product of the weight vectors). In other words, the priorities obtained should be used to calculate the importance of elements in the next level (from up to down). This process should be repeated until the final priorities of the alternatives in the lowest level of the structure are reached.

The next step is to measure the inconsistency of the judgments, defined as the consistency index in the AHP:

$$CI = \frac{\lambda_{max} - n}{n - 1} \quad (6)$$

Saaty (1980) also stated a consistency ratio(CR), as the ratio of the consistency index for a particular set of judgments, to the average consistency index for random comparisons for a matrix of the same size. A good overall judgment produces a consistency ratio of 0, while the contrary produces a ratio of 1. When the consistency ratio exceeds 0.10, the comparison matrix (A) needs to be re-examined (Saaty, 1980; Zhu and Dale, 2001). This is explained since Human judgments may not always be consistent because the scale used to measure them may introduce some inconsistencies (Thieler et al., 2009; as cited in Bagheri et al., 2021).

$$CR = \frac{CI}{RI} \quad (7)$$

Where RI is the random index obtained from the average CI of 500 randomly filled matrices (Table 3).

Table 3. Random indices.

n	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
RI	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49

Source: (Saaty, 1980)

4.3.2. Blue Carbon Potential Index structure

Twelve indicators were selected and disaggregated into biophysical and socioeconomic factors to outline two components (sub-indexes), the Blue Carbon Index (BCI formed by biophysical indicators) and the Blue Carbon Compatibility

Index (BCC formed by socioeconomic indicators). Furthermore, each indicator is depicted by the aggregation of indicators which include genesis, morphology, geology, AGB, NDVI, and elevation (See Figure 7). On the other hand, the BCC is composed of LULC, population pressure, and protection and conservation status indicators.

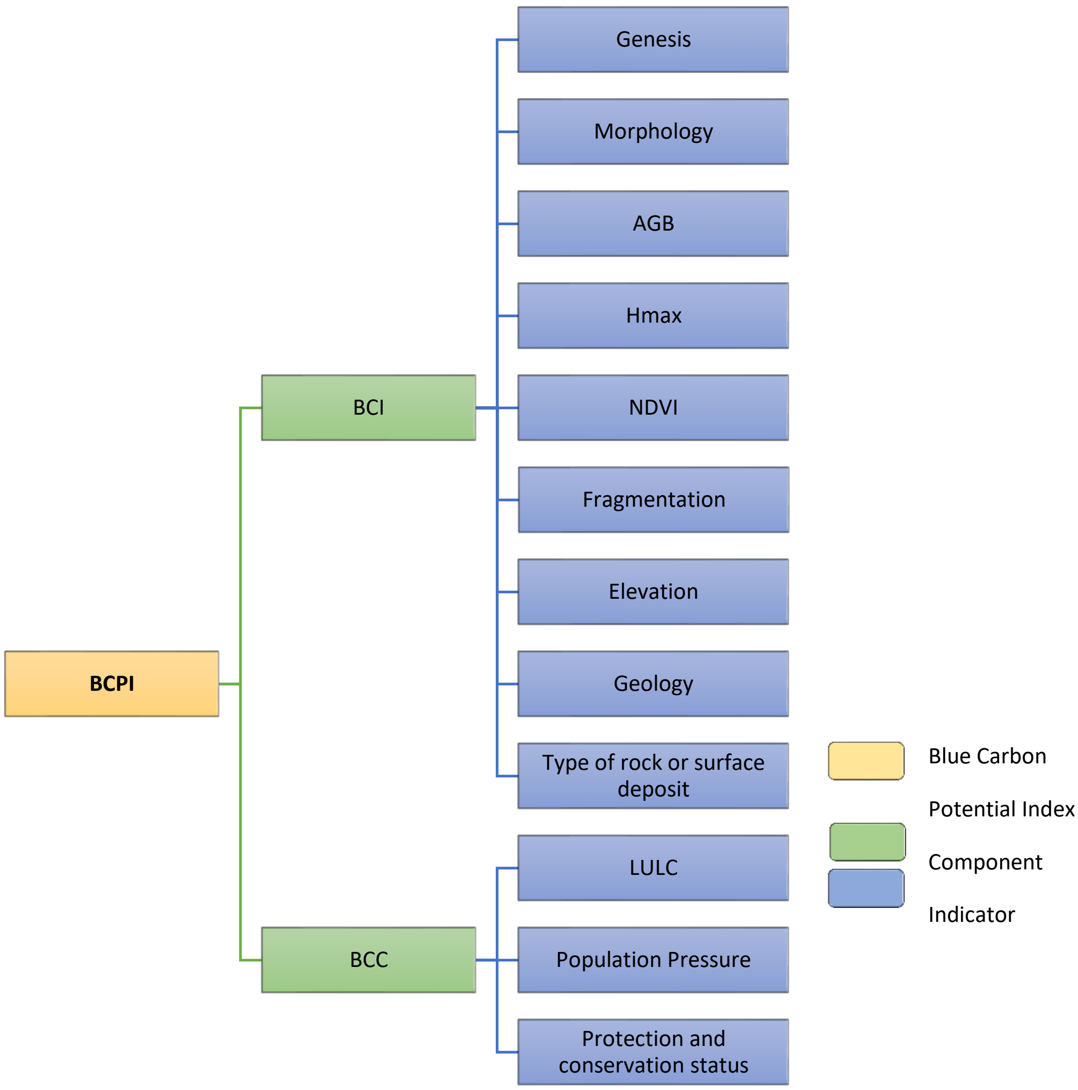

Figure 7. Blue Carbon Potencial Index Structure.

4.3.3. Determination of indicators weight

Firstly, a formulary indicating the process to follow was sent to the participants with the purpose of providing instructions before the meeting. An expert opinion session was performed to determine the weights for criteria and indicators which comprise the BCPI. Two experts with wide experience and previous research in mangrove forest, ecosystem services, as well as landscape ecology. They provided paired judgments to fill the comparison matrixes using Saaty's scale. A first round was carried out comparing the BCI and the BCC, where they showed consensus in their judgment by setting equal importance to the two sub-indexes. However, in the second round, no consensus was achieved, with one opinion suggesting using equal weights for all indicators and the other advocating for uneven ponderation among them. Therefore, two BCPIs were built, one with pondered indicators and the other with no weights included.

4.3.4. Spatial Multicriteria Analysis

The rule chosen for the spatial decision-making problem is the weighted linear combination, which is given by equation 9.

$$BCPI = \sum_{i=1}^{n} w_i x_i \prod_{j=1}^{m} c_j \qquad (9)$$

Where w_i is the weight of factors i , x_i is the criterion score of factor i , n is the number of factors, c_j is the criterion score of constrains j , and m is the number of constrains (Eastman, 1999; Omo-Irabor *et al.*, 2011). The result of the summation is the decision represented as a single parameter output map, although, in this case, two final outputs were conceived, the weighted BCPI and the equal-weighted BCPI.

5. RESULTS

5.1. Literature Review: Drivers of gains and losses in mangrove carbon sequestration.

Understanding the drivers of carbon sequestration in mangroves is imperative for effective conservation, management, and even enhance the resilience of these ecosystems against climate change impacts (MacKenzie, Sharma and Rovai, 2021). This literature review aims to recognize the factors that promote carbon uptaking as well as the causes of blue carbon loss.

As addressed in Chapter 2, blue carbon sequestration refers to the process by which CO_2 is taken from the atmosphere and stored in coastal ecosystems, including mangroves. To do so, the major factors influencing carbon burial rates and soil stocks in these wetlands are precipitation (Sanders *et al.*, 2016), temperature (Chmura *et al.*, 2003; Lovelock, 2008; Mcleod *et al.*, 2011), geomorphology (Twilley et al., 2018; Rovai et al., 2018; Rogers et al., 2019), nutrients (Mcleod *et al.*, 2011; Palacios *et al.*, 2021), salinity (Ball, Cochrane and Rawson, 1997), tree composition (Lang'at *et al.*, 2013; Atwood *et al.*, 2017), forest age (Osland *et al.*, 2012; Marchand, 2017; Carnell *et al.*, 2022), and sediment accretion (Alongi, 2012; Macreadie *et al.*, 2017; Murdiyarso *et al.*, 2021).

Apart from ruling the distribution of species in the globe, precipitation and temperature are indicated as important controls in mangrove soil carbon stocks (MacKenzie, Sharma and Rovai, 2021). While rainfall provides adequate water supply and nutrient transport in mangrove forests, temperature encourages productivity (photosynthetic activity) and accelerates decomposition rates of litter in wetland soils (Chmura *et al.*, 2003). Indeed 86% of mangrove carbon stocks variability in the soil is explained by precipitation (Sanders *et al.*, 2016). However, the primary influences on carbon sequestration rates in wetland soils should be explained by regional or local factors (Chmura *et al.*, 2003).

As mentioned before, geomorphology plays an important role in shaping the differences in mangrove pools since is highly linked with water bodies, tides, and wave action (Twilley et al., 2018). For instance, the mangrove forests in estuaries count on clastic systems associated with bidirectional currents (freshwater and seawater), where the deposition of sediments builds a suitable platform allowing colonization (Rovai *et al.*, 2018). Thus, the root system of mangroves traps and binds these sediments which in turn enhances carbon burial and long-term sequestration when the sedimentary environment is not disturbed (Pérez, Libardoni and Sanders, 2018).

Studies have stated that diverse tree assemblages in mangrove forests contribute to blue carbon storage (Rahman *et al.*, 2021). The association between soil C stocks and mangrove species richness has been demonstrated to be higher, 70 -90% in mixed mangrove stands (Atwood *et al.*, 2017). Lang'at et al. (2013) claim that belowground biomass is enhanced in mangrove forests by the presence of other mangrove species (especially *Avicennia marina*) and thus productivity and carbon sequestration.

Regarding nutrient availability, it can lead to positive or negative effects on carbon sequestration. Carbon burial capacity is highly linked with primary productivity which in turn can be enhanced by enough nitrogen input, increasing the carbon fixation by mangroves (Mcleod *et al.*, 2011). On the other hand, Palacios et al. (2021) found that a high nutrient pulse reduces the soil organic superficial stocks by 23%, eutrophication that may be caused mainly by agricultural practices, LULCC (Nitrogen exports by rivers), and runoff and soil erosion processes (P leached rivers) (Borbor-Cordova *et al.*, 2006). Although further research is needed, existing studies indicate that reducing nutrient loading can enhance carbon sequestration by preserving natural competition (macrophyte production, microalgae, and bacterial activity) and limiting carbon release in coastal ecosystems (Macreadie *et al.*, 2017).

On the contrary, mangrove forests also face threats that contribute to blue carbon loss. Some of these drivers of carbon stocks reduction include storms (Kauffman and Cole, 2010; MacKenzie, Sharma and Rovai, 2021), erosion and tidal export (Mcleod *et al.*, 2011; Alongi, 2014), LULCC (Donato *et al.*, 2011; Kauffman *et al.*, 2014, 2016, 2018), hydrological alterations (Alongi, 2014), and sea level rise (Gilman, Ellison and Coleman, 2007; Gilman *et al.*, 2008).

Natural events such as cyclones and tsunamis may cause the loss of mangrove cover, diminish the levels of productivity of remaining trees and lessen carbon storage (Kauffman and Cole, 2010; Sippo *et al.*, 2018). As a result, precipitation increases influence mangrove thriving and reduces salinity stress modifying soil carbon stocks (MacKenzie, Sharma and Rovai, 2021). However, approximately 45% of the global mangrove cover has been lost extensively due to tropical cyclones accounting for the past sixty years (Sippo *et al.*, 2018), suggesting that natural events are one of the main natural causes of mangrove loss opening the debate of their value on climate change mitigation.

Studies have shown that the loss 2.1% of mangrove cover between 2000 and 2016 was 2.1%, with 62% due to anthropogenic activities rather than natural causes (Goldberg *et al.*, 2020). The authors of the cited study stated that the LULCC to obtain commodities is attributed to 47% of mangrove loss, followed by mining and petroleum extraction at 12%, and new settlements and urban expansion at 3%. In addition, Sasmito et al. (2019) determined that LULCC in general terms reduces the biomass carbon reservoir by 82% and the soil carbon reservoir by 54%. Moreover, this study revealed that rice fields contributed more than aquaculture and grazing in soil carbon stock reduction.

In this regard, Kauffman et al. (2014, 2016, 2017, 2018, 2020) studied deeply the variation of carbon stocks affected by a specific anthropic disturbance in different world's mangrove forests. For example, they determined that pristine mangroves change from 1358 Mg C ha^{-1} to 458 Mg C ha^{-1}, and 1131 Mg C ha^{-1} to 95 Mg C ha^{-1} when converting into pastures and shrimp ponds respectively, accounting for the total ecosystem carbon (Kauffman *et al.*, 2014, 2016). Similarly, the percentage of soil carbon stocks change by the disturbance of these wetlands by sewage, shrimp farm effluents, and eutrophication is -35.12%, -61.01%, -33.82% respectively (Palacios *et al.*, 2021; Santos-Andrade *et al.*, 2021).

Bioturbation, as the disturbance of soil and sediments by living organisms, plays a critical role in carbon cycling in vegetated coastal habitats (Macreadie *et al.*, 2017), by influencing organic matter and correlation with sediment microbes (Thomson, 2017). For instance, this process may influence mangrove growth by the crab burrow density (Smith, Wilcox and Lessmann, 2009), which in turn some species were claimed to contribute to sediment carbon storage in mangroves (Andreetta *et al.*, 2014). However, high densities of bioturbators can have negative impacts on soil carbon accumulation and preservation, by increasing tidal flushing and CO_2 release in crab burrows in salt marshes (Xiao *et al.*, 2021). Therefore, the role of bioturbators in enhancing or not carbon sequestration on mangroves is still not fully understood and requires further research, but its control may be a key strategy to optimize carbon sequestration in blue carbon ecosystems (Macreadie *et al.*, 2017).

The overall literature review permitted to understand how the complex mangrove ecosystem works in uptaking carbon and storing it in its four distinctive reservoirs. Likewise, natural, and anthropic disturbances affect in different magnitude to these reservoirs directly or indirectly. Figure 8 summarizes the findings of this step in the present study and Annex 1 depicts the studies considered.

Furthermore, the selected indicators related to blue carbon uptake, storage, and loss are explained below. In addition, the classification approach followed for each indicator is addressed within the explanation of each indicator, which likewise is part of the findings of the literature review.

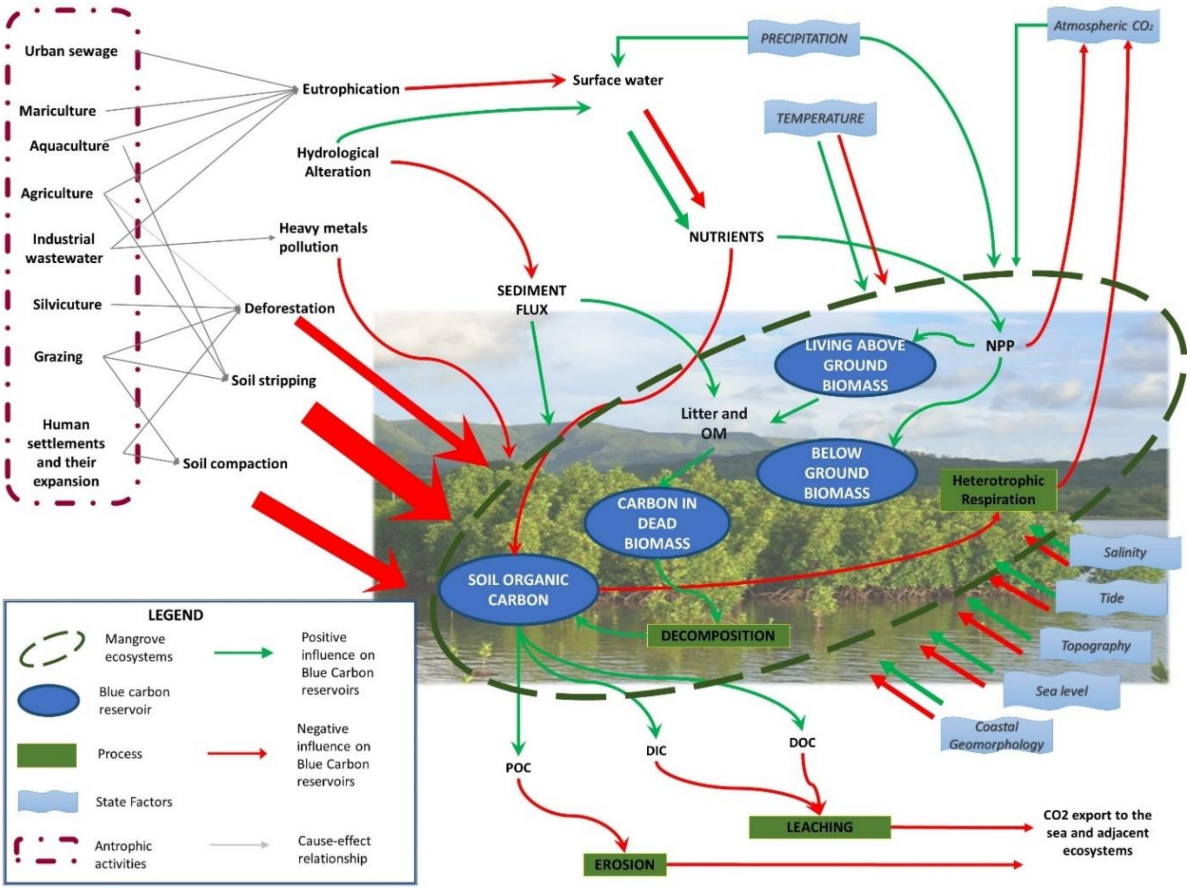

Figure 8. Influence of anthropogenic activities on the Blue Carbon Pool System in Mangrove Ecosystems. The figure indicates that the change in land use and the productive activities of society generate disturbances in different magnitudes on the mangrove ecosystems. Likewise, the fragility of these wetlands can be appreciated due to state factors over which humans have no control. On the other hand, the system presents natural carbon losses due to natural processes such as leaching, erosion, and respiration. Own elaboration.

5.1.1. Geomorphology

Mangrove forests are typically found in coastal areas that are characterized by dynamic geomorphological processes, that in turn shape depositional environments by river, waves, and tide action; or carbonate coast formed by biological process action (Woodroffe, 1992; as cited in Twilley et al., 2018). These processes can influence sedimentation patterns, nutrients, and the accumulation of organic matter in mangrove soils, which result in coastal environmental settings that embrace riverine/deltas, tidal systems, lagoons, carbonate, and arheic environments (Dürr *et al.*, 2011). The allochthonous sediment supply in river-dominated systems highly depends on the catchment size. In the case of tidal systems, the sediment allocation depends on the bank erosion and resuspension of sediments by tides. Carbonate stings depend on calcareous sediment or mangrove peat produced on-site

(Woodroffe, 1992). Regarding carbon storage in soil, Kauffman et al. (2020) claim that carbonate and arheic settings have fewer soil C stocks than riverine/deltaic mangroves. Thus, geomorphological factors influence carbon storage in wetland and floodplain environments (Rogers *et al.*, 2019). Table 4 explains how the geomorphic values were classified in relation to the blue carbon potential index.

Table 4. Approach applied to ranking Geomorphic indicators into carbon sequestration potential. Adapted from (Rogers *et al.*, 2019).

Geomorphic indicator	Description of indicator	Cell label (Value)	Cell description
Genesis	Processes involved in the origin of the relief shapes exhibit zones of high fine sediment accumulation.	High (3)	Marine and fluvio-marine
		Moderate (2)	Depositional Fluvial
		Low (1)	Structural Tectonic Erosive Polygenic Fluvial-lacustrine Landslides.
		Nil (0)	Not applicable.
Morphology	Flat and floodable landforms of the relief depict ideal conditions supporting mangroves.	High (3)	Ma, Nb, Spi, Est*.
		Moderate (2)	Slt, Crl, Na, Nb, Plc*.
		Low (1)	Tb, Co, Pc, Va, D, No, Py, Ces*.
		Nil (0)	Ct, C2, Ges, R5, R4, R3, R2, R1, C1, C5, Vse, Ta, Tm, Ti, Can, Cds, Sm1, Sm2, Vi, Sm4*.
Geology	Sediments of finer grains common in alluvial and estuarine plains have higher carbon storage capacity compared to sandy sediments.	High (3)	Marine deposits, alluvial deposits, fluvial marine deposits
		Moderate (2)	Alluvial deposits (Terrace)
		Low (1)	Saline deposits, colluvial alluvial deposits
		Nil (0)	Colluvial deposits, PzMzP, Km, K3y, K3Gy, E2Se, Mp, OMTz, E3An, E2-3Az*.
Type of rock or surface deposit		High (3)	fine-grained silts and clays
		Moderate (2)	Fine-grained silts, clays, and sand
		Low (1)	Medium-grained silts, clays, and sand with the presence of gravel. Coarse sands, and silts with the presence of clays.
		Nil (0)	Sandstones, argillites, limestones, and gravels

**Geomorphic class codes are explained in Annex 1 according to* (IEE, 2011a).

5.1.2. Elevation

Mangroves are halophytes species, which are adapted to the abundance or scarcity of salt (Parida and Jha, 2010). Nevertheless, the salinity content in substrate, scarcity or excess, may affect the growth of several mangrove species (Downton, 1982 as cited in Parida & Jha, 2010). Hence, it was assumed that tidal saltwater input is imperative to support coastal mangrove forests considering the tidal range of the Guayas River estuary of 0.25 – 3.0 m (Boto & Bunt, 1981; as cited in Twilley et al., 1997) amplified to a maximum of 4.0m. This extension of the range enables the possibility of including localized regional topography, which could amplify the tidal ranges in estuaries beyond the highest scored value. Hence, a digital elevation model from the SIGTierras program (The National System of Information and Management of Rural Land and Technological Infrastructure) with a 4m tile size was employed to this end (See Table 5).

Table 5. Approach applied to ranking Elevation indicator into carbon sequestration potential.

Indicator	Description of indicator	Cell label (Value)	Cell description
Elevation	Suitable areas for mangrove forests require sea water input.	Nil (0)	4.001-691 m.a.s.l.
		High (3)	0.000–4.000 m.a.s.l.

5.1.3. Mangrove's Above Ground Biomass

As explained in the chapters before, above-ground biomass (AGB) is one of the carbon pools of mangrove forests, accounting for 19.57% of global mangrove carbon stocks (Hamilton & Friess, 2018). This pool embraces at least 70% of the net primary production, which in turn is the net carbon gain by plants (Chapin et al., 2011). Simard et al. (2019), estimated the distribution of AGB based on remote sensing (SRTM) and in situ data (including plots from Ecuador of basal area weighted height), using allometric equations of previous studies, estimating total forest stand AGB density in Mg ha^{-1}.

For simplicity, the values were classified into three classes to depict low, moderate, and high mangrove AGB as indicated in Table 6.

Table 6. Approach applied to ranking AGB indicator into carbon sequestration potential.

Indicator	Description of indicator	Cell label (Value)	Cell description
AGB	AGB represent carbon stored in living biomass and contribute to the peat generation process.	Low (1)	0.524 – 100
		Moderate (2)	100.001-200
		High (3)	>200

5.1.4. Mangrove's canopy maximum height (H_{max})

The canopy height map is proposed as another environmental physical indicator of blue carbon potential. The employed data set was generated by Simard et al., (2019), using GLAS Spaceborne lidar- maximum canopy heights and SRTM (Digital elevation model) and validated using in situ observations.

In previous studies, samples in tall-mangrove and medium-mangrove strata were estimated. Despite above-ground biomass was higher for tall mangroves, higher C concentrations were measured in medium-statured mangroves, where soil stocks accounted for 80% of the TOC (Merecí-Guamán *et al.*, 2021). This is explained by more water-saturated zones that promote organic matter retention and restrict soil respiration in medium-statured mangroves (Inoue, 2019 as cited in Merecí-Guamán et al., 2021). The height oscillation of each mangrove species is 0.4-40m *Rhizophora mangle L.* (Mangle rojo), 1.5-40m *Rhizophora racemosa* (Mangle cholo), 0.5-20 m *Avicennia germinans L.* (Mangle negro), and 1.5-10m *Laguncularia racemosa* (Mangle blanco)(MAE, FAO and Cornejo, 2014). This premise is used to reclassify the dataset of canopy maximum height as follows (Table 7).

Table 7. Approach applied to ranking AGB indicator into carbon sequestration potential.

Indicator	Description of indicator	Cell label (Value)	Cell description
H_{max}	The soil carbon stock of medium-statured mangroves is higher than taller-mangroves strata.	Low (1)	>21.001(Tall-statured mangroves)
		Moderate (2)	0.848 -10 (Small-statured mangroves)

Indicator	Description of indicator	Cell label (Value)	Cell description
		High (3)	10.001-21 m (Medium-statured mangroves)

5.1.5. Normalized difference vegetation index (NDVI)

This dimensionless index represents a ratio of the difference between near-infrared (NIR, 0.725-1.1 m) and red (0.58-0.68 m) portions of the spectrum (Turner and Gardner, 2015) and is calculated with the following formula:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)} \qquad (8)$$

The NDVI provides an indirect measure of vegetation status and growth (Jensen, 1996 as cited in Turner & Gardner, 2015), thus, the favorable physical environment including soil, moisture, temperature, and light availability. Therefore a large and positive NDVI value conveys a good site quality for thriving mangrove forests (Fang *et al.*, 2014). A mosaic composed of 31 most recent multispectral images (December 23, 2022 to February 10, 2023) at a resolution of 3 m was built to obtain the NDVI of the study area. The employed images were provided by Planet Team (2022,2023), products radiometrically and geometrically corrected named Planet-Scope Ortho Scenes. The classification of the raw values follows the healthiness classification scale employed by Ruan et al. (2022), as indicated in Table 8.

Table 8. Approach applied to ranking NDVI indicator into carbon sequestration potential.

Indicator	Description of indicator	Cell label (Value)	Cell description
NDVI	The higher the NDVI value, the healthier the mangrove forest is.	Nil (0)	0 – 0.4
		Low (1)	0.4001-0.6
		Moderate (2)	0.6001-0.8
		High (3)	>0.8

5.1.6. Fragmentation

The term fragmentation is defined as “the breaking up of a habitat or cover type into smaller, disconnected parcels; often associated with, but not equivalent to, habitat loss” (Forman et al., 1995 as cited in Turner & Gardner, 2015). When a wetland is fragmented, many ecological processes involving connectivity are consequently affected, thus, the ability of mangroves to capture and store carbon is likely influenced (Bryan-Brown *et al.*, 2020). Turschwell et al. (2020) suggested that mangroves are more resilient to pressures when greater the patches are because less fragmented forests are less accessible to anthropogenic disturbances.

Connectivity through the landscape describes the linkages among their elements, including the flows of materials, such as water, nutrients, and species. In wetlands, the connectivity is associated with superficial water flow between wetlands, groundwater movement, and even migratory birds and amphibians (Boudell, 2018). Although direct evidence is yet needed, studies imply that C capture, accumulation, and preservation are influenced by top-down processes such as tropic cascades (Atwood *et al.*, 2015). A study demonstrated that edges in fragmented forests reduce by 50% compared with areas under the canopy (Brinck et al., 2017; as cited in Turschwell et al., 2020).

The usage of landscape metrics was performed to describe fragmentation in the study area through Fragstats 4.2 software, which is a spatial pattern analysis program widely used in landscape ecology. It provides quantitative indicators of spatial configuration or composition of the map, whereas a main aspect of the former is aggregation. This metric refers to how patch types are clustered or joined, and it is related to dispersion, clumping, interspersion, subdivision, and isolation concepts (McGarigal, Ene and Cushman, 2023).

The clumpiness index (CI) evaluates the level of aggregation in mangrove patches across the landscape. A lower clumpiness index suggests greater dispersion and fragmentation and vice versa (Bryan-Brown *et al.*, 2020). The range of the index is between -1 and 1, where a negative value near -1 means that the focal patch or class analyzed is maximally disaggregated. When this index equals 0 corresponds to a patch or class randomly distributed. The contrary, when equal to 1 or more near to that value, consists of a patch or class maximally aggregated (McGarigal, Ene and Cushman, 2023).

In addition, the Mean patch size (MPS) was calculated as the average size of mangrove patches in the landscape. A smaller MPS indicates higher fragmentation and vice versa because it has been indicated to create fragments of different sizes and promote isolation among the fragmented patches (Kanniah *et al.*, 2021).

Thus, both metrics were developed in the frame of sub landscapes analysis, providing the tiles (subzones) in raster format. The tiles were defined by the official cartography of hydrographic units, which in turn is based on the Pfafstetter coding System (Pfafstetter, 1989) until level five. As a result, eight zones were obtained and employed as an input for Fragstats analysis as shown in Figure 9. For simplicity, the metrics of each zone were classified into three classes to depict low, moderate, and high mangrove fragmentation as indicated in Table 9.

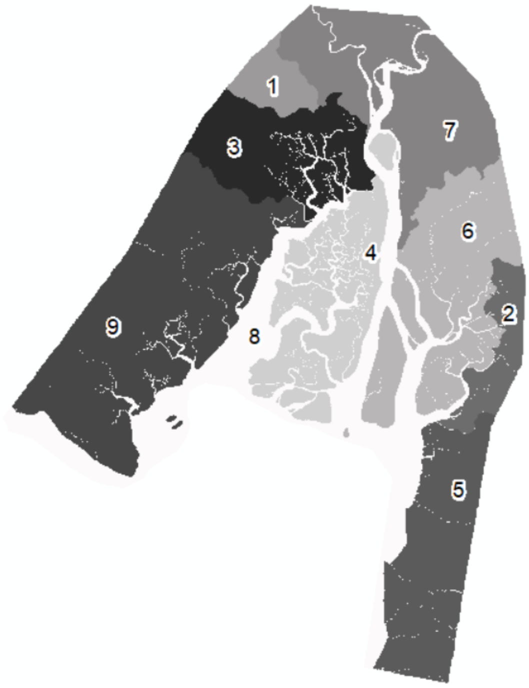

Figure 9. Sub landscapes for fragmentation analysis.

Table 9. Approach applied to ranking Fragmentation indicator into carbon sequestration potential.

Indicator	Description of indicator	Cell label (Value)	Cell description
Fragmentation	The higher the CI and the MPS value, the less fragmented the mangrove forest is in the zone.	Nil (0)	Areas with no mangrove cover
		Low (1)	0.85<CI ≤ 0.90 or MPS ≤100 m^2
		Moderate (2)	0.9<CI ≤ 0.95 or 100<MPS ≤200 m^2
		High (3)	CI > 0.95 or MPS >200 m^2

5.1.7. Protection and conservation status

Avoiding the logging of vegetation cover and maintaining the conditions of the belowground peats will prevent C emissions to the atmosphere. These include allowing the flow of sediments in the hydrological environment as well as terrestrial organic matter inputs to the ecological system (Kelleway *et al.*, 2016). In this regard, Natural protection areas and AUSCM (SUCAs) are more likely to avoid human disturbances, and thus better conditions for carbon sequestration are assured.

The Ecuadorian State defines different categories for natural heritage areas that in turn are based on the classification proposed by UICN. These categories are established due to the main objective of management of the protected area, the extension, biodiversity, and environmental maintenance and conditions. Thus, this hierarchy was arranged to build this indicator as shown in Table 10.

Table 10. Approach applied to ranking Protection status indicator into carbon sequestration potential.

Indicator	Description of indicator	Cell label (Value)	Cell description
Protection and conservation status	The higher the conservation status of a certain area, the more suitable conditions for blue carbon conservation.	Nil (0)	Areas without protection regime
		Low (1)	SUCA or Wildlife production reserve
		Moderate (2)	National Recreation Area or Wildlife Refuge
		High (3)	Ecological Reserve

5.1.8. LULC

Land use and land cover (LULC) may support understanding how socio-economic activities enhance or threat the blue carbon stocks. In doing so, the vector-based land use dataset (MAG, 2020) was converted into raster format, reclassifying it according to land-use categories and their compatibility with the carbon sequestration services by mangroves (See Table 11).

Table 11. Approach applied to ranking LULC indicator into carbon sequestration potential.

Level 2 land-use category	Cell label (value)	Description of LULC
Settlements	Low (1)	Urban residential, rural residential, industrial parks, waste dump, recreation, health, and education facilities.
Infrastructure	Low (1)	Pipelines, waste dumps, landfills, cemeteries, aquaculture infrastructure, agriculture infrastructure, airports, communication facilities, and roads.
Artificial water body	Moderate (2)	Reservoirs, channels, pools, dams.
Natural water body	Moderate (2)	Estuarine waters, lakes and lagoons, evaporation basins, and streams.
Agriculture	Low (1)	Continuous or rotation cropping may include large areas of rice or sugar cane and plantations of banana or cacao. This may include the planting of mixed crops and land on fallow cycles.
Grazing	Low (1)	Herbaceous vegetation dominated by grass species. introduced, used for livestock purposes, that for their establishment and conservation.
Forest plantation	High (3)	Anthropically formed forest mass with one or different native or introduced timber species, with silvicultural management and dedicated to various purposes such as wood production, protection, soil recovery, or recreation. The Teak and bamboo plantation is common in the study area.
Native forest /shrub/ herbaceous cover	High (3)	Dry forest, native forest, dry scrub, and dry grasses, and their different alteration levels.
Mangrove	High (3)	Little disturbed, moderately disturbed, and very disturbed mangroves.
Special	Moderate (2)	Beach, cliff, foreshore protection, dikes, sand spits

5.1.9. Population pressure

This indicator aims to represent several likely human pressures on mangroves: deforestation to build aquaculture ponds, use of timber resources, coastal development, and urban expansion (Hamilton, 2020). High population densities are associated with greater mangrove loss (Barbier and Cox, 2003; Govender *et al.*, 2020; Turschwell *et al.*, 2020), especially in countries with no crackdown on non-compliance the laws like Ecuador. Census population data disaggregated by census zones are available from the last Ecuadorian census of 2010 (1:10.000), performed by the National Institute of Statistics and Census (INEC by its acronym in Spanish).

This dataset was categorized into 4 classes (See Table 11), using the natural breaks method.

Table 12. Approach applied to ranking Population pressure indicator into carbon sequestration potential.

Indicator	Description of indicator	Cell label (Value)	Cell description
Population pressure	The higher the population is within an area, the less capacity of blue carbon ecosystems to generate blue carbon.	High (3)	0–300 persons
		Moderate (2)	301-453 persons
		Low (1)	454-603 persons
		Nil (0)	604-4881 persons

5.2. Analytical Hierarchy Process

According to the AHP method, the BCI and the BCC are equally important (See Table 13).

Table 13. Pairwise comparison matrix of Components.

	BCI	BCC	Weight
BCI	1	1	0.5
BCC	1	1	0.5

However, the AHP method revealed that the most important socioeconomic indicator in the BCC conformation is LULC (0.221), followed by population pressure (0.194), and the Protection and conservation status (0.085) (Table 14).

Table 14. Pairwise comparison matrix of indicators for Blue Carbon Compatibility (BCC).

	LULC	Population Pressure	Protection and conservation status	Weight	Overall weight
LULC	1	1	3	0.443	0.221
Population Pressure	1	1	2	0.387	0.194
Protection and conservation status	0.333	0.50	1	0.170	0.085

Regarding the indicators for BCI, AGB was the most important factor with a weight of 0.103, followed by Hmax (0.094), and elevation (0.090) (Table 15).

Table 15. Pairwise comparison matrix of indicators for BCI.

	Genesis	Morphology	Geology	Type of rock or surface	Elevation	AGB	Hmax	NDVI	Fragmentation	Weight	Overall weight
Genesis	1.000	2.000	0.500	1.000	0.250	0.333	0.333	0.333	0.250	0.047	0.024
Morphology	0.500	1.000	0.500	0.333	0.333	0.250	0.250	0.500	0.250	0.035	0.018
Geology	2.000	2.000	1.000	0.500	0.500	0.333	0.333	0.333	0.333	0.057	0.029
Type of rock or surface deposit	1.000	3.000	2.000	1.000	0.250	0.333	0.333	0.333	0.333	0.062	0.031
Elevation	4.000	3.000	2.000	4.000	1.000	0.333	1.000	4.000	3.000	0.180	0.090
AGB	3.000	4.000	3.000	3.000	3.000	1.000	0.500	2.000	4.000	0.206	0.103
Hmax	3.000	4.000	3.000	3.000	1.000	2.000	1.000	2.000	2.000	0.187	0.094
NDVI	3.000	2.000	3.000	3.000	0.250	0.500	0.500	1.000	0.500	0.100	0.050
Fragmenta-tion	4.000	4.000	3.000	3.000	0.333	0.250	0.500	2.000	1.000	0.124	0.062

Figure 10 summarizes the results of the AHP method applied to the pile of indicators involved in the BCPI construction.

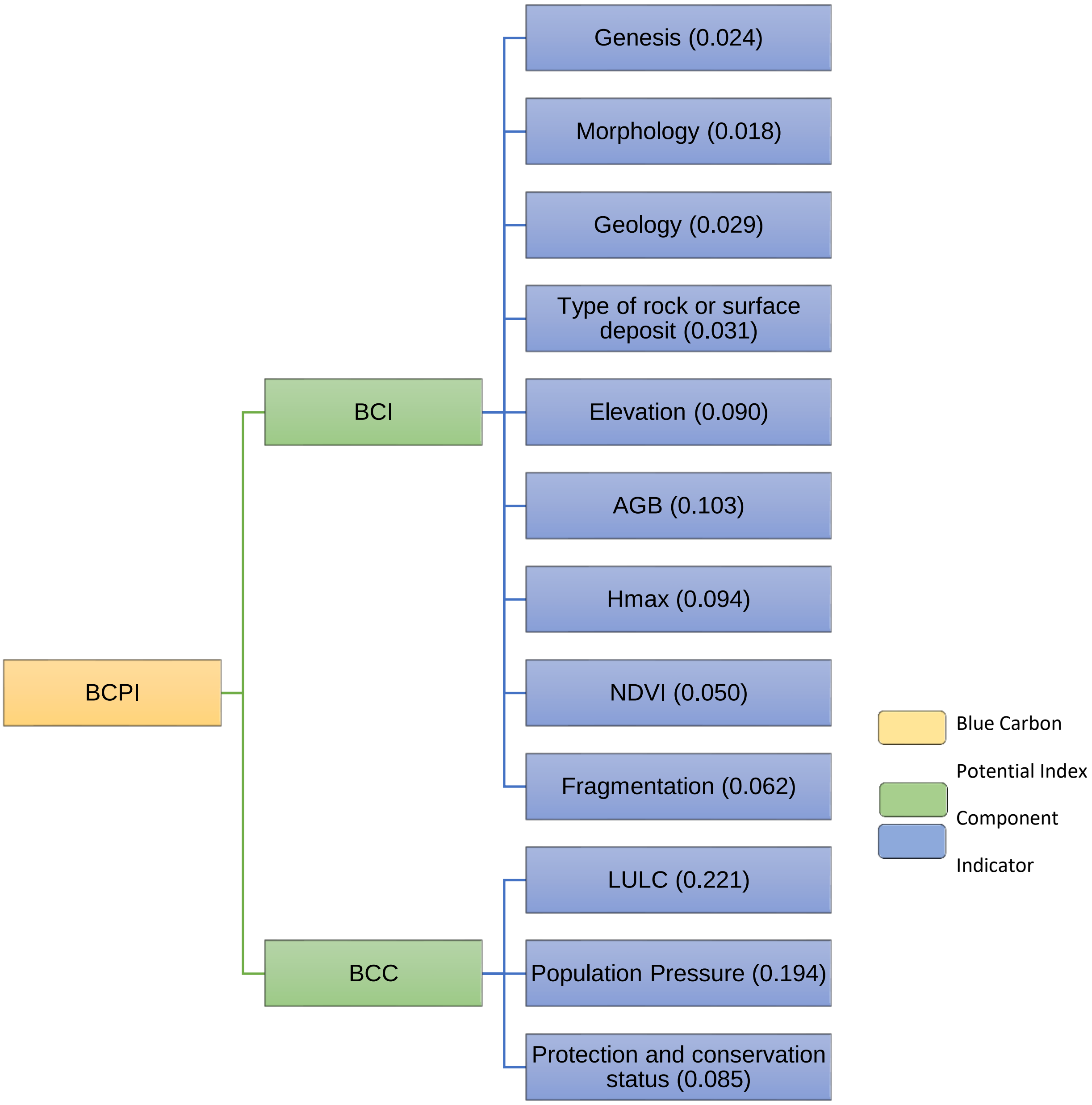

Figure 10. Weighted results of indicators of the AHP method.

The calculation of consistency radio was performed in the third level of the hierarchy, evidently when comparing more than three different alternatives (components or indicators). The CR showed consistency in the judgments (>0.1) and were 0.089 and 0.017 for BCI and BCC indexes respectively. In Annex 3, the calculation of CR is amplified.

5.3. Blue Carbon Potential Index

The Blue Carbon potential levels are shown according to the chosen indicators in Table 16 and Figure 13. Among the biophysical factors, geology and mangrove fragmentation comprise the largest area with high potential of blue carbon with 206845.04 ha (37,85 %) and 140463.96 ha (25.70 %) respectively. On the contrary, AGB, Hmax, and rock type deposits had strongly limited areas as depicted in Figure 11 and Table 16.

	High Potential		Moderate Potential		Low Potential		No Potential	
	ha	%	ha	%	ha	%	ha	%
Genesis	100877.75	18.46	119575.97	21.88	98258.23	17.98	227822.92	41.68
Morphology	99879.39	18.28	81266.01	14.87	59291.00	10.85	306098.47	56.01
Geology	206845.04	37.85	153.32	0.03	14980.78	2.74	324555.73	59.38
Rock type	59323.28	10.85	49492.24	9.06	99651.50	18.23	338067.84	61.86
Elevation	264234.51	48.34	0	0	0	0	282300.36	51.65
AGB	8564.85	1.57	24315.57	4.45	54365.31	9.95	459289.14	84.04
Hmax	36713.61	6.72	11979.90	2.19	38557.53	7.05	459283.83	84.04
NDVI	63353.52	11.59	110009.97	20.13	89389.44	16.36	283781.94	51.92
Fragmentation	140463.96	25.70	96522.93	17.66	186194.08	34.07	123353.89	22.57
LULC	197650.53	36.16	37123.07	6.79	232272.72	42.50	79488.55	14.54
Population pressure	306272.21	56.04	81999.66	15.00	182528.88	3.39	139734.12	25.57
Protection Status	40138.10	7.34	9114.09	1.67	54245.83	9.93	443036.85	81.06

Table 16. Potential Blue Carbon Areas based on the indicators.

The extent of AGB and Hmax are very similar in Figure 13, but their spatial patterns after the reclassification differ (Table 16). The growing and small mangroves (categories 1 and 2 in the AGB indicator) represent just 7.103% of the study area and the more developed mangroves with more than 200 Mg/ha account for barely 0.773%. Meanwhile, regarding the Hmax, the dominant class is comprised of the tall-statured mangroves accounting for 3.481% of the zone.

Regarding the socioeconomic indicators of BCC, the population pressure entails 306272.21ha (56.04 %) of high potential, followed by LULC with 197650.53 ha (36.16%). Although, 81.06% of the study area is not suitable for carbon sequestration in terms of protection status as indicated in Figure 12.

Despite no studies in the region were found linking the carrying capacity of the mangrove forest, the population density in the area ranges from 0 to 89 508 people/km^2 and comprises a total population of 2,207,478 inhabitants, including Teguel, General Villamil, Balao, Durán, and the most crowded city of Ecuador, Guayaquil (INEC, 2010). These values are relatively low compared to larger metropolitan areas surrounded by mangrove forests such as Ho Chi Minh City, which its population density in urban districts varies from 2,360 persons/km^2 to 3326 persons/km^2 (Nhan Thi Ho *et al.*, 2018); accounting with a total population of 8 993 082 inhabitants in the metropolitan area (Vietnam, 2020).

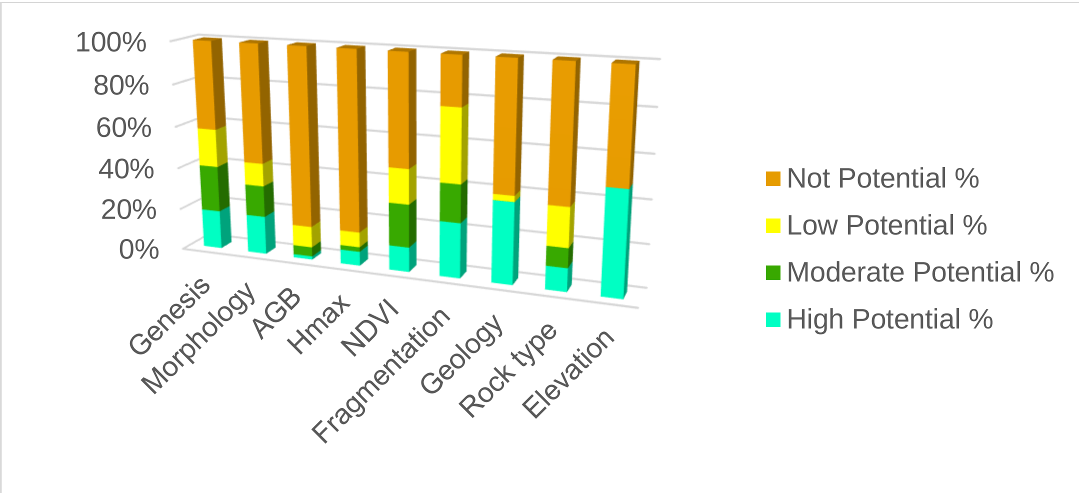

Figure 11. Potential levels of BCI.

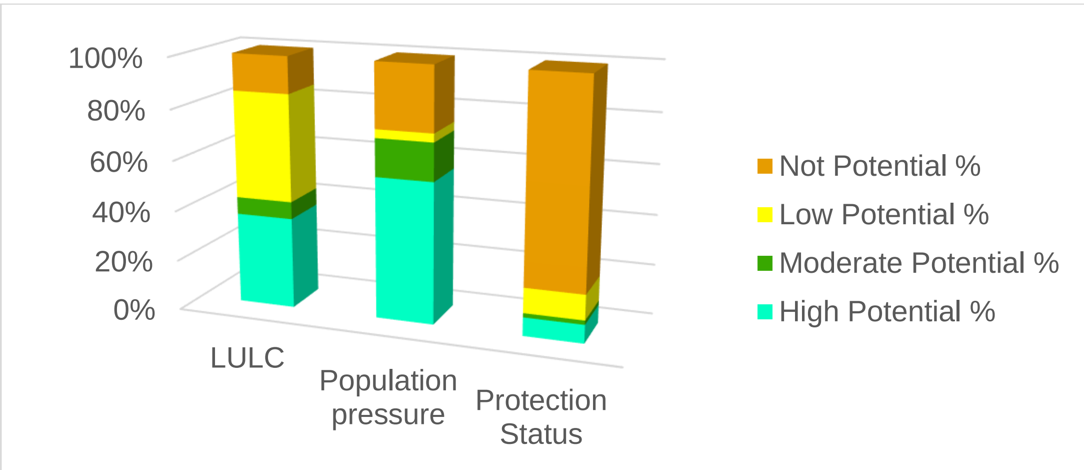

Figure 12. Potential levels of BCC indicators.

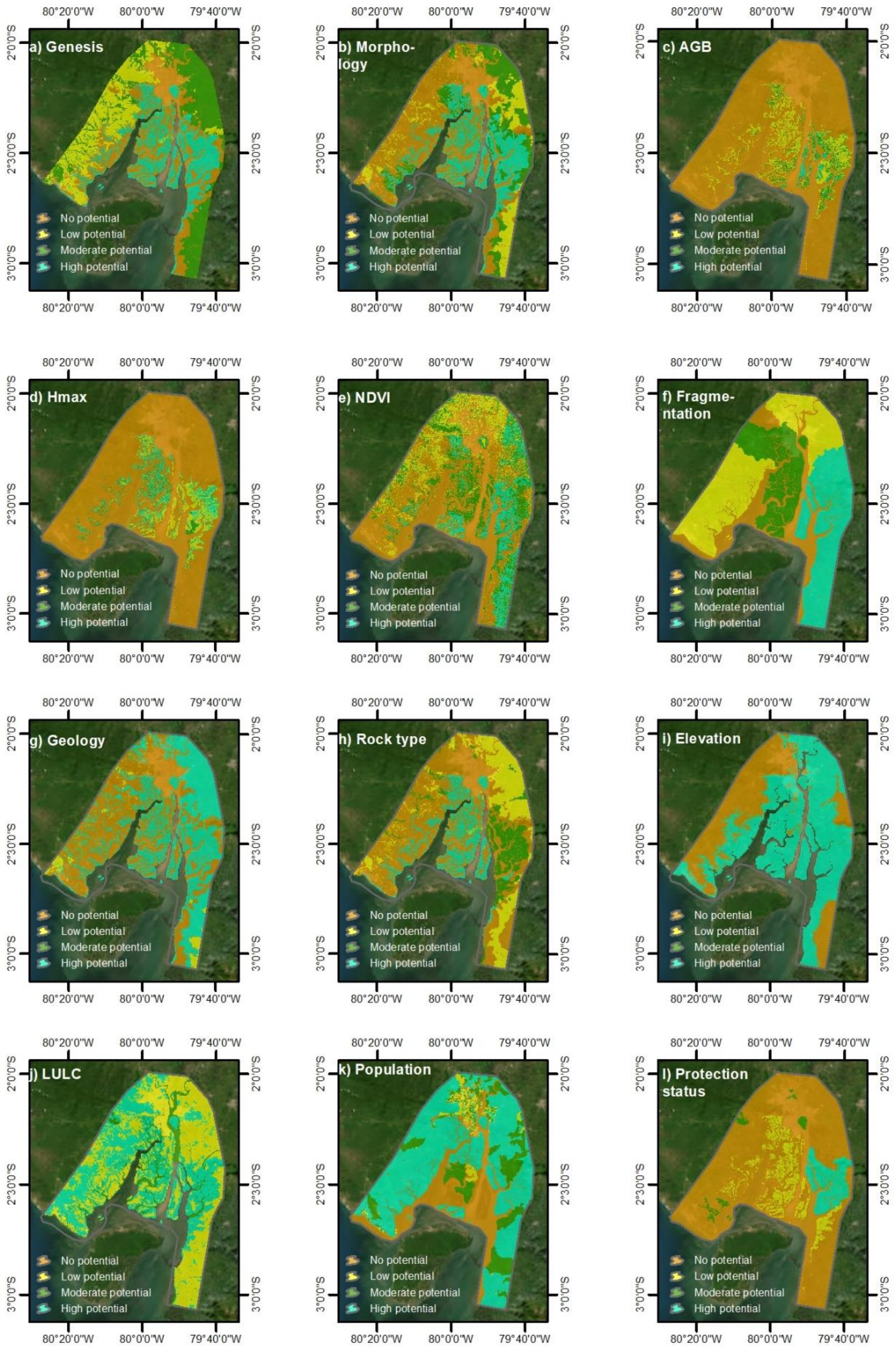

Figure 13. Maps of potentiality levels of the indicators that encompass the BCPI.

In order to compare the outputs of components of the BCPI, regardless of the SMCA method, the BCI and the BCC were plotted with the weights obtained from the AHP procedure and with equal weighting method as depicted in Figure 14.

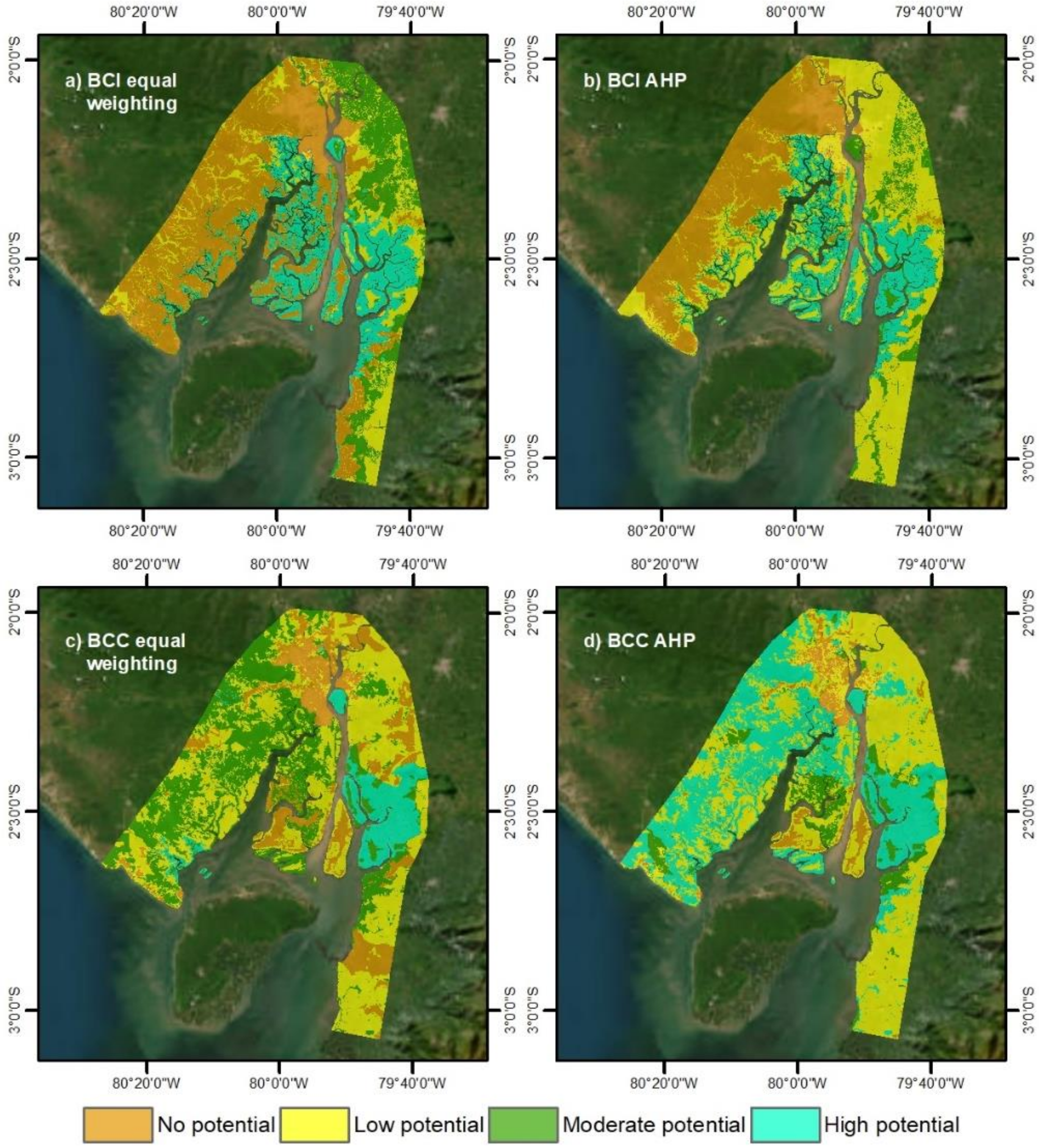

Figure 14.BCI and BCC maps with equal weighting method and AHP.

The BCC with AHP weighted indicators showed the highest potential percentage (35.77%) of any other generated components (See Table 17). Considering the difference between the potential classes results for BCC and BCI, it could be seen that the overall difference between using or not using specific weights was significant (12.67% on average and a maximum difference of 27.046% in BCC moderate potential). This suggest how susceptible are the sub-indexes when using the AHP method and the weighted linear combination, though, the influence of each indicator to the main perspective is not overlooked in this case.

Table 17. Percentage of potential classes disaggregated by weighting method.

	High Potential	Moderate Potential	Low Potential	Not Potential
	%	%	%	%
BCI equal weighting	20.198	17.097	18.337	44.369
BCI AHP	17.590	10.187	42.047	30.176
BCC equal weighting	8.772	35.735	49.305	6.188
BCC AHP	35.771	8.689	49.316	6.224

Nevertheless, the variation of the potential classes when comparing the decision rules (AHP vs equal weighting) for the BCPI was very small; with an average of 2.67% of change, a minimum of 0.11% (High potential) and a maximum of 5,23% (Not potential). This implies that in this study case, there is no significant difference between using the expert judgment weighting method and the equal weighting method (See Table 18 and Figure 15).

Table 18. Percentage of potential classes of BCPI

	High Potential		Moderate Potential		Low Potential		Not Potential	
	(ha)	%	(ha)	%	(ha)	%	(ha)	%
BCPI equal weighting	69305.94	15.93	57682.26	13.26	251270.9	57.76	56798.1	13.06
BCPI AHP	68815.98	15.82	70512.03	16.21	261672	60.15	34057.17	7.83

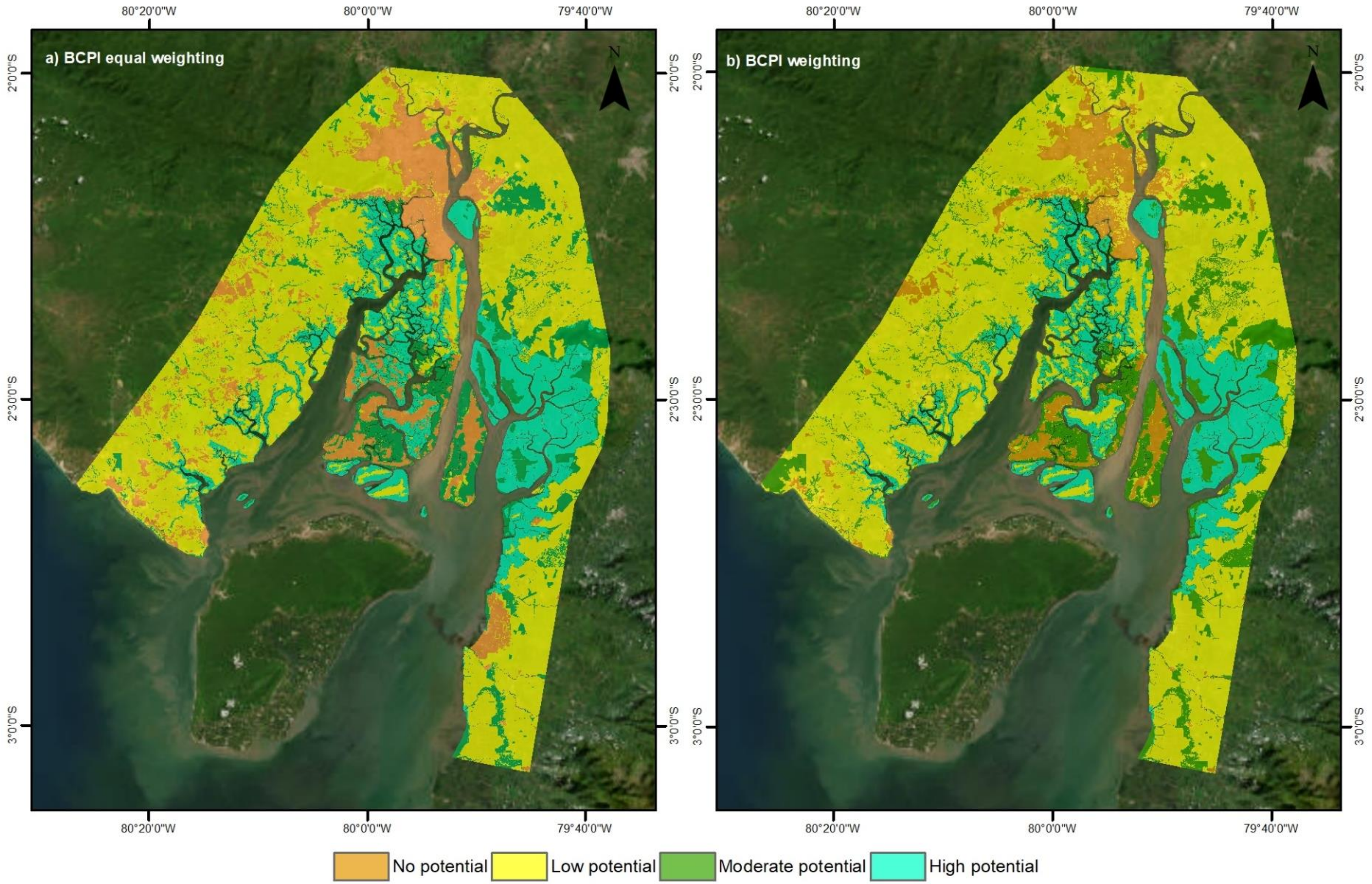

Figure 15. BCPI maps with AHP and equal weighting procedures.

5.4. Prioritization of blue carbon sequestration

After developing the BCPI, digital values higher than 0.8 were selected separately for visual ease and collated with the mangrove cover and current protected areas. As a result, 13 intervention polygons were sketched and classified according to a likely treatment to encourage carbon sequestration (See Figure 16).

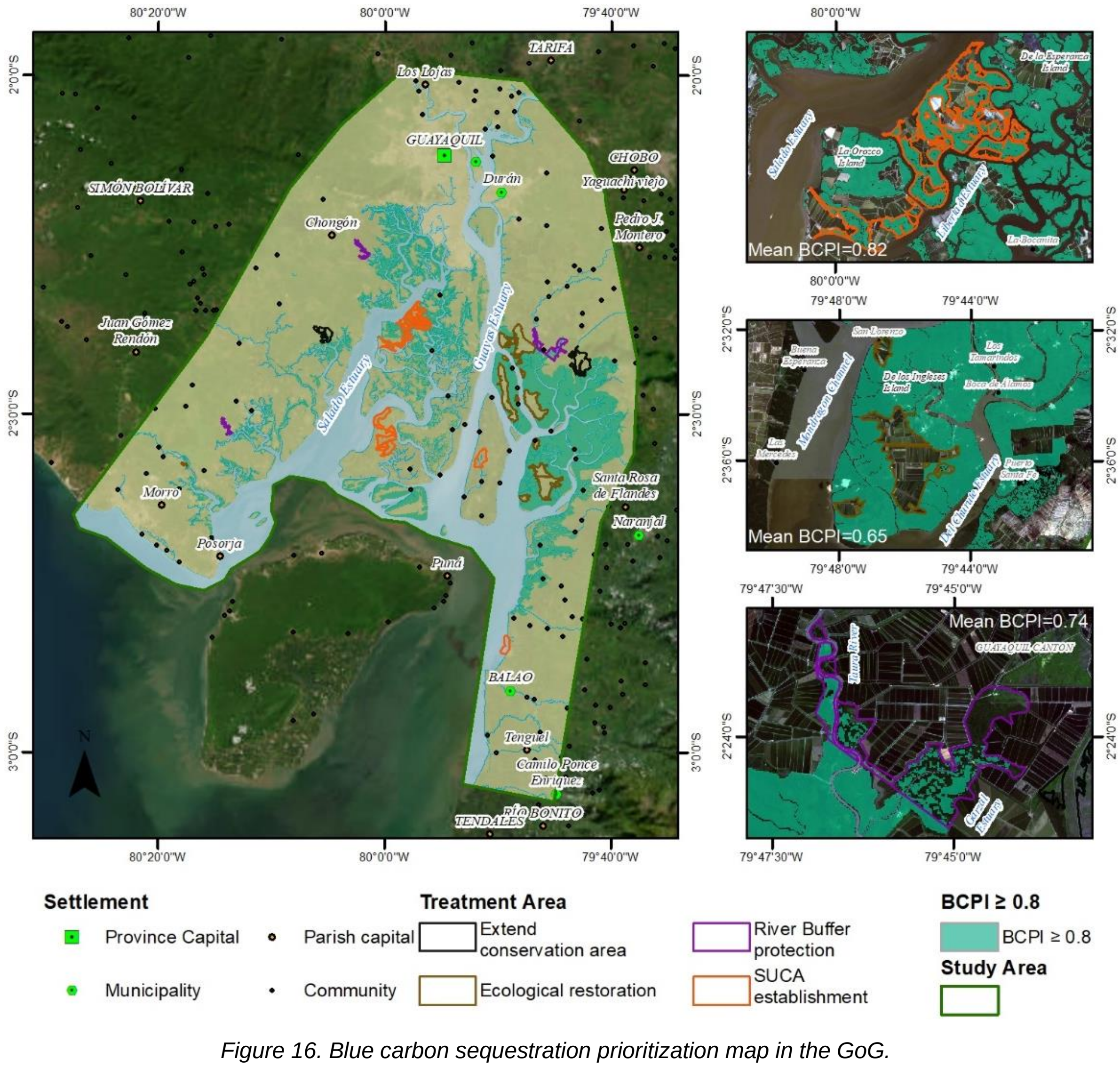

Figure 16. Blue carbon sequestration prioritization map in the GoG.

Then three areas were prioritized considering their extension that would represent wider carbon reservoirs after a proper restoration of the mangrove forest. The first area obtained a mean BCPI of 0.82, is proposed as a candidate for a SUCA, and is comprised of 1183.47 ha with moderately intervened mangroves near the Libertad Estuary. The second one ranked an average BCPI of 0.65 with 3230.487 ha and entails aquaculture ponds inside the ecological reserve Manglares Churute. Finally, this study suggests setting river protection areas in the surroundings of Taura River and Garzal Estuary, which accounts for 640.139 ha and reached a mean BCPI of 0.74.

On the other hand, the highest values of BCPI (> 0.9) are localized at the east of the GoG in the ecological reserve Manglares Churute; followed by some areas of the wildlife refuge Manglares el Morro as depicted in malachite green in Figure 15.

6. DISCUSSION

Since performing a direct measurement of carbon reservoirs in situ to map the blue carbon potential would result in extremely highly cost and time-consuming, indirect mapping through SMCA was proposed seeking to integrate different criteria through a decision-making rule based on certain weighting methods. However, this approach constitutes the first step to inquiring about the localization of the greatest blue carbon reservoirs in the GoG but does not reach the accuracy of classic protocols for measuring this regard. Even so, this method has been described as a reliable method to measure blue carbon pools (Claes *et al.*, 2022).

The weighted linear combination is widely used for suitability in GIS assessments for its versatile application (Malczewski, 2000), therefore it was applied in the present study. Another advantage of this decision-making rule is its attribute of substitutability as a low score in certain indicators can be compensated with a high value on another (Eastman & Jiang, 1996 as cited in Eastman, 1999). This was evident when combining the BCI and BCC into the BCPI where environmental factors constrained the result index values by socioeconomic factors, especially in upstream zones where mangrove development is not suitable (See Figure 14). Nevertheless, in reality, it cannot be assumed that the criteria are completely independent and additive as the method suggests and that have embraced all the complexities of the decision-making problem (Greene *et al.*, 2011).

Despite the AHP may encourage transparency, participation, and in some cases simplifying the understanding of the decision-making process by allowing the decision-makers to focus on a formally structured problem (Karlsson *et al.*, 2017), no consensus was attained. Clearly, the AHP is a subjective method rather than a statistical method (Sahin *et al.*, 2013), thus, the claim that the high complexity of the mangrove carbon sequestration system might not be completely represented in a lineal hierarchy where the variables are treated as independent is as valid as the fact that the different indicators affect in uneven quantity this ecosystem service. For instance, remarkable differences were detected when developing the BCI and the BCC through the two different weighting methods, being more restrictive in this case the equal weighting method as seen in Figure 14.

The BCPI structure is determined by the indicators taken into consideration and their ponderations. Therefore, this step could be restructured in sub-criteria of blue carbon storage, preservation, generation, and permanency of coastal wetlands as Rogers et al. (2019, 2022) proposed in their first-pass assessment framework. Nevertheless, this structure could not be fostered entirely due to the richness of the available dataset employed and the scale addressed. Yet, the sub-criteria utilization allows the addition of more factors to BCPI construction as long as the subjected indicators are less than seven (Saaty & Ozdemir, 2003; as cited in Karlsson et al., 2017). Although the AHP does not have a limit on the number of variables to compare per level, that number is proposed as manageable to ensure effectiveness in the judgments and to avoid overwhelming the decision-makers.

The final BCPI is highly influenced by the AGB since only the presence of mangrove forests is a proxy of blue carbon potential. However, the elevation factor plays an important role in the BCPI limiting the in big manner the non-suitable zones for blue carbon vegetation rise. This constitutes again an example of the substitutability attribute as stated before. However, among the compatibility indicators, population pressure was considered highly important in the AHP, where the contrary phenomenon occurs being this more permissible in depicting suitability zones. Hence, the AHP process grants the decision-makers moderately higher control over the indicators employed than the equal weighting method.

Although the selected prioritized areas were meaningfully chosen by its extension, the SMCA revealed also suitable places for expansion in certain current protected areas. These are the cases of the Ecological reserve Manglares Churute to the boundaries of the Association of artisanal fishermen crabbers “Nuevo Porvenir”, “6 de Julio”, and “Balao”; and the upstream zone adjacent to the SUCA granted to the Association of artisanal fishermen crabbers and related "Ríos de aguas vivas", Indeed, these two areas are valuable for carbon uptake, since conservation is twenty-four to sixty times cheaper than restoring mangroves, and in the meantime avoid further CO_2 emissions (Siikamäki et al., 2012 as cited in Gattuso et al., 2018).

The highest values of BCPI were within the protection areas with the highest status protection in the area, as less human disturbance is expected inside these boundaries. Is still important to note that both places are composed of different statured mangrove species, which in turn may indicate higher carbon sequestration.

The BCPI Map indicates areas of potential carbon stocks after a proper restoration of mangrove areas as long as the forest reaches maturity. These potential reservoirs might be seen as a mixture of biomass increase in addition to other ecosystem services and prevented losses from the permanent decomposition process of soil carbon rather than immediate carbon gains (Worthington and Spalding, 2018).

6.1. Limitations

The SLR has been pointed out as one of the most influential drivers of change in mangrove composition and functioning as a consequence of climate change (Semeniuk, 1994; Doyle et al., 2003). Resilience and permanency of Mangroves given the fluctuations of the sea level mainly relays on keeping pace with the SLR by increasing the soil surface underneath due to sediment accretion processes (Cahoon *et al.*, 2006; Gilman, Ellison and Coleman, 2007; Ellison, 2015). Landward migration on these wetlands is effective as long as surface elevation follows the SLR and no anthropic or natural barriers impede the dynamics (Fu *et al.*, 2019), otherwise, it causes mangrove loss. According to the Intergovernmental Panel on Climate Change, the SLR is foreseen to increase between 0.29 m and 1.1m by the end of this century (IPCC, 2022). This indicator was not employed as an indicator of mangrove permanency since the current assessment addresses the present temporal dynamics of blue carbon potential. Although is recommended for further studies with future scenarios evaluation.

Other indicators that would enhance the BCPI assessment are salinity, sedimentation, and tree composition as the important role they play in the carbon sequestration process by mangroves indicated in the literature review. Unfortunately, no datasets in this regard were already available and as the BCPI seeks to become the first study previous to further carbon accountability studies, the sampling of these factors would result in high-costly inefficient at the landscape scale. Also, tidal connectivity presents the same limitations as the previous drivers mentioned. Even though the inputs to map this factor (tidal channels and creeks) might be in the custody of the Oceanographic and Antarctic Institute of the Navy (INOCAR by its acronym in Spanish), the effort to quantify the degree of connectivity between the different areas in the coastal environment implies a considerable amount of time.

Validation of BCPI involves an independent dataset that may include in situ measurements to determine the total carbon stocks of the forest or independent trustable datasets of proxies of blue carbon potential. Given that the blue carbon potential is not directly observable, its validation relies better on the employment of proxies such as SOC or sediment carbon density by analyzing carbon in cores. This process is crucial to grant robustness and consistency when compared with the real system, but was not achieved because of the current national insecurity, the uneven presence of piracy, and the recurrent ENSO phenomenon striking the study area.

7. CONCLUSIONS

Twelve relevant biophysical and socioeconomic indicators were selected to describe carbon sequestration in the GoG. In doing so, the reclassification of the variables into high, moderate, low, and null blue carbon potential successfully provided valuable spatial information in terms of carbon sequestration.

The BCPI based on the integration of biophysical and socioeconomical indicators supported by the SMCA, allowed a tailored quantification of carbon sequestration potential in the GoG. This index provides a comprehensive understanding of the spatial distribution of areas with high blue carbon potential, which in the study case are located in the ecological reserve Manglares Churute and certain areas of wildlife refuge Manglares el Morro (BCPI>0.9).

Moreover, the provided framework to assess coastal landscapes through the SMCA supported by GIS granted the opportunity to identify and prioritize high-potential areas for blue carbon sequestration in the GoG. Thus, the BCPI may serve as a valuable tool to scale and quantify this potential regarding conservation and management endeavors in the GoG. Stakeholders and decision-makers can allocate resources and target initiatives to maximize carbon sequestration, enhance mangrove forest resilience, and mitigate climate change impacts.

No significant difference was found when employing expert judgment weighting and equal weighting methods because of the substitutability attribute embedded in the weighted linear combination method. Therefore, is recommended for future studies the exploration of factor interaction method (FIM) when seeking to construct a BCPI, since it allows to include in the assessment possible linkages or independence between the factors.

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ANNEX

Annex 1: Studies included in the review.

Nro.	Author	Database	Country	Spatial scale	Driver addressed	Feedback (+/-)
1	(Ruan *et al.*, 2022)	Science Direct	Asia	Regional	Health of vegetation	+
2	(Carnell *et al.*, 2022)	Science Direct	Australia	Local	Forest maturity	+
3	(Palacios *et al.*, 2021)	Science Direct	Australia	Local	Nutrients	-
4	(Murdiyarso *et al.*, 2021)	Nature	Indonesia	Local	Sedimentation	+
5	(Santos-Andrade *et al.*, 2021)	Science Direct	Brazil	Regional	Domestic sewage Aquaculture	-
6	(MacKenzie, Sharma and Rovai, 2021)	Science Direct	Worldwide	Worldwide	Environmental Drivers	+/-
7	(Rahman *et al.*, 2021)	Nature	Bangladesh	Regional	Mangrove tree composition	+
8	(Xiao *et al.*, 2021)	Wiley	USA	Local	Bioturbators	-
9	(Turschwell *et al.*, 2020)	Science Direct	Worldwide	Worldwide	Fragmentation Population pressure	-
10	(Govender *et al.*, 2020)	MDPI	South Africa	Regional	Pollution	-
11	(Goldberg *et al.*, 2020)	Wiley	Worldwide	Worldwide	LULC	-
12	(Bryan-Brown *et al.*, 2020)	Nature	Worldwide	Worldwide	Fragmentation	-
13	(Sasmito *et al.*, 2019)	Wiley	Worldwide	Worldwide	LULC	-
14	(Rogers *et al.*, 2019)	Springer	Australia	Regional	Geology	+/-
15	(Worthington and Spalding, 2018)	Research Gate	Worldwide	Worldwide	Logging Anthropogenic pressures	-
16	(Sippo *et al.*, 2018)	Science Direct	Worldwide	Worldwide	Cyclones SLR	-
17	(Kauffman *et al.*, 2018)	Wiley	Brazil	Regional	Aquaculture	-
18	(Twilley, Rovai and Riul, 2018)	Wiley	Worldwide	Worldwide	Geomorphology	
19	(Pérez, Libardoni and Sanders, 2018)	Research Gate	ND	Regional	Sedimentary environment Anthropogenic preassures Type of sediment	+/-

20	(Carugati *et al.*, 2018)	Nature	ND	Local	Biodiversity (Benthic)	+
21	(Hamilton & Friess, 2018)	Research Gate	Worldwide	Worldwide	Deforestation	-
22	(Kauffman *et al.*, 2017)	Research Gate	Central America and Asia	Local	Aquaculture Cattle	-
23	(Atwood *et al.*, 2017)	Research Gate	Worldwide	Worldwide	Primary productivity Mangrove Tree composition	+
24	(Macreadie *et al.*, 2017)	Research Gate	Worldwide	Worldwide	Bioturbators nutrients	+/-
25	(Marchand, 2017)	Science Direct	French Guyana	Country	Forest maturity	+
26	(Kauffman *et al.*, 2016)	Springer	Mexico	Local	LULC: cattle	-
27	(Sanders *et al.*, 2016)	Wiley	Indo-pacific	Regional	Precipitation	+
28	(Andreetta *et al.*, 2014)	Science Direct	Kenya	Local	Bioturbators	+
29	(Chellamani, Singh and Panigrahy, 2014)	Research Gate	India	Regional	Health of vegetation	+
30	(Kauffman *et al.*, 2014)	Wiley	Dominican Republic	Local	LULC: logging, aquaculture	-
31	(Lee *et al.*, 2014)	Wiley	Worldwide	Worldwide	Sedimentation Peat formation	+
32	(Lang'at *et al.*, 2013)	Springer	Kenya	Local	Mangrove Tree composition	+
33	(Osland *et al.*, 2012)	Springer	USA	Regional	Forest maturity	+
34	(Donato *et al.*, 2011)	Research Gate	Indo-pacific	Regional	Forest stature soil depth	+
35	(Parida and Jha, 2010)	Springer	Worldwide	Worldwide	Salinity	+/-
36	(Kauffman and Cole, 2010)	Springer	Micronesia	Country	Storms	+/-
37	Polidoro 2010	Research Gate	Worldwide	Worldwide	Fresh water Agriculture Aquaculture	-
38	Smith 2009	Springer	USA	Regional	Bioturbators	+
39	Gilman 2008	Science Direct	Worldwide	Worldwide	Precipitation Temperature Storms Sea Level Rise	+/-
40	(Borbor-Cordova *et al.*, 2006)	Springer	Ecuador	Regional	Nutrients	+/-
41	(Barbier and Cox, 2003)	Wiley	Worldwide	Worldwide	Deforestation Population	-

Annex 2: Geomorphology classes and codes according to the technical report of Geomorphology dataset (IEE, 2011a).

Code	Description
Ma	Tidal marsh: Plain reliefs with slopes from 0 to 2%, characterized by an important presence of sea water through waves and tidal changes. Due to favorable conditions, this ecosystem accounts for a wide variety of fauna and flora, chiefly mangroves. They are comprised of fine deposits of marine origin, mainly silt, sands and clays.
Nb	Plain level: This relief form has as a main characteristic plain terrain, with predominantly slopes from 0 to 2%. It is distributed in the northwest of Daule river, and in the Guayaquil's south in Puente Lucia, and Los Laureles sector, and even in Tenguel Parish. The predominant vegetation cover are yearly crops of rice, banana, cacao, and natural vegetation.
Spi	Flat intervened surface: This zones are estuaries and marsh zones, which have been intervened mainly for the construction of shrimp ponds and tilapia fish farms. They are located mostly in the north of Guayaquil Canton nearby sea zones. The slope ranges from 0 to 2%.
Est	Estuaries: Water bodies where the mouth of a river opens into a marine ecosystem, with moderate salinity because of the mixture of freshwater and sea water. I possess a slope varying from 2 to 5% with less than 5 m of difference. They are in the coastal zone in the southeast part of the canton. They are comprised of fine silts, sands and clays.
Slt	Salt surface structure: Coastal natural shallow natural areas with high accumulation of salty water, where though evaporation salty deposits are formed. They present almost flat slopes with a 5 m difference among sites.
Crl	Spit: Enlarged sand deposits or gravel deposits generally parallel to the coastal line. They are formed as a result of sedimentary marine inputs and littoral forming deposits that substitute the coastal contours as a dike or a set of dikes.
Na	Wavy level with presence of water: Comprised by an association of soft undulations with metric amplitude from 3 to 5 m and permanently flooded hollows. This is the typic aspect of a wavy model where just the summits emerge.
Nb	Plain level: Considered as the base level of a plain. Present a flat topography and slopes under 2% with a difference not superior to 5 m. They are directly affected by floods.
Plc	Coastal plain: Plain surfaces or slightly inclined straight to the coast and limited by a short escarpment. The elevation difference between sites is not superior to 15 m and slopes under 5%. They and comprised by marine and continental sediments (Gravels, sands and silts).
Tb	Lower terrace and current riverbed: It consists of the riverbed and a level superior. It is comprised of alluvial deposits. They constitute remnants of ancient sedimentation levels, and they represent the lowest surface level from the current level of deposition. Thus, its linked to fast floods of rivers.
Co	ancient alluvial colluvium: They are formed by the deposition of alluvial material added the gravitational lateral inputs of surrounding hilly shapes. They show certain grade of dissection covered by growth vegetation, which in turn indicate a higher level of mature.
Pc	Clogging surface: Plain surfaces to wavy surfaces with no dissection or very low dissected, with slope ranging from 2% to 5%. It is characterized by deposition of fine gravels, sands, silts and in less proportion, clays.

Code	Description
Va	Fluvial valley: Elongated relief shape with relatively plain slope (not superior to 5%) and transversal section narrow. It has as its axis a river that usually flows in a sinuous way. It uses to be floodable in winter season.
D	Alluvial Bank: They are wedge-shaped bands of sediment bordering fluvial channels. They dip gently from the edge of the channel to the outer edge of the floodplain. They are more developed on the concave sides of the channel.
No	Slightly wavy level: Comprised by almost plain surfaces to slightly waved with recent alluvial deposits. The elevation difference is not beyond the 2 meters and the slope is inferior to 5%.
Py	Marine Beach: Almost flat surface that extends from the shoreline until the low tide line, formed by the accumulation of sediments supported by waves, river currents and wind. The slope range from to 5%.
Ces	Alluvial fans: With origins like fluvial fans, these are presented as surfaces straightly plains, with wide ripples and reduced which difference do not exceed 5 m.
Ct	Inlier: Form of residual relief of isolated character, formed as a result of the erosive processes of primary reliefs.
C2	Frontslope: Corresponds to the steepest and shortest slope that presents a slope, and that usually has slopes greater than 70%, and a relative level difference > 50 m.
Ges	Pediment: They are formed at the foot of the reliefs, which are made up of a weak stratum of detritus; they present slightly inclined slopes, which in some cases are covering the older reliefs.
R5	High hilly relief: They constitute elevations that reach 200 m of relative height difference.
R4	Medium hilly relief: They constitute elevations with relative slopes that reach 100 m. The summits have different degrees of dissection.
R3	Low hilly relief: They constitute elevations with relative slopes of up to 25 meters.
R2	Very low hilly relief: They constitute elevations whose slopes reach 12%, while their elevation difference reach up to 15 m.
R1	Undulating relief: They are reliefs of low vertical drop < 5 m. with elongated and/or rounded summits with convex slopes. Their slopes usually reach up to 5%.
C1	Cuesta Surface: Structural slope of a cuesta, which is formed by low-dipping monocline series, formed as a consequence of the partial degradation of gently folded sedimentary strata.
C5	Dissected surface of cuesta: Structural slope of a hillside, characterized by its high degree of dissection, formed by series of dissection, formed by low-dipping monocline series resulting from the partial degradation of gently folded sedimentary strata.
Vse	Erosion surface watershed: Corresponds to slopes with medium to steep gradients that largely cut into the erosion surfaces due to phenomena related to the reactivation of denudation as a result of the lowering of the base level of erosion.
Ta	High terrace: It is located on the middle terrace and corresponds to the oldest level of deposition of the river. It presents an accentuated dissection and more lush vegetation than the lower levels.
Tm	Middle terrace: Flat surface limited by an escarpment, located above the low terrace. It corresponds to an old sedimentation level of the river. It presents slopes of up to 5%, because it has already been modeled by erosive agents.

Code	Description
Ti	Undifferentiated terrace: Flat surfaces, remnants of previous sedimentation levels located above the maximum water level of a river, in which it is not possible to determine the different terrace levels from the current level of sedimentation.
Can	Old colluvium: It is composed of detrital materials, transported from the upper parts of the slopes by the action of gravity and deposited in the intermediate parts or at the foot of the slopes. The deposited materials deposited are of a poorly sorted angular character and without stratification, with small amounts of fine-grained material, it presents a higher degree of dissection, has more developed pioneer vegetation, which indicates a certain level of maturity or age.
Cds	Fluvial Fan: Cone-shaped sediment deposit usually formed at the foot of a slope characterized by the presence of dissected surfaces due to having been subjected over a long interval of time to secondary remodeling processes, mainly surface runoff. a long interval of time to the action of secondary remodeling processes, mainly surface runoff. Its slopes reach 25% while its relative slope can reach 50 m.
Sm1	Coastal terrace surface: They are sedimentary reliefs, generated by the action of marine trangressions and epirogenic movements; the process can be repeated more than once, generating several levels of marine tables or terraces. The marine table surface refers to the flat or tabular extension located in the upper part of the table, with a relative elevation difference no more than 15m and slopes of less than 5%.
Sm2	Dissected coastal terrace surface: These are terrace surfaces of marine origin, characterized by their high degree of dissection due to the action of a denudation process on the surface. They present slopes of less than 12% and elevation difference up to 15m.
Sm4	Coastal terrace hillside: Sloping lateral element of a coastal terrace, corresponding to its hillsides, with slopes ranging from 12 to 40%. It represents a lithologic change or not.
Vi	Undifferentiated valley: These are flat-bottomed valleys that remain flooded most of the year and are characterized by the absence of permanent fluvial dynamics, becoming hydromorphic zones that can be sporadically flooded by recent rivers or stagnant estuaries.
PzMzP	Punta Piedra Formation: Metamorphic rocks from the Paleozoic that are found in Punta Piedra hill and the western shore of Guayas river.
Km	Macuchi Formation: It is a series composed mostly of porphyritic lavas (andesites and basalts), breccias, agglomerates, sandstones and volcanic limonites, the rocks are highly fractured and weathered (Upper Cretaceous).
K3y	Cayo Formation: A compression phase, initiated by a displacement of the ocean floor, gave rise to the accumulation of pelagic sediments of siliceous consistency and turbiditic character, giving rise to this formation (Upper Cretaceous). The lithology corresponds to green siltstones, yellowish sandstone, chloritized greywackes, tuffs, and agglomerates,
K3Gy	Guayaquil Member: Its lithology comprises grayish brown silicified argillites with layers of Chert (dark gray flint nodules). It is made up of yellowish siliceous shales when they are not altered and are orange to reddish in color when weathered. It is found in Cerro Azul, in the Holcim cement quarries; they form high hilly reliefs (Upper Cretaceous).
E2Se	San Eduardo Formation: A calcareous turbiditic flysch was deposited on the edges of the Chongon-Colonche range (Middle-Lower Eocene). Lithologically, the formation is composed of bioclastic limestones (biomicrites), microcrystalline limestones, well stratified, light gray to cream-

Code	Description
	colored, locally black and generally dense. It originates in the Holcim quarries extending to the slopes of the Chongón and Colonche hills; it is in discordant contact with the Cayo formation.
Mp	Progreso Formation: Upper Miocene. In general, the rock type is represented by yellowish soft sandstones, gray clays and shales; in the Puná Island sector, this formation is presented as medium-grained gray calcareous sandstones and contains a large amount of fossils.
OMTz	Tosagua Formation and Zapotal member: Lower Miocene, the rock type presents intercalations of laminated shales and chocolate-brown clays in centimetric banks and the presence of gypsum.
E3An	Ancón Group: Lithologically, it is composed of yellowish-brown, slightly compacted medium-grained sandstones, intercalated with clays and greenish-gray shales (Superior Eocene).
E2-3Az	Azúcar Group: Middle to upper Eocene. It is quite strong and consists of three basic units, the lower Estancia (sandy-clayey), the middle Chanduy conglomeratic series, and the upper Engabao (sandy-clayey), the contact varies from place to place being generally faulted and rarely concordant with the underlying Cretaceous terrain.

Annex 3: Determination of Consistency Ratio (CR)

(a) CR for comparison of BCC indexes

	A*W
	1.340
	1.170
	0.511
λ max=	3.021

n=	3
CI	0.010
RI	0.58
CR	0.018

→ 0.018<0.1→ *Consistent judgments*

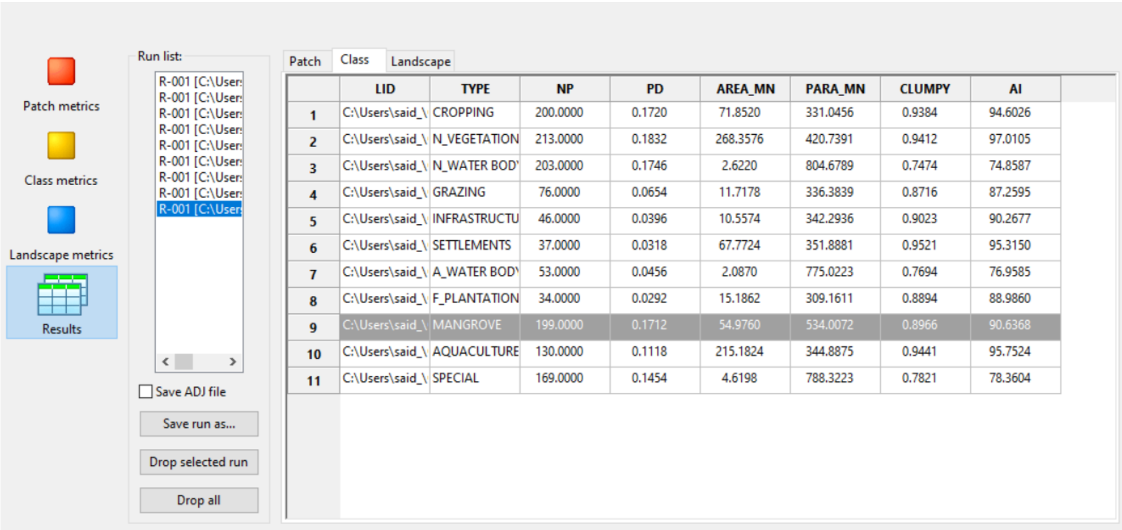
(b) CR for comparison of BCI indexes

	A*W
	0.449
	0.348
	0.549
	0.580
	1.866
	2.178
	1.869
	0.973
	1.217
λ max=	10.030

n=	9
CI	0.129
RI	1.450
CR	0.089

→ 0.089<0.1→ *Consistent judgments*

Annex 4: Inputs and outputs in Fragstats analysis.



	LID	TYPE	NP	PD	AREA_MN	PARA_MN	CLUMPY	AI
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2	C:\Users\said_\	N_VEGETATION	213.0000	0.1832	268.3576	420.7391	0.9412	97.0105
3	C:\Users\said_\	N_WATER BOD'	203.0000	0.1746	2.6220	804.6789	0.7474	74.8587
4	C:\Users\said_\	GRAZING	76.0000	0.0654	11.7178	336.3839	0.8716	87.2595
5	C:\Users\said_\	INFRASTRUCTU	46.0000	0.0396	10.5574	342.2936	0.9023	90.2677
6	C:\Users\said_\	SETTLEMENTS	37.0000	0.0318	67.7724	351.8881	0.9521	95.3150
7	C:\Users\said_\	A_WATER BOD'	53.0000	0.0456	2.0870	775.0223	0.7694	76.9585
8	C:\Users\said_\	F_PLANTATION	34.0000	0.0292	15.1862	309.1611	0.8894	88.9860
9	C:\Users\said_\	MANGROVE	199.0000	0.1712	54.9760	534.0072	0.8966	90.6368
10	C:\Users\said_\	AQUACULTURE	130.0000	0.1118	215.1824	344.8875	0.9441	95.7524
11	C:\Users\said_\	SPECIAL	169.0000	0.1454	4.6198	788.3223	0.7821	78.3604