German Environment Agency

30. May 2025

The relevance of autochthonous vs. allochthonous carbon in Blue Carbon ecosystems for climate change mitigation

As part of the research project FKZ 3722 42 510 0 ‘Climate protection measures in coastal regions and waters’

1 Introduction

For a long time, human-induced climate change was considered an issue that would affect future generations, but not us. However, as we increasingly experience its effects in our own bodies and neighbourhoods, we are beginning to realize that it is already here. It is part of the so-called "triple planetary crisis", which includes climate change, biodiversity loss and pollution.

Therefore, rapid action is required. At the 2015 Paris Agreement, the global community committed to taking measures to prevent global warming from exceeding 1.5°C. This primarily means reducing emissions of carbon dioxide and other greenhouse gases (GHG). However, it is clear that reducing emissions to the extent necessary to achieve the goals of the Paris Agreement, i.e. a reduction by 45 % until 2030, is challenging (UNEP, 2019). Other pathways to reach this goal, such as actively removing carbon dioxide (CO_2) from the atmosphere, have gained momentum. Various technical processes intended to enable large-scale removal are being trialled, but their success is by no means guaranteed.

In this context, the concept of ecological climate protection emerges as a pivotal element. In the distant past, the planet's temperature would have been significantly higher and its habitability would have been greatly diminished. If a substantial portion of CO2 emissions had not been promptly eliminated from the atmosphere and sequestered in terrestrial biomass and soil, as well as in oceanic water, biomass and sediments, the consequences would have been far more severe. Nature has implemented preventative measures through the evolution of life in the ocean approximately 3.5 billion years ago and on land approximately 400–500 million years ago, something we currently call "nature-based solutions".

The concept of nature-based solutions (NbS) extends beyond their role in climate protection. Nonetheless, NbS encompasses measures intended for the protection, conservation, restoration, and sustainable utilization of terrestrial, freshwater, coastal, and marine ecosystems. These measures also contribute to biodiversity, the provision of ecosystem services, as well as human well-being. Consequently, the implementation of ecological climate protection strategies can yield numerous benefits.

But how large is the potential of NbS for climate protection in view of annual greenhouse gas emissions of an estimated 60 gigatonnes of CO_2 equivalents (Gt CO_2e)? Taken together, the storage potential of forests, cropland, pastureland and terrestrial and coastal wetlands is estimated at 10-12 Gt CO_2e per year (Griscom et al., 2017), which clearly demonstrates that NbS are not an alternative to reducing emissions. Overall, however, the estimates are subject to major uncertainties, which make an overestimation of the storage potential very likely (Reise et al., 2022). While research in terrestrial areas is well advanced, it lags far behind in coastal and marine areas.

In recent years, carbon storage in coastal "Blue Carbon" ecosystems (BCE) gained attention. The term "Blue Carbon" was introduced in 2009, which led to an increased focus on the role of the ocean and coastal wetlands in mitigating climate change within the scientific community, as well as in political and public discourse.

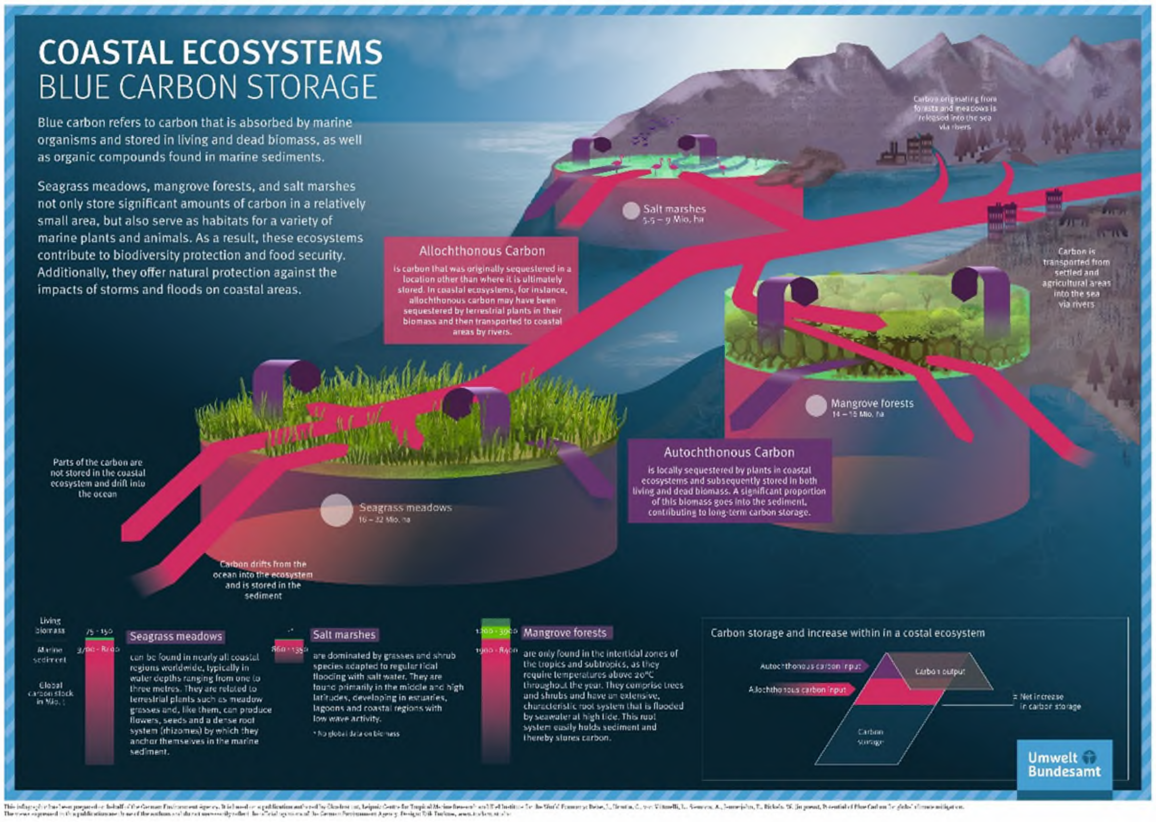
Blue Carbon is now a term used by many in connection with climate change mitigation, but there is no clear scientific definition for it. As a result, it has taken on a variety of meanings, leading to inconsistencies in the dialogue between science, politics and civil society. The establishment of some important criteria laid the common basis for a discussion that is necessary for political and social negotiations. Lovelock and Duarte (2019) outlined six such criteria taking into account that conserving, restoring and protecting marine ecosystems avoids CO_2 emissions associated with their destruction. The criteria for including coastal ecosystems as actionable Blue Carbon habitats are: (1) the scale of GHG removals or emissions is significant, (2) the fixed CO_2 is stored long-term, (3) the BCE suffers from undesirable anthropogenic impacts, (4) management of the BCE is possible to maintain C stocks and reduce GHG emissions, (5) interventions cause no environmental or social harm, and (6) the alignment with other policies: mitigation and adaptation (Lovelock and Duarte, 2019).

The BCEs currently accepted by science and society, fulfilling the aforementioned criteria, are mangrove forests, seagrass meadows and salt marshes. Ecosystems under discussion are macroalgae, seaweed, marine sediments and unvegetated tidal flats. However, for the latter the current state of research does not yet allow an assessment of the additionality of carbon storage through human intervention (Lovelock & Duarte, 2025).

While BCE are among the most carbon-dense natural sinks per unit area on the planet, there are still large uncertainties in the quantification of carbon stocks and fluxes, i.e. in their carbon sequestration, hence, we refer to climate change mitigation *potential*. An additional uncertainty in this context, though hardly considered as yet, is the origin of the carbon stored in BCEs. They are intertidal ecosystems which also receive inputs from adjacent ecosystems. A large part of the stored carbon results from production in the ecosystem, the so-called "autochthonous" carbon. However, there is also an external input, the so-called "allochthonous" carbon (Figure 1).

It is debatable whether allochthonous carbon is an accounting relevant term for the quantification of the climate mitigation potential of a BCE. Per definition, allochthonous carbon is the result of CO_2 uptake in a different location and possibly in the distant past. This has serious implications for carbon accounting mechanisms in Nationally Determined Contributions (NDCs) and National Inventory Reports (NIRs) under the United Nations Framework Convention on Climate Change (UNFCCC) on the one hand, and also for Blue Carbon projects (BCPs) on voluntary carbon markets on the other hand. However, this issue is not properly addressed in carbon accounting in the voluntary carbon market as yet. This paper discusses the importance of distinguishing between autochthonous and allochthonous carbon and presents different approaches for determining both, as well as potential associated challenges. Furthermore, this paper analyses to what extent quantification approaches for BCPs by crediting programmes on the voluntary carbon market differentiate between autochthonous and allochthonous carbon and provides options for improving the quantification of allochthonous carbon for such projects in the future.

Figure 1: Conceptual overview and carbon reservoirs of Blue Carbon ecosystems.



Source: Reise et al. (2024). Available for download in high resolution at https://www.umweltbundesamt.de/publikationen/potential-of-blue-carbon-for-global-climate-change.

2 Definition of autochthonous and allochthonous carbon and relevance for climate change mitigation

The uptake of CO_2 in BCE and its direct conversion into biomass or organic matter and storage in the respective BCE directly contributes to active removal of CO_2 from the atmosphere, hence it is relevant in terms of climate change mitigation. This internally produced organic carbon is the "autochthonous" carbon. However, through the continuous exchange with adjacent terrestrial and marine ecosystems, BCE also receive and store large amounts of externally produced organic matter, the "allochthonous" carbon.

The element carbon has a central role in climate, and carbon budgets usually include only the amount of the element carbon itself, sometimes also per unit area and time. However, in nature we usually do not find carbon in elemental form, but always in chemical compounds also including other elements. This, in turn, plays an important role in the distinction between and relevance of "autochthonous" and "allochthonous" carbon in climate change mitigation. The quantitatively most important source of the observed atmospheric warming, the gas CO_2 is a fairly simple inorganic molecule. However, when it comes to the quantitatively most important sink for carbon, biomass or organic matter resulting from the conversion of CO_2 through photosynthesis, we are talking about complex organic molecules which also contain numerous other chemical elements.

There is a large diversity of chemical compounds existing, which have different physical and chemical properties and different functions in plant and animal life. Moreover, there are numerous transformation and degradation pathways that convert organic compounds into other ones. Ultimately, the decomposition of organic matter ends in the release of CO_2. However, depending on the various transformation pathways and the properties of the intermediate compounds, this can take from decades to millennia. The most important organic compounds that can be found in the natural environment are hydrocarbons, carbohydrates, lipids, proteins, nucleic acids and humic substances (Libes, 1992). The composition as well as the transformation of organic matter can also differ largely between terrestrial and aquatic ecosystems. In addition, the transport of allochthonous organic matter from its source ecosystem to a BCE, where it is stored in the long-term, prolongs the time the organic matter is exposed to transformation and degradation. Hence, the autochthonous and allochthonous portions of organic matter stored in BCE can vary largely in their chemical composition, which affects their vulnerability to further degradation and hence the long-term storage in deposits. Knowledge on the biogeochemical composition and transformation of the autochthonous and allochthonous portions of organic matter is therefore an important prerequisite for assessing the long-term storage of carbon in natural sinks on earth.

In terms of accounting for carbon stored in BCE to determine the mitigation impact of these ecosystems, the allochthonous portion of carbon buried in BCE sediments needs to be excluded, because the BCE did not remove the allochthonous carbon from the atmosphere. This is relevant for carbon accounting in national inventories of GHG emissions and of particular importance for Blue Carbon projects designed to create carbon offsets through sequestration, and which issue carbon credits to be sold on the voluntary carbon market. Projects that receive carbon credits under carbon crediting programs on the voluntary carbon market must demonstrate so-called "additionality". The project must demonstrate that greenhouse gas emission reductions or removals (ERR) in the project area would not have occurred without the project intervention. However, in the case of allochthonous carbon the CO_2 that was converted into organic matter was removed from the atmosphere in a different location and possibly in the distant past, and its long-term storage may have occurred anyway (Jennerjahn, 2021a, Williamson and Gattuso, 2022). Hence, allochthonous carbon does not fulfil the additionality criterion.

Despite this fact there are also recommendations not to deduct allochthonous carbon (Lovelock et al., 2023; Houston et al., 2024). For example, in the Australian Carbon Credit Unit scheme it is argued that any carbon exported from the terrestrial hinterland would be decomposed and lost to the atmosphere on its transit to the BCE. Therefore, all soil carbon including the allochthonous portion in BCE projects is considered additional, because it would not have been deposited if the project had not existed, and it would not have been accounted for in any GHG inventory or NDC progress tracking (Lovelock et al., 2022, 2023). Houston et al. (2024) argue that in BCPs allochthonous carbon should only be deducted when an observational or experimental approach allows calculating the allochthonous carbon in the project area to ensure that any carbon credits issued are genuine and additional. However, in all other cases, they suggest not to deduct allochthonous carbon because of the general inconsistencies of the available methods, and the lack of scientific rigor and universal applicability in accounting for additionality.

To a certain extent, the arguing is comprehensible. However, taking a conservative approach to avoid overestimating ERRs and preserving environmental integrity, the opposite approach should be followed. All allochthonous carbon should be deducted and the most conservative approach should be chosen to calculate GHG ERRs from soil carbon accumulation in BCPs.

3 Determination of autochthonous and allochthonous carbon

Because of the complex nature of the chemical compounds forming the organic matter, the distinction between autochthonous and allochthonous carbon requires sophisticated and reliable methods. There is a number of methods available that allow – with varying degrees of certainty – to distinguish between different sources of organic matter, including the analysis of elemental composition, bulk stable isotopes, compound-specific stable isotopes, biomarkers, molecular properties, and environmental DNA (Geraldi et al., 2019). Bulk elemental C and N (carbon and nitrogen) and stable carbon and nitrogen isotope (δ13Corg, δ15N) composition have been widely used to determine terrestrial and marine organic matter sources (e.g., Fischer, 1991; Meyers, 1994; McClelland et al., 1997; Saintilan et al., 2013; Watanabe and Kuwae, 2015; Kennedy et al., 2016; Kusumaningtyas et al., 2019). These are also the most commonly used methods. However, because of value range overlaps and other constraints, these methods do not always deliver unequivocal results.

Other helpful isotope-based methods are the analysis of bulk stable hydrogen, oxygen and sulfur isotopes (e.g., Peterson and Fry, 1987; Lovelock et al., 2017). The analysis of specific organic compounds, i.e. biomarkers, such as n-alkanes or phenolic compounds is also being used to trace organic matter sources (e.g., Derrien et al., 2017). Similarly, the analysis of the compound-specific stable isotope composition of, for example, amino acids, carbohydrates and lipids have been used for isotopic fingerprinting and source tracing in food webs and marine sediments (e.g., Chikaraishi, 2006; Larsen et al., 2015). The most recent technique which is now widely used is the analysis of environmental DNA that allows fingerprinting and tracing organisms to species level (e.g., Thomsen and Willerslev, 2015). Despite the rapid development of the technique there are still many constraints undermining the accurate representation and quantification of individual contributions. For example, eDNA analysis of sediments may underrepresent marine phytoplankton compared to terrestrial plants due to differential preservation of their DNA (Boere et al., 2011). This would lead to underestimating the autochthonous marine organic matter fraction in such sediments. Nevertheless, this technique holds great potential for the future.

All these compounds have the advantage to be very organism- or process-specific which sometimes allows to identify contributions by individual species, which helps to overcome the constraints of the bulk isotope analysis. On the other hand, these substances usually occur in traces only and do not necessarily represent the bulk organic matter, which makes the quantification of autochthonous and allochthonous contributions difficult. Moreover, many of these organic compound determinations require very specific and costly equipment, and sample processing and analysis can also be very time-consuming. Accordingly, elemental and isotope composition techniques are still the most widely used. In most cases, endmember mixing models are used to calculate from the measured isotope and/or biomarker etc. values of the quantitative contributions of autochthonous and allochthonous portions of, for example, sediment organic matter. These depend on the availability of proper samples of all endmembers, which in addition need to have distinctly different chemical signatures. Moreover, endmember mixing models still have multiple limitations (Fry, 2013).

4 Distribution of autochthonous and allochthonous carbon in Blue Carbon ecosystems

Despite the rapid growth of data and knowledge on BCE in the past 15 years, there are still large data gaps and uncertainties, which is documented in the large variability of estimates of the global extent and carbon stocks of tidal marshes, mangrove forests and seagrass meadows available in the literature (Table 1).

Table 1: Global distribution of Blue Carbon ecosystems and their carbon stocks

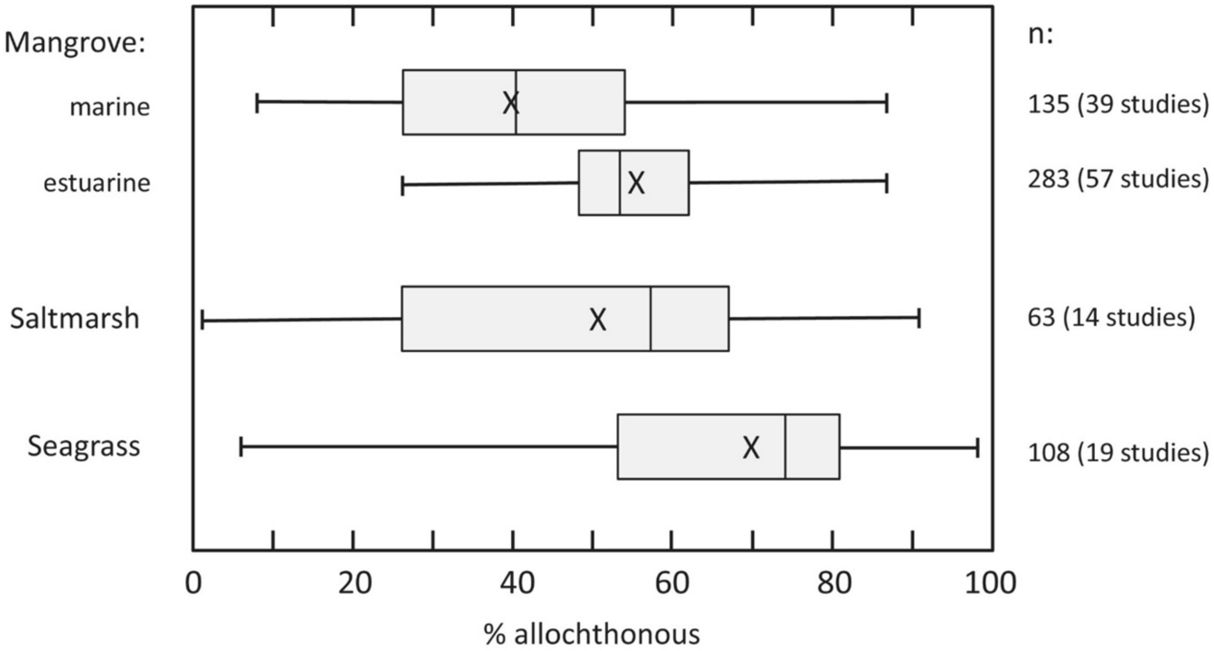
Ecosystem	**Area (km^2)**	**Global C stock (Tg C)**	**Global C stock (Tg CO_2e)**
Tidal marshes	54,951a – 90,800b	862 – 1350g	3161 – 4950
Mangrove forest	137,760c – 147,359d	1230h – 3900i (biomass) 1900k – 8400l (soil) 3130 – 12,300 (total)	4510 – 14,300 6967 – 30,800 11,477 – 45,100
Seagrass bed	160,387e – 316,284f	76 – 151m (biomass) 3760g – 8400m (soil)	279 – 554 13,787 – 30,800

Data sources: a – McOwen et al., 2017; b – Murray et al., 2022; c – Giri et al., 2011; d – Bunting et al., 2022; e – McKenzie et al., 2020; f – UNEP-WCMC and Short, 2021; g – Macreadie et al., 2021; h – Hamilton and Friess, 2018, I – Simard et al., 2019; k – Ouyang and Lee, 2020; l – Kauffman et al., 2020; m – Fourqurean et al., 2012.

In addition to data gaps and uncertainties related to estimating carbon stocks, these stocks vary largely in different environmental circumstances. This becomes obvious when breaking estimates of carbon stocks down to regional/local scale. For example, in the Segara Anakan Lagoon in Java, Indonesia, sediment carbon stocks vary roughly between 100 – 600 Mg C ha^{-1} within one mangrove ecosystem. The autochthonous and allochthonous contributions to sedimentary organic matter displayed similar large variations. Both of these findings are closely related to differences in the environmental settings in the western and eastern parts of the lagoon. The western part receives high inputs of freshwater and dissolved and particulate substances introduced by the Citanduy River that drains an agriculture-dominated hinterland, while the tidal exchange with the Indian Ocean is relatively minor. In contrast, the eastern part of the lagoon depends largely on the tidal exchange with the Indian Ocean and receives little freshwater input from the hinterland (Yuwono et al., 2007). Consequently, carbon stocks are relatively low in the western part because of dilution with mineral soil material, but the portion of allochthonous carbon is high, amounting to more than 60%. Because of the lack of such an input from the hinterland, carbon stocks in the eastern part of the lagoon are high and the portion of allochthonous carbon is fairly low, amounting to less than 30% (Kusumaningtyas et al., 2019).

This example nicely illustrates the high variability of carbon stocks in different settings and the variability of autochthonous vs. allochthonous contributions to these stocks on an ecosystem scale. On a global scale, a recent synthesis of the relatively small set of existing data also finds large variability in the portion of allochthonous carbon in BCE (Figure 2; Williamson et al., 2025a). Despite the large variability, median values of 41% and 54% of allochthonous carbon in marine and estuarine mangroves, respectively, and 58% in saltmarshes and 74% in seagrass meadows, clearly depicts that allochthonous carbon is a quantitatively significant portion of carbon buried in BCE.

Figure 2: **Global analysis of % allochthonous organic carbon in mangrove, saltmarsh and seagrass sediment.**



Source: Williamson et al. (2025a).

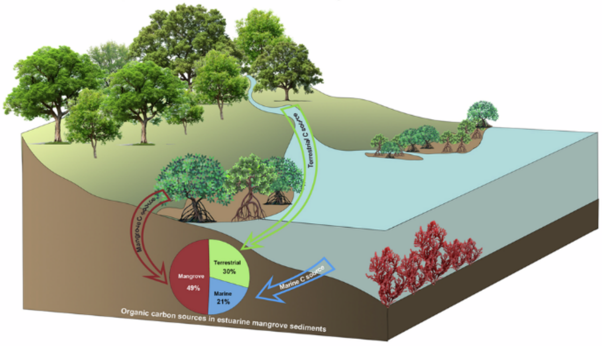
Notes: Mangrove data are based on Zhang et al. (2024) and separated into marine and estuarine settings. The data for saltmarshes and seagrass is derived from literature searches. Boxes show medians and quartile ranges; X indicates arithmetic means; whiskers show full ranges. Saltmarsh and seagrass data are available at Williamson et al. (2025b) with data sources and statistical summaries.

It is known that combinations of drivers like biophysical conditions, environmental settings and hydrodynamic forcings lead to the observed large regional variability of carbon stocks (Rovai et al., 2018; Twilley et al., 2018; Mazarrasa et al., 2023; Krause et al., 2025). The large variability of allochthonous carbon contributions on a global scale also indicates the need for further local and regional scale data and a better understanding of the drivers on the local to regional scale. As yet, the existing data base is sufficient to distinguish between estuarine and marine mangrove ecosystems, which display large differences in carbon stocks and allochthonous contributions. While estuarine mangroves receive notable portions of allochthonous carbon from the terrestrial hinterland and the ocean, marine mangroves receive allochthonous carbon almost exclusively from the ocean (Figure 3). It is conceivable that similar variability related to differences in geomorphic settings, biotic factors and other factors exists for saltmarshes and seagrass meadows given the large variability of allochthonous contributions depicted in Figure 2.

Figure 3: **A conceptual diagram summarizing organic carbon (OC) sources in estuarine and marine mangrove sediments.**

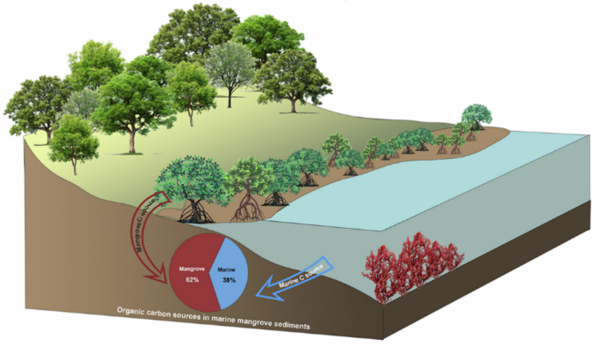
(a) Organic carbon sources in estuarine mangrove sediments

Total SOC stock: 1502 ± 154 Tg C Area: 43669 km^2
SOC stock per unit area: 282 ± 8.1 Mg ha^{-1}



(b) Organic carbon sources in marine mangrove sediments

Total SOC stock: 3025 ± 345 Tg C Area: 103573 km^2
SOC stock per unit area: 250 ± 5.0 Mg ha^{-1}



Source: Zhang et al. (2024).

5 Guidelines and methods for addressing allochthonous carbon in carbon crediting programs

The soil or sediment carbon is by far the largest carbon pool in BCE. Aboveground and belowground biomass can make up 10-20 % of the whole carbon stock in mangrove ecosystems, but is almost negligible in saltmarshes and seagrass meadows (Alongi, 2014; Adame et al., 2024). If the soil or sediment pool is considered in determining the mitigation impact of BCPs under carbon crediting programs, the deduction of allochthonous carbon should be mandatory. As established earlier, its inclusion would not fulfil the essential criterion of additionality. Allochthonous carbon is transported *into* the project area of a BCP and does not result from additional removal of atmospheric CO_2 through human intervention stemming from within the project area.

There are currently four carbon crediting programs operating on the voluntary carbon market that offer registration of BCPs. These are Verra's Verified Carbon Standard (VCS), the Gold Standard for the Global Goals (GS4GG), the Climate Action Reserve (CAR) and Plan Vivo. The general standard documents of all these programs do not mention specific carbon pools. Carbon pools and quantification methods are only specifically addressed in the methodological protocols. The soil/sediment carbon pool is mentioned in the protocols of all four aforementioned crediting programs. However, the quantification requirements for GHG emissions and carbon stocks of soils/sediments and the autochthonous and allochthonous portions differ significantly between the different crediting programmes and the respective methodologies applicable to BCPs (Table 2).

Table 2: Quantification requirements for soil carbon in different carbon crediting programs

Crediting program	Standard	Methodology	Soil carbon	Allochthonous carbon	Quantification approach
Climate Action Reserve	Reserve Offset program	Forest Protocols: Guatemala 1.0, Mexico 3.0, Panama 1.0	No	No	N/A
Gold Standard Foundation	Gold Standard for the Global Goals	Sustainable Management of Mangroves 1.0	Yes	Yes	Own data, literature, models, defaults
Plan Vivo Foundation	Plan Vivo Standard 5.0	PM001, PU002	(Yes)	No	Model
Verra	Verified Carbon Standard 4.7	VM0033, VM0007	Yes	Yes	Own data, literature, models, defaults

Sources: Methodological requirements of carbon crediting programs. Information as of 16 May 2025.

One of the most conservative approaches is chosen by the Climate Action Reserve. Considering the large natural variability of carbon sequestration in BCE it develops region-specific protocols, of which currently three are existing. Acknowledging the large uncertainties in determining the soil carbon pool, soil carbon stocks are excluded from quantifying the mitigation impact of Blue Carbon activities in the Guatemala, Mexico and Panama Forest Protocols.

The crediting methodology for the sustainable management of mangroves of the Gold Standard published in 2024 requires the quantification of soil carbon as well as that of its autochthonous and allochthonous portions. The methodology allows quantification through measuring carbon in an adequate number of soil cores. However, if this is not possible, soil carbon can be calculated by using data and models from peer-reviewed literature. Lastly, quantification of soil carbon is also possible by using regional or national default values. The determination of autochthonous and allochthonous portions of soil carbon is also mandatory, but there are no details provided on how that can be done.

The calculation approach required in Verra's VM0033 methodology is very similar to that of the Gold Standard. However, it has the most sophisticated approach to determine the allochthonous portion of soil carbon. First, it follows the same approach as for the overall quantification of soil organic carbon, i.e. the use of own field-collected data, published values and models. It explicitly mentions individual default factors for saltmarsh, seagrass and mangrove soils, respectively, which are derived from the peer-reviewed literature. In case a model is used, the portion of allochthonous soil organic carbon must be verified through direct measurements from a system with similar water table depth and dynamics, salinity and plant community type as the project area.

The quantification requirements for soil carbon in Plan Vivo methodologies are the least advanced of all four crediting programs. The quantification of soil carbon is generally required, but no further details are provided on how to incorporate it. Modelling appears to be considered the only option. Autochthonous and allochthonous carbon are not mentioned at all.

It appears that the determination of allochthonous carbon for an accurate quantification of the climate-active soil carbon is considered of minor relevance in current carbon crediting programs, likely due to uncertainties in measuring and verifying this carbon fraction. While Verra's approach appears to be most advanced and detailed, its wide spectrum of quantification options leaves room for large uncertainties in calculation results.

6 Current status of addressing allochthonous carbon in ongoing Blue Carbon projects

The relevance of distinguishing between autochthonous and allochthonous portions of soil carbon in BCE in terms of the climate change mitigation potential emerges only slowly in the community of scientists and practitioners. In the voluntary carbon market, as shown above, soils are not considered at all by the Climate Action Reserve Forest Protocols. The Plan Vivo standard does not foresee a distinction between autochthonous and allochthonous carbon. The Gold Standard is new and does not have any BCP registered as yet. Verra's VCS 4.7 standard methodology VM0033, which is in operation since 2022, was the first to consider this distinction, while previous versions did not consider it.

There are currently 17 BCPs verified to receive carbon credits as a result of GHG ERRs based on project interventions, all of them in mangrove ecosystems. Of those, 11 are registered under various versions of the Verra VCS standard, only few of which follow the VM0033 methodology and, hence, have to deduct allochthonous carbon from the soil carbon pool. Accordingly, little information is available on how allochthonous carbon is quantified by such projects or on the reliability of the resulting figures.

One example of a project for which such kind of information is available is the Delta Blue Carbon-1 project located in the mangrove forest of the Indus delta in Pakistan registered under the VCS. With an area of 350,000 ha it is by far the largest BCP in the world and with a crediting period of 60 years also the one with the longest duration. While the project developers are to be commended for producing field-collected data, the total number of eight 1-meter long soil cores can hardly be considered representative for an area of 350,000 ha, considering the large spatial variability of carbon content even on a local scale (see section 4). The project's average carbon stock within the top meter of soil is estimated at 163.6 Mg C ha^{-1}, which is moderate compared to the global average of 305±166 Mg C ha^{-1} (Jennerjahn, 2021b). The cores contained 2.0±0.6 % of organic carbon according to the quantification by the project developers (Indus Delta Capital Limited, 2021). Allochthonous carbon was deducted following an empirically-derived equation published in the peer-reviewed literature by Needelman et al. (2018). According to the equation, which is a power function, the proportion of allochthonous carbon increases as the total organic carbon concentration decreases. Applying this equation resulted in a 93% deduction of allochthonous carbon from total soil carbon. While the productivity of Indus Delta mangroves is fairly high, the flow of the Indus River was strongly reduced due to damming since the 1940s (Milliman et al., 1984; Amjad et al., 2016). It is therefore quite unlikely that the portion of allochthonous carbon of mangrove sediments is as high as 93 %. However, such a high deduction results in a conservative estimate of the ERR related to soil carbon accumulation, and hence, will likely prevent over-crediting.

Another project that assessed allochthonous soil carbon is the Vida Manglar project in the Gulf of Morosquillo at the Caribbean coast of Colombia registered under the VCS. Although applying the older Verra VM0007 quantification methodology, which does not require assessing allochthonous soil carbon, the allochthonous portion of soil carbon was assessed in mangrove soil cores that were obtained in the project area. Findings from a study that was published in peer-reviewed literature were used for that purpose (Völkel et al., 2018). Besides the mangrove soils, sediments from the nearby Sinu River were collected 70 km upstream. In order to assess the allochthonous carbon, the organic carbon content and the stable carbon isotope composition ($\delta^{13}C_{org}$) of all samples were measured. The soil carbon stock was determined to be 660.93±259.18 Mg C ha^{-1} in basin mangroves (1 m cores) to 259±42.61 Mg C ha^{-1} (80 cm cores) in fringe mangroves. The determined organic carbon concentration varied between 3-15% in basin mangroves and between 16-31% in fringe mangroves, while it was almost zero in river sediments. The $\delta^{13}C_{org}$ similarly varied between -27 ‰ to -28 ‰ in mangrove as well as in river sediments. Because of the large difference in carbon content of mangrove soils and sediments from the Sinu River, and despite a similar stable carbon isotope composition, the authors concluded that the mangrove soil carbon is almost exclusively autochthonous. This, however, is quite unlikely. The river sediment 70 km upstream of the mangrove ecosystem represents the fraction of material that is not transported by the river. Instead, it would have been helpful to analyse the suspended particulate matter in the river and its plume, i.e. the transported material, for its carbon concentration and stable carbon isotope composition in order to obtain realistic information on the potential contribution of river-derived allochthonous carbon to the mangrove soils or sediments. While it is still possible that the majority of mangrove soil carbon is autochthonous, the data do not conclusively prove this.

One project that is still in the pipeline under the VCS but not yet verified is the Virginia Coast Reserve Seagrass Restoration project. The project is based on a long success story of seagrass restoration along the Virginia coast (Orth et al., 2020). As the project, which is following the VM0033 methodology, is still in the planning phase, information on it is only available from the project description (The Nature Conservancy, 2021). It states that the values for GHG emissions from soils "have been discounted for baseline soil carbon dioxide, allochthonous soil carbon, soil methane, and soil nitrous oxide emissions as measured in bare sediment and therefore represent the net GHG emissions impact from soil as a result of seagrass restoration". However, no further information is provided, and it remains unclear how allochthonous carbon is actually accounted for.

7 Options to improve the quantification of allochthonous carbon in ongoing Blue Carbon projects

Technical and financial barriers pose significant difficulties in accurately determining the portion of allochthonous carbon. Although a variety of methods is available, they all carry some degree of uncertainties and vary in costs. Accordingly, there is also no universally applicable method agreed upon by the user community. The stable carbon and nitrogen isotope approach is mostly chosen, likely because it is less time-consuming and less expensive than most of the other methods (Geraldi et al., 2019). Regardless of the method chosen, the determination of allochthonous carbon is expertise- and resource-intensive. It requires sophisticated technology and experienced experts, which is costly and, hence, is a significant financial barrier besides other existing barriers (Friess et al., 2022a, b) for BCPs on the voluntary carbon market.

Those barriers prevent most BCPs from determining allochthonous carbon, or even soil carbon as a whole, through own field-collected samples. Calculating the portion of allochthonous carbon instead with default values or by using the method of Needelman et al. (2018) may end up in extremely high deductions of allochthonous carbon. One example is the case of the Delta Blue

Carbon-1 project in Pakistan which deducted 93% allochthonous carbon from the overall carbon measured in soils from the project area. Such a deduction leads to a conservative estimate of ERRs, which helps to avoid over-crediting. However, the deduction of a portion of 93% allochthonous carbon in an area where mangrove carbon is considered to be autochthonous to a large extent, likely leads to an underestimate of the ERRs, hence, possibly to under-crediting. In such a case, a project could benefit from the investment into the determination of allochthonous carbon through measurement of samples from the project area. A more accurate determination of that deduction would possibly allow for calculating a higher ERR potential, resulting in a higher amount of carbon credits to be issued.

Another option to improve the determination of soil carbon as a whole and the portion of allochthonous carbon in it without large-scale investment could be a collaboration between project developers and academic science organisations who have a scientific interest in such kind of data. Despite the boost of Blue Carbon science in the past 15 years, there are still large data and knowledge gaps to be covered. Therefore, in many cases there may be a mutual interest of both groups in such a project. Academic scientists could provide their expertise, facilities and budget to obtain new samples and data. They would benefit from being able to produce and publish new knowledge on a scientifically and societally relevant theme: climate change mitigation. Project developers could provide their project area as research area to academic scientists and would benefit by receiving a robust and accurate data base for calculating the ERR potential of their project. Interestingly, there has been collaboration between academic science and practitioners in producing all the relevant knowledge and methods to improve carbon accounting for a long time. However, when it comes to the project scale, project developers usually do not have relevant expertise and facilities available as the relatively poor data situation regarding own samples and measurements in existing BCPs shows. Therefore, improved collaboration between academic science and project developers could be a win-win situation for both sides.

8 Summary and conclusions

Soil or sediment carbon is by far the largest natural carbon sink in the coastal zone that can store carbon over timescales of centuries to millennia. This results from the uptake of CO_2 from the atmosphere and its conversion into biomass or organic matter by photosynthesizing organisms, the so-called autochthonous carbon. This happens to a large extent in the coastal vegetated ecosystems saltmarshes, mangrove forests and seagrass meadows, also called Blue Carbon ecosystems. However, part of the carbon deposited in the Blue Carbon ecosystems or in other coastal regions is imported from other terrestrial and marine ecosystems, resulting from CO_2 uptake in those systems, the so-called allochthonous carbon.

In terms of carbon accounting in carbon crediting programs issuing carbon credits to BCPs, only the autochthonous carbon is climate-active, i.e. the deposited carbon results from CO_2 uptake and conversion into biomass and is stored for a long time in the project area. In contrast, the allochthonous carbon results from CO_2 uptake somewhere else and its long-term storage would have occurred anyway. The portion of allochthonous carbon varies largely, but is generally high, on average ranging between 40-70% in Blue Carbon ecosystems (Williamson et al., 2025). Not accounting for the part of the carbon that is not "climate-active" carbon bears the risk of overestimating the GHG ERRs, hence, over-crediting in such a BCP. As a consequence, issuing carbon credits based on overestimated GHG ERRs could result in an overall increase of GHG emissions if the resulting credits are used to offset emissions elsewhere.

Nevertheless, there are also recommendations against deducting allochthonous carbon (Lovelock et al., 2023; Houston et al., 2024). One argument is that any carbon exported from the terrestrial hinterland would be decomposed and emitted to the atmosphere on its way to the BCE. Hence, all soil carbon including the allochthonous portion in BCE projects is considered additional, because it would not have been deposited if the project had not existed. Because of the general inconsistencies of available methods and the lack of universal applicability others argue that allochthonous carbon should only be deducted when analyses and data from the project area are available. However, this is not common sense, and as long as the mentioned large uncertainties exist, there is no alternative to taking a conservative approach to avoid overestimating ERRs and preserving environmental integrity.

Because of the existing limitations and uncertainties not only in carbon accounting in coastal ecosystems, but in all terrestrial and marine ecosystems, the precautionary principle should be followed. Allochthonous carbon should be quantified separately and generally deducted from soil carbon accumulation in Blue Carbon ecosystems. A closer collaboration between project developers and academic science that holds incentives for both sides could greatly improve the quantification of GHG ERRs in Blue Carbon projects in the future.

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Imprint

Publisher

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DOI

https://doi.org/10.60810/openumwelt-7980

Completion: June 2025