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Review

Recommendations for strengthening blue carbon science

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SUMMARY

Blue carbon (BC) habitats (e.g., mangroves, tidal marshes, and seagrasses) are important CO_2 sinks but are among the most threatened ecosystems on Earth. Substantial research over the last decade has quantified BC to evaluate the climate benefits associated with habitat conservation and restoration. However, the exponential growth in BC science has resulted in differing approaches that hinder comparison across studies and increase uncertainty. Here, we synthesized existing data to depict the range of uncertainty associated to different BC methodologies and argue that cumulative biases linked to multiple methodologies can result in BC estimates differing by up to 10-fold. We identified 14 common research procedures that can be improved to strengthen BC biophysical assessments and support implementation of BC projects, and outlined good practices to align research with policy, management, and ethical values. Standardization of practices will help generate high-quality BC projects that can deliver multiple co-benefits for humans and the environment.

INTRODUCTION

The conservation and restoration of vegetated coastal habitats (e.g., mangroves, tidal marshes, and seagrasses) is emerging as a nature-based solution supporting biodiversity, climate-change mitigation and adaptation, and additional ecosystem functions that support the well-being of humans and the planet.[1,2] Since the recognition of their importance in the global carbon cycle,[3–5] the research effort aiming at understanding carbon stocks and fluxes within blue carbon (BC) habitats has increased exponentially over the last decade.[6] Assessments of carbon stocks and accumulation rates, together with emissions linked to habitat losses, are essential to aid the development of national and global BC inventories and to provide estimates of the climate-change mitigation benefits linked to the protection and restoration of these habitats.[7–11] Research efforts have recently expanded to include holistic estimates of greenhouse-gas (GHG; i.e., CO_2, CH_4, N_2O) fluxes in various BC habitats[12] subjected to different management scenarios. BC projects should ensure that estimates of soil organic carbon (OC) stocks, carbon accumulation rates (CARs), and GHG fluxes are reliable and reproducible for robust monitoring, reporting, and verification (MRV) of reduced and avoided emissions. This is required for the implementation of climate-mitigation policies (e.g., nationally determined contributions [NDCs] and CO_2-emission-trading schemes[13–16]).

The multidisciplinary nature of the BC research field, comprising ecology, geology, biogeochemistry, engineering, law, and political science, has resulted in a range of differing approaches. The disparity of methodologies being implemented in BC science and policy can result in large uncertainties that undermine the capacity and importance of developing high-quality

BC projects based on robust and conservative calculations of baselines and additionality. Therefore, improving and standardizing BC research practices and methods can facilitate comparison across studies, whereas the inclusion of ethical and socioeconomic assessments could increase the sustainability and societal impact of BC projects.[17–19] Although key knowledge gaps related to social aspects in BC science have recently been addressed,[20,21] the implementation of fair approaches is critical and urgent owing to the rapid expansion of BC science, in part fueled by the United Nations Decade of Ocean Science for Sustainable Development (2021–2030) that provides impetus for implementing BC strategies to return multiple benefits for people and the planet.

This study evaluates common biophysical approaches used in BC science and policy and highlights issues that researchers and managers working in this field may consider when planning and implementing BC studies and policies. From this critical assessment, we describe key challenges and estimate uncertainties within the BC research field based on measured and modeled data and provide recommendations toward obtaining robust, reproducible, and comparable estimates of carbon storage and GHG fluxes within and beyond BC habitats. The challenges we have identified pertain to issues regarding: (1) the availability of good remote sensing and field data; (2) the need to incorporate the carbonate cycle into BC estimates to accurately account for the OC storage; (3) best practices for collecting and handling field samples (both plant and soil components), and OC data analysis and interpretation; (4) assumptions about site stability and OC provenance (within vs. outside of the site); (5) accounting for all GHGs (including CH_4 and N_2O); (6) aligning research goals with policy priorities, and specific data requirements for project efficiency; and (7) the involvement of local communities to ensure benefit to local stakeholders and researchers and to improve the sustainability of BC projects. Here, we present 14 ways to strengthen BC science to aid the large-scale uptake of BC projects to support national climate-change commitments.

DEFINING BC AND COMMON METHODOLOGIES USED

The Intergovernmental Panel on Climate Change (IPCC) guidelines define BC as "all biologically-driven carbon fluxes and storage in marine systems that are amenable to management."[22] In this study, we focused on the widely accepted BC habitats under the IPCC guidelines (i.e., mangroves, tidal marshes, and seagrasses). Recently, however, a broader and more inclusive definition of BC habitats has been proposed, including mud flats, unconsolidated sedimentary systems, macroalgae, and tidal freshwater wetlands.[23–26] BC habitats accumulate OC over centennial to millennial time scales in their soils through trapping and storing organic matter derived from the foundation habitat (autochthonous) and surrounding environments (allochthonous).[1] Most of the OC is stored in the soils,[27] and the BC storage capacity is quantified through assessments of biomass and soil OC stocks and/or soil accumulation rates and their provenance (Figure 1). Within this context, both biomass and recent soil OC stocks accumulated over the past decades could constitute BC if maintained in a steady state. However, these OC pools are more dynamic than the soil OC accumulated >100 years ago and, therefore, their climate benefit and inclusion in BC accounting has been questioned.[18,28–30] Nevertheless, a vast majority of peer-reviewed literature,[1,4,8,31] the IPCC, and many national policies and carbon-crediting methodologies consider biomass and soil OC stocks as BC.[13,32,33] The OC stocks and sequestration by BC ecosystems do not constitute climate benefits per se, but conservation or restoration actions that enhance OC sequestration in biomass or soils and/or avoid emissions from biomass and soil OC pools can result in climate benefits.

Current methodologies used in BC science for the analysis of OC in soil matrices with presence of inorganic carbon (e.g., carbonates) can result in large uncertainties; therefore, there is a need to implement more robust procedures.[34] For instance, it is still not clear whether the coarse plant material (>2 mm) present within the soil should be removed prior to OC analyses owing to its doubtful living (e.g., mangrove roots that can reach several meters down in the soil) or degraded (for example, remains of seagrass debris) nature. Soil OC stocks are reported for a given area (usually as m^2 or ha) and standardized to a specific soil depth, which in the literature is usually set to 1 m, whereas the timescale for soil OC accumulation rates can range from decades to millennia. Compression of unconsolidated soils during coring operations can add further complexity and uncertainty to the estimates of soil OC stocks and accumulation rates. On the other hand, deciphering the provenance of soil OC is important not only to determine the quality of the OC stored in relation to degradation and remineralization kinetics but also to satisfy the requirement of most MRV methodologies toward certifying carbon credits to discount the allochthonous OC component in soil OC storage.[35]

Variability in BC stocks and accumulation rates can differ in orders of magnitudes within the same BC habitat but also across broader regional and global scales. Thus, there is a need to conduct thorough BC assessments encompassing biotic and abiotic factors that drive this variability to avoid large uncertainties in BC estimates.[36] Limited resources or inaccurate experimental designs and approaches can thereby result in insufficient sampling and/or analytical efforts and large biases in BC estimates.

Additional GHG flux measurements in soils, water, and air are increasingly being conducted to estimate *in situ* CO_2e (CO_2 equivalent, the measure for standardizing GHG emissions to their global warming potential) fluxes measured over periods of days to whole seasons or annual cycles, including lateral GHG transport. The importance of this carbon flux in BC habitats, which includes the export of dissolved and particulate OC, and alkalinity beyond BC habitats, or the precipitation and dissolution of carbonates, is increasingly being recognized.[12,21] These measurements provide additional information on GHG fluxes over short timescales (daily to annually) in comparison to the longer (decadal to millennial) OC storage measured in soils. At the same time, the lack of a complete account of all GHG fluxes does not exclude the value of OC stocks and accumulation-rate measurements.

Finally, applied BC science should be aligned with policy criteria to support MRV requirements. Because of the urgent need to mitigate and adapt to climate change and the increasing recognition of BC strategies to support these processes,[16,37,38] it

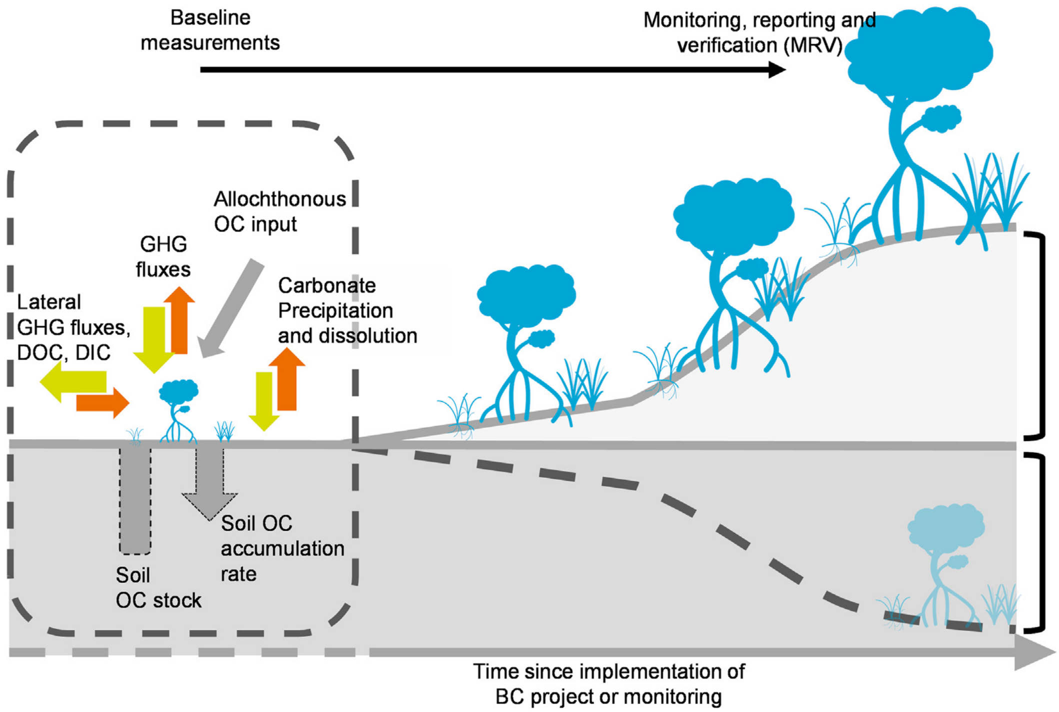

Figure 1. Conceptual figure of blue carbon (BC) baseline measurements and pathways for assessing climate benefits from conservation and restoration activities

BC baseline measurements including the quantification of BC stocks and accumulation rates, OC provenance (allochthonous and autochthonous carbon sources), and carbonate precipitation and dissolution processes as well as additional measurements of GHG and lateral fluxes of dissolved organic and inorganic carbon (DOC and DIC) for a comprehensive assessment of the net CO_2 sink capacity of BC habitats. The baseline BC assessments (dashed box) can be quantified within project boundaries for estimating additionality scenarios following different management activities or to estimate BC stocks and/or accumulation rates (either through avoided emissions or enhanced sequestration).

is critical to develop robust methodologies for estimating carbon stocks and fluxes. Thus, establishing baseline conditions and monitoring of OC fluxes *in situ* as a consequence of project activities (i.e., additionality through the initiation of conservation and restoration actions; Figure 1), including estimating uncertainties related to permanence and risk of reversal from threats, such as extreme climate events,[18,29,39] are needed. Management actions can contribute to climate-change mitigation by increasing the resilience of BC habitats to threats and by avoiding disturbances and associated emissions from biomass and surface soil OC.[7,40,41] Although from a climate perspective these dynamic pools with residence times <100 years are less relevant,[18,42] the climate benefit of the biomass and recently accumulated soil OC stocks will depend on the evolution of these OC pools under and without management actions. Nevertheless, all BC pools should be monitored upon the onset of conservation and restoration actions to avoid the risk of overestimating the climate benefits of BC projects, which includes assessing the risk of leakage and permanence.

Robust sampling designs, modeling to estimate GHG fluxes at multiple spatial and temporal scales, and the incorporation of co-benefits in decision making and voluntary offsetting frameworks are essential for translating BC science into policy. Indeed, the involvement of local researchers and coastal communities in the creation of BC projects is crucial to achieving the social and economic benefits linked to restoration actions.

BC METHODS AND PRACTICES: CHALLENGES AND UNCERTAINTIES

Local, regional, or global data to produce BC estimates

The use of the highest-resolution BC data available to decrease uncertainty and ensure consistency in BC estimates should be considered good practice. Global estimates of BC often use mean or median BC stock and GHG flux values multiplied by global area or change in ecosystem extent. These large-scale estimates have been useful to stimulate policy development, inform international treaty commitments, and generate national data for GHG inventories. At the same time, large-scale estimates can result in large uncertainties in local-scale BC assessments or projects (Figure 2A). BC stocks and accumulation rates are highly variable depending on ecosystem type, climate, geomorphic setting, and timescales.[33,36,43–45] As an example, the CAR in Figure 2A was calculated over the last century. However, using CARs over different timescales that typically range from decades to millennia can result in different outcomes.[46] At multiple spatial scales, variations in and between BC stocks and fluxes are influenced by the depth of inundation, hydrodynamic energy, and nutrient and light availability, among other factors, that can also vary over environmental gradients within intertidal and subtidal zones.[46–48] Although there have been significant improvements in estimating soil and biomass BC stocks (and emissions from their disturbance) derived from extensive field, experimental, and modeling studies,[43,49] global- or

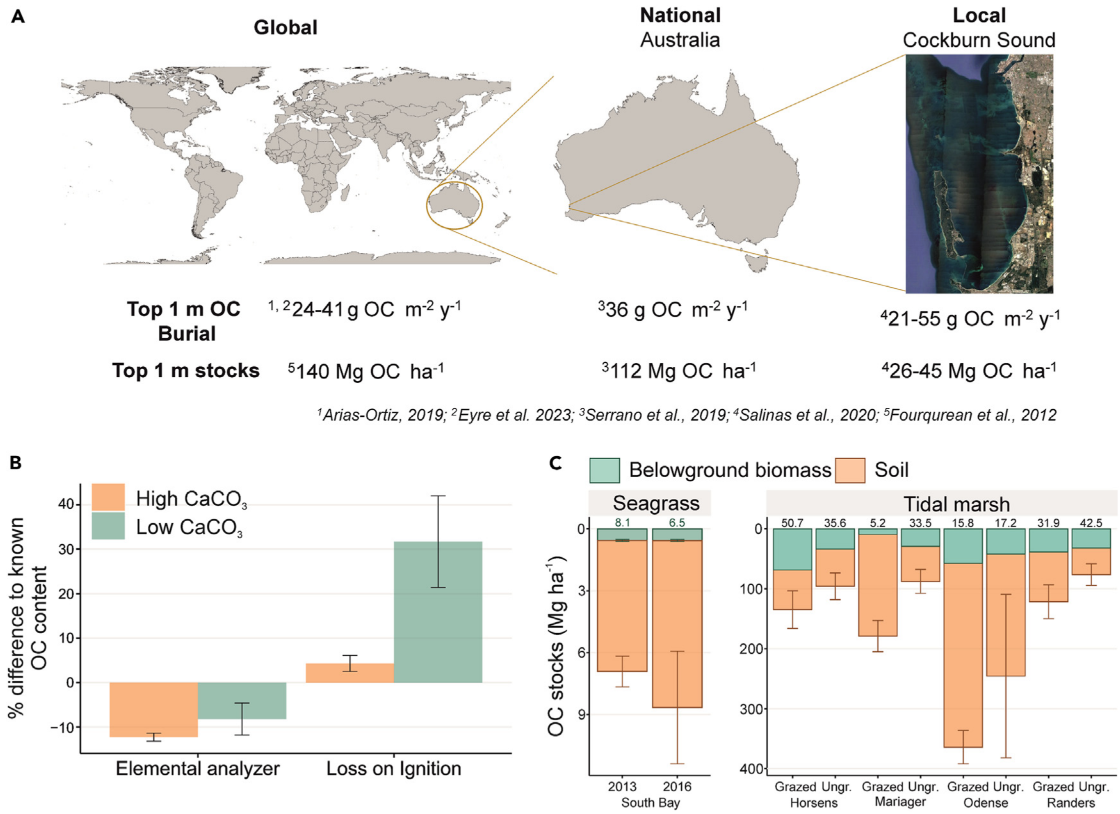

Figure 2. BC practices for quantifying organic carbon (OC) stocks and/or accumulation rates using global, national, or site-specific data, and handling of carbonates and living belowground biomass for estimating soil OC stocks

(A) Up to 5-fold differences in the estimates of seagrass soil OC stocks and accumulation rates based on global datasets,[30,31,51] national datasets,[43] and site-specific datasets[52] in Australia.

(B) Relative (mean ± SD) deviation in OC content from artificial soil mixtures with known OC contents based on measurements through loss-on-ignition and elemental analysis methods. Data from Serrano et al.[34]

(C) Mean (±95% confidence interval) soil OC stocks in seagrass (0–12 cm) and tidal marsh (0–100 cm) with the inclusion and exclusion of living belowground biomass. The proportion of living belowground biomass (ranging from 6% to 8% in seagrasses and from 5% to 51% in tidal marshes) is shown as the (green) values above the bars. Data from Oreska et al.[53] and Graversen et al.[54]

national-scale assessments and models have large uncertainties. For instance, sensitivity analysis has shown that projected mangrove deforestation rates are a source of error for avoided emissions calculations.[50]

Acknowledging that local data are not always available, compromises are often made based on limitations (e.g., timing of needed BC estimates for policy, capacity to collect data, and cost of data acquisition). Typically, baseline data from beyond a site's boundaries or carbon removal estimated from relationships established using global data are being used to estimate carbon fluxes in BC projects as opposed to local BC values.[55] However, with site-specific data, which remain limited worldwide, estimates of BC storage at local scales could vary up to 5-fold compared to global median values (as exemplified in Figure 2A).

Recommendations

At all spatial scales, stratification over known variations in environmental conditions that influence BC stocks and accumulation rates can improve the accuracy of estimates and thereby contribute to robust assessment of the climate benefits of BC projects.[17,56,57] Indeed, the use of site-specific data will always be more reliable than assuming that regional or global estimates are representative of a specific study area. To obtain estimates of BC assessments at national levels when regional data are not available, the IPCC offers global mean values of BC stocks and sequestration rates that can be used in conjunction with other global (e.g., ecosystem cover), regional (e.g., climate zone), or local (for instance canopy cover, hydrodynamic exposure, elevation and distance from the shoreline) data to reduce the uncertainty of estimates.[33,58–60] To enhance the representation of BC data across regions of interest, the use of remote sensing techniques to aid the sampling design and the scaling of estimates is recommended.[61] When making BC estimates at any scale of assessment, evaluating the confidence in BC estimates (i.e., uncertainties) through quantitative analyses is good practice, as modeled estimates have multiple inputs (such as soil carbon density, aboveground biomass, ecosystem cover) that can have multiplicative errors.[57,58,62,63]

Estimating soil carbon content when carbonates are present

BC soils commonly contain inorganic carbon in the form of biogenic calcium carbonate ($CaCO_3$). The process of calcification may result in CO_2 emissions, and the inorganic carbon fraction should therefore be deducted when assessing BC stocks and accumulation rates,[64,65] albeit recent research shows that calcifying algae can also be net CO_2 sinks while consuming alkalinity.[66] The presence of inorganic carbon within BC soils complicates the quantification of OC content, which is commonly analyzed by elemental analysis (EA) or loss on ignition (LOI) techniques. Other methods for determining OC, e.g., the Heanes method, Walkley and Black method, and non-destructive mid-infrared (MIR) and Fourier transform infrared (FTIR) spectroscopy,[67,68] are not commonly used in BC studies but have been shown to accurately estimate OC and carbonate contents in BC soils.[69,70] The Heanes and the Walkley and Black methods have high accuracy for OC content[34] but are not suitable for samples containing reduced iron, sulfur, and manganese compounds, which are present in many BC soils.[71] Although the EA method provides a direct measure of the OC content, it requires pretreatment of the sample with acid to remove carbonates that can result in OC losses linked to the removal of easily hydrolyzed organic or acid-soluble compounds during the rinsing of excess acid.[72,73] The EA method has been shown to result in 8%–12% underestimation of OC stocks (Figure 2B) and, therefore, it should be avoided or used only when carbonates are present. Miyajima et al.[74] provide a protocol for quantifying OC losses from acidification. Other disadvantages of EA are the relatively high analytical costs and, in some cases, limited access to instruments. The LOI method provides an estimate of the organic matter content, which needs to be converted to OC using transfer equations.[27,31] LOI is one of the most widely used methods for measuring soil organic matter content due to its low cost and relative availability of necessary equipment consisting of a balance, ceramic crucibles, and a muffle furnace. However, LOI estimates can vary according to the amount and sources of organic matter, diagenetic processes, $CaCO_3$ content, and the temperature and length of combustion, among other factors.[75–77] For instance, LOI could result in 4%–32% overestimation of soil OC (Figure 2B) due to the loss of water from clay minerals and the loss of some carbonates and salts during combustion.[76,78–80] Overall, the use of different methodologies for OC content determination in soils with the presence of carbonates can result in up to 0.3-fold biases in BC storage estimates (Figure 2B).

Recommendations

BC estimates need to rely on robust measurements of OC content in soils, and a recommendation for reducing uncertainty with the available methods is to calibrate LOI against EA-measured values to create site-specific or region-specific relationships.[81] MIR spectroscopy has shown to be a suitable method for determining OC and inorganic carbon in a wide range of BC soils.[69] However, further studies are required to develop a more accurate method for OC analyses in BC soils that is suitable for uptake across soil samples with different organic and inorganic compositions at low cost and with limited technical requirements. Considering that both OC and inorganic carbon are relevant for the net CO_2 sink function of BC habitats, we recommend measuring of both carbon fractions separately when present in the soil.[64]

Handling of coarse plant material within the soil

Accounting for living belowground OC can increase the soil OC pool by 5%–51% in seagrass or tidal marshes (Figure 2C). Therefore, differences in the methodological approaches used can result in inconsistencies when comparing studies. Typically, assessments of OC stocks in BC habitats include the living and dead above- and belowground biomass and the soil organic matter.[27] Although it is desirable to estimate these five components separately,[53,54] most BC studies merge the living and dead belowground biomass with the soil OC pool.[82,83] This in part is due to the challenges involved with the separation of living and dead biomass, the inconsistent definitions of thresholds for size and type of soil particles accounted for in BC ecosystems compared to terrestrial habitats (i.e., particles <2 mm[84,85]), and the difficulties associated with estimating the volume occupied by each OC stock and their associated density. In terrestrial forests and mangroves, the roots can reach soil depths >1 m and become an important component of the living belowground OC pool, whereas the living belowground biomass pool in tidal marshes and seagrasses may be less prominent. In mangroves, allometric equations are often used to estimate the larger belowground living biomass, which often has high levels of uncertainty (as much as 40%) because of low data availability.[86] While smaller living root fractions can be separated by the floating method (live roots tend to float while dead roots sink),[87] this method is time consuming to implement, and the buoyancy of root fragments varies, resulting in uncertainty.

The high production rate of belowground biomass in tidal marshes and tropical seagrasses compared to mangroves and their accumulation under anoxic conditions (below the mixing depth) likely entails a high preservation of dead belowground biomass particles >2 mm that could be included as part of the soil OC stock. Therefore, from a practical standpoint, once dead biomass is embedded within the soil matrix it is often considered part of the soil OC stock, independent of its size, but there is no standardized method for how to handle living belowground biomass. The inclusion or exclusion of coarse living or dead biomass from soil OC stocks and accumulation-rate estimates can result in up to 0.5-fold variability (Figure 2C).

Recommendations

Specifying the fraction of the belowground OC pool studied (i.e., living and dead biomass >2 mm, and soil OC < 2 mm) and quantifying the influence of large particles, e.g., shells and stones, in soil OC density is considered gold standard but may not be feasible in all BC projects. However, a transparent description of the methods used should be reported, and estimating the biomass OC pool (i.e., living above- and belowground biomass) and the soil OC pool separately is recommended to standardize soil BC estimates and ease comparison between studies.

Compression of unconsolidated soils when estimating BC stocks

Compression of unconsolidated soils when sampling soil cores can lead to overestimation of soil OC stocks and inflate the estimates of climate benefits linked to conservation or restoration projects (Figure 3A). Soil compression during coring operations is common[88] but varies greatly among BC habitats depending on the nature of the soil (e.g., organic matter content, grain size, porosity, and density).[89] Whereas some coring methods can eliminate or minimize soil compression (such as Russian

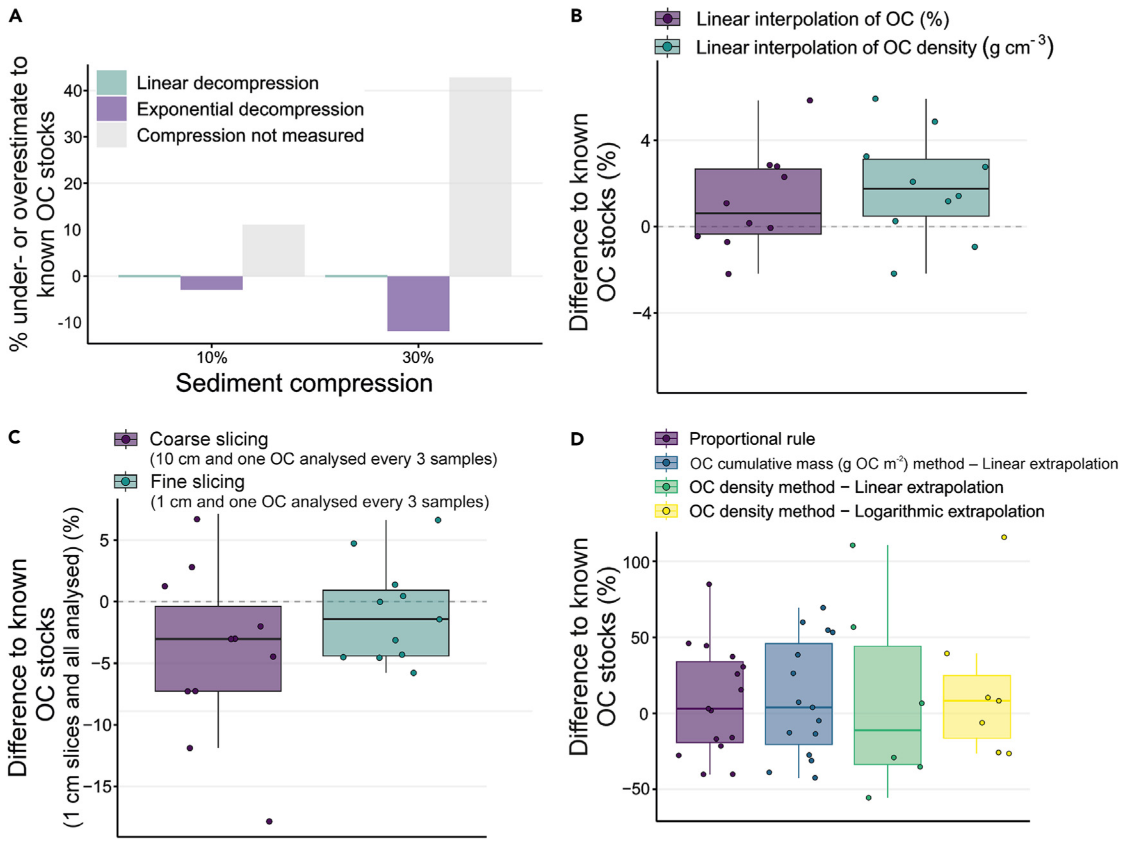

Figure 3. Methodological issues related to soil coring and slicing, and the interpolation and extrapolation of organic carbon (OC) stocks
(A) Under- or overestimation of OC stocks (%) linked to 10% and 30% linear soil compression during coring. The models were run based on a 1-m-long core profile that has a theoretical stock of 20 mg OC ha^{-1} and a constant down-core OC content. Different approaches used in BC science are illustrated: (1) correcting for compression using a linear function; (2) correcting for compression using an exponential function; and (3) disregarding correction for compression (see Data S1 for decompression calculations).
(B and C) Variation in soil BC stock estimates (% deviation from known OC stocks) taking as a reference the soil OC stock estimated based on one single OC analysis in pooled samples along a 1-m core, in comparison to (B) a linear interpolation of 50% of OC values along the core and (C) fine and coarse core slicing resolution. The comparison of interpolation methods to the known OC stocks showed no significance (ANOVA, df = 2, $F = 0.097$, $p = 0.91$) nor did the comparison of fine and coarse slice resolution (ANOVA, df = 2, $F = 0.001$, $p = 0.99$). Data obtained from Serrano et al.[91]
(D) Variation in 1-m-thick soil OC stock estimates (%) in mangrove habitats when comparing known OC stock values to extrapolated values from 40-cm down to 1-m soils using four different methodologies: (1) the proportional rule method whereby the average OC content (g OC m^{-2}) in the top 40 cm was multiplied by 100 and divided by 40 to obtain 1-m soil OC stocks; (2) the cumulative extrapolation method whereby the cumulative mass of OC (g OC m^{-2}) in the top 40 cm was linearly extrapolated to 1 m; (3) a linear regression was fitted to the OC density (g OC cm^{-3}) values within the top 40 cm to extrapolate soil OC stocks to 1 m; and (4) a logarithmic regression was fitted to the OC density (g OC cm^{-3}) values within the top 40 cm to extrapolate soil OC stocks to 1 m. The comparison of known OC stocks to either of the extrapolations showed no significance (Welch's ANOVA, df = 54, $F = 16.4$, $p = 0.82$). Data from Serrano et al.[43]
In (B), (C), and (D), lines in the boxes represent median values, the box edges show the 75% and 25% percentiles, and the error bars represent the 95% confidence interval.

and piston corers[90]), other common coring techniques such as those where a PVC tube is hammered into sediments can result in up to 60% compression.[91] The coring method should be chosen based on the substrate characteristics and other logistics, but systematically estimating the compression of soils during coring can give more robust estimates of soil OC stocks. Compression measurements can be made at least once during the collection of the core by measuring the length of the corer that has been driven into the soil and the total length of soil within the corer prior to retrieval.[27] However, compression may not be linear with depth when different soil strata are present[88] and, therefore, multiple compression measurements during coring can be made to correct for non-linear compression.[92] Exponential compression of unconsolidated soils during coring typically occurs in settings where upper soils have higher organic matter content and/or low dry bulk density compared to the more compacted and inorganic soils underneath. In addition, common practices in BC science include the extrusion of the soil from the corer by pushing a piston from the bottom of the corer that can induce a second bottom-up compression factor.[27] To avoid additional compression, soil corers can be cut lengthwise to access the soil samples. If soil extrusion is preferred, additional correction for non-linear compression can be applied. Overall, failing to measure and correct for soil compression can result in overestimating OC stocks; for example, a scenario of 30% compression during coring can result in >40% overestimation (Figure 3A).

Recommendations

When feasible, use coring equipment that minimizes compression. If the coring technique results in compression, increasing the corer diameter can reduce soil compression during coring.[93] Correcting for compression of unconsolidated soils is required to robustly estimate OC stocks through either linear or exponential functions.

Sampling resolution of soil cores for carbon analysis

If the aim of the project is to assess BC stocks to a standardized depth, running only one OC analysis per core (i.e., pooled samples for the entire core[93]) will reduce uncertainties in OC stock estimates while also removing issues linked to non-linear compression and reducing the cost of OC analysis. However, slicing sediment cores at multiple depth intervals (typically ranging from 0.5 to 10 cm in thickness) to determine down-core changes in OC or obtain discrete samples for deriving age-depth chronologies are common practices in BC science.[94] This approach typically results in a large number of samples derived from each core, but with OC analyses conducted in only a subset of samples along the core (for example at 5-cm intervals), which requires interpolation of OC contents and increases the uncertainties in BC stock estimates (Figures 3B and 3C). If the project requires down-core OC analysis (e.g., to adhere to MRV of BC projects), this can be achieved by cutting the core lengthwise into two hemi-cores and milling one whole hemi-core for standardized BC stock analyses while keeping the other for detailed subsampling. If interpolation is required, the results show no significant difference between the known OC stocks and the interpolated carbon content (in %) or carbon density (in g OC cm^{-3}) values, with <5% uncertainty in our model (Figure 3B).

Recommendations

Preferably all core subsections should be analyzed for OC. If this is not feasible, one OC analysis for the whole hemi-core can reduce uncertainty in comparison to the interpolation approach, as well as lowering project costs for BC stock estimates. Irrespective of the approach used, it is important that the project clearly describes the methodologies used and archives data transparently using, for example data repositories including the Coastal Carbon Atlas.

Extrapolation of OC stocks to a standardized soil depth

For comparison of OC stocks among sites, either within the same study or with literature values, it is common to report OC stocks to a standardized soil depth. Usually OC stocks are reported for the top 1 m of soil, which corresponds to the assumed soil depth most vulnerable to loss and emissions following BC habitat degradation.[33] However, soil cores are sometimes shorter than 1 m, and typically the OC stocks to 1-m depth are extrapolated to facilitate comparisons.[31,95] The assumptions made in these extrapolations can lead to large inaccuracies in OC stock estimates. OC content is commonly higher in surface soils, and extrapolation of the OC-rich superficial soils to 1 m would therefore lead to an overestimation. Assuming 1-m OC stock underneath BC habitats can also inflate landscape carbon stocks where the actual OC stock related to the BC habitat is shallower and therefore includes "pre-BC soils."[96–98] By contrast, estimating OC stocks to 1 m by default can also underestimate the total OC storage of, e.g., *Posidonia oceanica* soils that can accumulate soils >10 m in thickness.[83] Ideally, the total soil depth related to the BC habitat should be recorded.

Different scaling methods and assumptions can also lead to different results. The modeling approaches used to extrapolate OC stocks beyond the sampling soil depth use either a proportional rule of modeling (i.e., using a mean value from all available OC density values) or a cumulative OC content with soil depth (adding up OC in core intervals or slices). Increasing, decreasing or variable OC contents with soil depth[17] can have a large impact on the extrapolated soil OC stocks below the sampled depth, particularly if unreported shifts in OC content occur below the sampled soil depth.[99] Although the different methods tested did not lead to significant differences in OC stocks, linear or logarithmic extrapolation could result in a 15% over- or underestimation of real OC stocks (Figure 3D).

Recommendations

Always strive to sample to the full soil depth related to the BC habitat. If extrapolation is needed, consider that OC concentrations typically decline with depth to avoid overestimation.[27] Reporting data of multiple sampled soil depths provides transparency, and allows for recalculations to other soil depths, if needed.

Estimating changes in soil carbon

For calculation of soil OC accumulation rates and the age of soil profiles over centennial to millennial timescales, the use of vertical accretion rate (mm $year^{-1}$) is common practice in BC science, as opposed to mass accumulation rate (MAR, g cm^{-2} $year^{-1}$). Sedimentation rates based on ^{210}Pb age models are usually expressed in mass per unit area over time (g cm^{-2} $year^{-1}$),[100,101] whereas most of the age-depth models derived from ^{14}C and surface elevation tables (SETs) are expressed as vertical accretion per year (mm $year^{-1}$). The use of MAR to estimate soil CAR or obtain age-depth models has the advantage of not requiring corrections for compaction. Hence, measurements taken using MAR have no added uncertainty associated with the precision of coring or core slicing (Figure 2D). The benefits of using the cumulative mass of the soil (in g cm^{-2}) instead of the soil depth (in cm) also include a better fit of the estimated ages from ^{210}Pb and ^{14}C dating as well as for naturally occurring compression of the soil with diagenesis. For example, in seagrass soils MAR provided a better-fitted age model based on known historical environmental changes on millennial scales.[44]

Assessment of OC accumulation rates in BC habitats requires measurement of OC content and the accumulation rate of the soil material, usually through indirect measurement and modeling of radioisotopes ^{210}Pb and ^{14}C. Obtaining chronologically coherent sediment profiles can be challenging in BC habitats owing to hydrodynamic processes (such as erosion or accumulation of reworked sediments) and bioturbation of coastal sediments.[94,102] Although the measurement of other radioisotopes such as ^{137}Cs or marker layers of, e.g., volcanic ash[103] may help verify sedimentation patterns/rates for specific time periods, the complex sedimentary processes occurring within BC habitats can hinder this approach. Direct measurements from SETs or soil layers marked with persistent substances such as feldspar are better suited to monitor changes in recent vertical sediment accretion or erosion and CAR (e.g., during restoration and conservation activities). Another less costly approach for direct measurements of net changes in soil elevation is subsurface sediment plates placed within the soil or the installation of rods.[104,105]

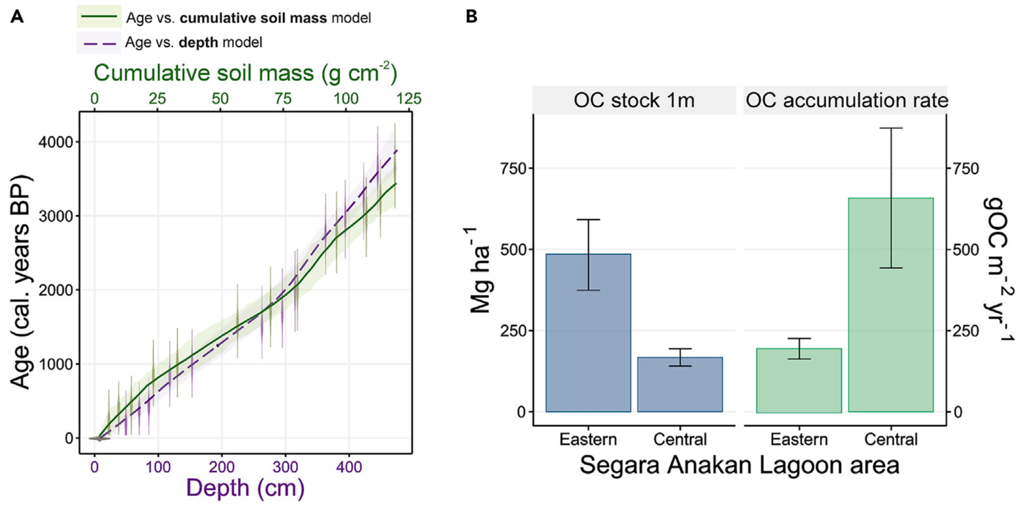

Figure 4. Methodological issues and practices related to estimating carbon accumulation rates and comparing OC storage

(A) Modeling soil age and accumulation rates using either the cumulative soil mass (g cm^{-2}) or soil depth (cm). The down-core trends with age are shown as a function of cumulative soil mass and corresponding soil depth. The purple and green curves show the modeled weighted mean age (±95% confidence interval). The probability density functions for each calibrated ^{14}C date are shown in transparent purple or green elongated shapes along the mean age curves. The model using cumulative soil mass shows a better fit between ^{210}Pb and ^{14}C ages, and it was not affected by compression of the soil during coring or the degradation of organic matter with aging. The model using cumulative soil mass resulted in ~3-fold lower soil-accretion rates than those calculated using soil depth (median [Q1–Q3] of 0.048 [0.038–0.052] and 0.142 [0.100–0.143] cm $year^{-1}$, respectively). Data from Serrano et al.[83] The models were fitted with Bacon.R software.[108]
(B) Soil OC stocks and accumulation rates (mean ± SE) in mangrove forests at the Eastern and Central Segara Anakan Lagoon area (Indonesia). The results showed that the mangroves located in the Central area are more efficient BC sinks than those in the Eastern area, even if OC stocks in the Central area are 3-fold lower than in the Eastern area. Data from Kusumaningtyas et al.[109]

The different methods used for estimating CAR encompass different timescales. For instance, SETs or horizon markers are used for short-term measurements, whereas ^{210}Pb is used for time spans up to 150 years, and ^{14}C is used for millennial timescales. Therefore, the large variability in CAR measured in BC environments could be directly related to the method used and the timescale of integration, which showcases the importance of referring CAR to a specific period to allow comparisons among studies. Typically, the longer the timescale encompassed, the lower the CAR, owing to OC diagenesis and soil compaction[106] as well as historically lower rates of sea-level rise.[107] The use of the different approaches outlined above for estimating sediment-accretion rates could result in up to 3-fold differences in CAR estimates (Figure 4A).

Recommendations

For estimating CAR in BC habitats, the use of MAR in age-depth modeling for both short (years to decades) and longer (decades to millennia) timescales is recommended, owing to the uncertainties associated with using sediment vertical accretion. The use of direct measurements of soil accretion (e.g., SETs or rods) is preferred to indirect or modeled approaches (i.e., radioisotopes) for estimation of CAR. Thus, although direct measurements of soil accretion typically only encompass a few decades, we recommend establishing such measurements at the onset of BC projects. For the implementation of MRV in BC projects, the deployment of direct *in situ* measurements at the beginning of the project is highly recommended because the use of retrospective dating approaches to estimate avoided emissions and/or enhanced sequestration linked to conservation and restoration actions has been widely criticized.[110] The estimation of dry bulk density, vertical accretion, and MAR over precise periods is recommended in all studies whenever possible in order to provide data that can be used for multiple purposes, including understanding the role of BC habitats in climate-change adaptation (e.g., sea-level rise, coastal erosion, and generation of biogenic sands[9]).

Misinterpreting larger carbon stocks as higher carbon withdrawal capacity

BC stocks reflect the OC accumulated within a fixed soil depth, whereas CAR represents the rate of OC accumulated over a certain period, usually measured over decades to millennia (Figure 4B). Both variables are relevant to inform national carbon inventories, to assess avoided emissions from OC stock protection, and to evaluate enhanced OC sequestration rates linked to the conservation and restoration of BC habitats. Nonetheless, OC stocks and accumulation rates provide very different information.[111] High BC stocks are not necessarily coupled with high CAR due to, e.g., variation in sea level,[112] sedimentation dynamics, sediment characteristics,[113] and organic matter mineralization processes.[46] Data on soil OC stocks provide quantification of the magnitude of the soil OC deposit, and repeated sampling coupled with an absolute marker to track changes in sediment elevation can be useful to estimate potential OC losses and CO_2 releases (emissions) due to habitat disturbance and subsequent soil erosion.[14] However, OC stocks do not provide information on the efficiency of the habitat to sequester OC (i.e., the rate of OC accumulation)[114,115] and should not be misinterpreted as an estimate of the OC withdrawal capacity.

Recommendations

To differentiate the carbon withdrawal capacity within and across habitats, it is important to focus on the rate at which

OC accumulates over time rather than comparing OC stocks alone.[116] CAR can be estimated based on retrospective approaches such as ^{210}Pb and ^{14}C radioisotopes or based on *in situ* measurements (e.g., SETs) to evaluate and compare OC withdrawal capacity among BC habitats. Linking OC stocks to OC withdrawal capacity can lead to misleading conclusions.

Assumptions of BC habitat stability over time and identifying baseline reference sites

The assumption that the entire soil core sampled is composed of soil accumulated by the contemporary BC habitat can lead to an overestimation of BC stocks due to possible habitat shifts in the past. For example, the accumulation of 1 meter of soil within BC habitats can take centuries to millennia,[117] encompassing fluctuations in environmental conditions, such as climate, salinity, sea level, inundation period, hydrodynamic conditions, and water depth.[118–120] In addition, past environmental changes may have been associated with a shift in community composition; for example, one BC habitat can shift to another BC habitat as observed when tidal marsh transitions to mangroves.[121] Knowledge of the temporal stability of BC habitats also provides important information for MRV methods when comparing to baseline reference sites (also called "control" sites; i.e., to assess the net contribution of vegetation to soil OC stores in before-after, control-impact [BACI] study designs[52]), which are often soils in unvegetated habitats.[122] Furthermore, information on ecosystem stability can aid the identification of BC storage hotspots for conservation and management and thereby optimize climate benefits linked to BC projects. Studies of ecosystem stability can assess the influence of human activities and interventions on OC stocks that may have caused major changes in coastal habitats over the last century.[123]

Soil BC can be influenced by spatial heterogeneity within a BC habitat that may vary over time. Seagrass meadows, particularly those formed by small and ephemeral species, can be highly dynamic ecosystems with seasonal, interannual, decadal, and/or millennial variation in areal distribution that influence OC accumulation.[122,124] Our understanding of the presence and spatial homogeneity of BC habitats is typically limited to current or decadal time periods because of spatial limitations of long-term monitoring programs and variable availability of remote sensing imagery.[125]

Recommendations

Care should be taken to avoid assuming habitat stability beyond the known history, which could result in misleading conclusions. Interpretation of BC data from cores below current seagrass meadows, tidal marshes, mangroves, or bare seafloor should consider potential shifts in ecosystem types over the period of accumulation assessed. Knowledge of past habitat composition can be obtained by sediment stratigraphy observations[44,97] or the analyses of proxies such as stable isotopes (e.g., δ^{13}C and δ^{15}N), FTIR spectroscopy, environmental DNA, and presence of associated organisms such as foraminifera along the cores.[126–129] Knowing soil-age chronologies can contribute to identifying periods of habitat change and provides a reference depth horizon to assess temporal changes of soil OC stocks and accumulation rates over time.

Quantifying the provenance of soil carbon within and beyond BC habitats

Soil OC stocks in BC habitats can be derived within the ecosystem by their foundation primary producers (autochthonous OC) and from external terrestrial or marine sources (allochthonous OC) that are imported and stored within the BC ecosystem. Hence, BC habitats act as filters and traps of particles, often carbon-rich, from adjacent ecosystems. BC habitats also support lateral fluxes of OC beyond the habitat in particulate or dissolved forms that can accumulate in adjacent and deep-sea environments.[12] Accounting for the export and sequestration of OC beyond the boundaries of BC habitats is complex owing to the large temporal and spatial scales involved, but it can be incorporated into carbon accounting schemes to provide more holistic carbon budgets once robust quantitative estimates are available.

The use of stable isotopes (mainly δ^{13}C and δ^{15}N), which can be analyzed through commercial isotopic laboratories, coupled with mixing models, is commonly used to apportion soil carbon stocks among potential sources. However, stable isotope analyses have high uncertainty, particularly in the case where δ^{13}C is similar across potential OC sources (e.g., terrestrial forests vs. mangroves).[130] Not accounting for the Suess effect, which is the decrease of δ^{13}C signatures, dissolved inorganic carbon values, and OC sources toward the present due to the burning of fossil fuels, can be another source of error.[131] There are emerging multidimensional OC fingerprinting approaches, combining compound-specific stable isotope analyses (especially fatty acids, sterols, and hydrocarbons) and molecular biomarkers, which give higher confidence and detail on the sources of carbon in BC soils.[126,132] However, their quantification and interpretation remains technically challenging.[133–135] Other techniques, such as thermogravimetric analyses have been used successfully for distinguishing soil OC compounds in terrestrial habitats.[136,137] These methodological approaches, preferably based on multiproxy analyses, could be important for deciphering the contribution of BC export to carbon stocks beyond the habitat,[138] which may give rise to future opportunities in carbon accounting schemes[25] and landscape-scale assessments of BC across shifting coastal mosaics.[139]

Many BC verification schemes and accounting methods are concerned about the risk of double counting (e.g., VCS VM0033), implying that a portion of the allochthonous carbon sequestered in BC soils may have been accounted for in other habitats, such as forest OC exported and deposited in BC soils with riverine inputs. This risk needs to be considered in site-specific BC projects with discrete boundaries, whereas for national or regional inventories the OC stock change is measured across large-scale landscapes, so the transfer of OC between habitats will not lead to double counting. The science behind this rationale is at the onset, with several unknowns linked to the fate of allochthonous OC if not buried within BC soils, which can include remineralization or burial elsewhere. Allochthonous OC, having a recalcitrant nature (for example charcoal), might have been buried even in the absence of the BC habitat, whereas more labile OC (e.g., terrestrial plant organic matter, phytoplankton, and macroalgae) might have been remineralized.

The amount of allochthonous carbon that could be discounted from carbon dioxide reduction (CDR) estimates can be as much as 50%, 40%, and 30% of the OC stored in the soils underneath seagrass, mangrove, and tidal marsh habitats, respectively,[96,140,141] thus resulting in a conservative approach that can underestimate BC accumulation by 0.3- to 0.5-fold, whereas recent research questioned the deduction of allochthonous carbon.[142] Indeed, current carbon accounting methodologies do not consider the OC exported beyond BC habitats (i.e., particulate and dissolved) and stored elsewhere (e.g., coastal and deep-sea sediments and deep-sea water bodies), with preliminary estimates suggesting that it could be as much as 30%–40% of the total OC buried by BC habitats.[12,143]

Recommendations

The fingerprinting methods are costly,technically challenging and difficult to implement in all BC studies but should be considered the gold standard. If these methods are not available, the use of default values to assess the contribution of allochthonous sources in BC soils (see for example, Needelman et al.[35]), which largely differs among geomorphic settings (e.g., riverine, estuarine, and coastal), could facilitate accounting for this factor in BC projects.

Carbonate precipitation and dissolution in BC habitats

BC habitats provide habitat to species of flora and fauna that precipitate carbonates in their bodies, whereas biogeochemical processes within BC habitats can promote carbonate dissolution or precipitation. These processes can lead to inaccuracies in the estimates of the net CO_2 sink and climate benefits of BC habitats because carbonate precipitation results in CO_2 emissions and carbonate dissolution entails CO_2 absorption.[144,145] Therefore, BC habitats sustaining high autochthonous calcification rates will enhance CO_2 emissions from inorganic carbon chemistry,[146] whereas carbonate dissolution will enhance the export of dissolved inorganic carbon as alkalinity, which can contribute up to 28% of the carbon sequestration in BC habitats.[147] Thus, biological and chemical processes resulting in inorganic carbon precipitation and dissolution can influence GHG fluxes within and beyond BC habitats.[148,149] Increased alkalinity production through restoration of seagrass, tidal marsh, and mangrove habitats can also be a pathway for CO_2 burial in BC ecosystems.[150]

Not accounting for inorganic carbon fluxes within and beyond BC habitats can lead to an over- or underestimation of BC storage. Import and burial of carbonates from adjacent habitats (such as lithogenic carbonates, corals, calcareous macroalgae, and maerl) further complicates BC accounting.[65] The rates of calcification, dissolution, import/export, and carbonate burial in BC soils are extremely variable, but carbonate production within some BC habitats can counteract as much as 30%–90% of the CO_2 sink capacity linked to OC burial.[45,151]

Recommendations

Modeling and integrating rates of CO_2 fluxes linked to carbonate precipitation and dissolution processes remains uncertain. Similarly, accounting for lateral fluxes (including increased alkalinity) could add to the net CO_2 sink capacity of BC habitats with global estimates of alkalinity outwelling from mangrove and tidal marshes suggesting up to 2-fold higher CO_2 sink capacity than soil OC accumulation.[152] However, further efforts are needed to incorporate both alkalinity export and consumption in BC accounting, including the fate of particulate, dissolved organic and inorganic carbon.

Accounting for methane and nitrous oxide for assessment of total mitigation potential

Methane (CH_4) and nitrous oxide (N_2O) are GHGs with high global warming potential, which can be emitted from natural and degraded BC habitats.[153] Determining whether a given BC ecosystem is a net sink or source of GHGs requires the simultaneous accounting for CO_2, CH_4, and N_2O fluxes. Emissions of CH_4 and N_2O vary strongly on both temporal (e.g., days, seasons, and years) and spatial (from regional/climatic to within-habitat/microbial) scales.[154] BC habitats can export a large fraction of their net primary production[155] and a portion can reach carbon sinks beyond the habitat, such as deep ocean sediments.[143] Therefore, GHG fluxes must be assessed over extended spatial and temporal scales[154,] and across multiple potential pathways, including lateral and vertical fluxes, since they can account for as much as 40% of the ecosystem production.[156] Monitoring all GHGs combined is expensive and technically challenging and, thus, there are few studies with high temporal and spatial resolution of GHG fluxes.

Multiple studies have shown that net drawdown of CO_2e through OC accumulation within BC habitats is often reduced by the release of CH_4 and/or N_2O.[157–159] N_2O and CH_4 emissions in BC habitats are influenced by human impacts,[160] e.g., excess nutrient inputs from agriculture[161] and environmental factors including temperature and salinity.[162–164] Calculating the CO_2e sink capacity of BC habitats including all GHGs adds to the complexity of BC budgets. To address this challenge, global average values of GHG fluxes from coastal habitats are available in IPCC guidelines[33,165] and more recent reviews.[164,166] Although previous studies suggested that CH_4 and N_2O emissions have a limited impact on seagrass BC sink capacity[167] compared to mangroves and tidal marshes,[154] their net CO_2e offset potential highly varies among seagrass species and habitat characteristics.[30] Overall, the inclusion or exclusion of CH_4 and N_2O fluxes in BC accounting can result in as much as 0.2- to 0.4-fold biases in the estimates based on average values from seagrass and mangrove habitats.[30,156,160,168]

Recommendations

Incorporating *in situ* and lateral GHG fluxes into net BC sink estimates should be seen as the gold standard. However, this is technically challenging and not feasible for many BC projects. As a minimum, BC projects should be developed with a good conceptual understanding of how the radiative impact of GHGs may affect the net GHG sink capacity of BC habitats and how they are influenced by human and climate-related changes.

Aligning science with policy criteria for robust verification frameworks

Propelling BC science to support readiness for blue economy financing and climate mitigation policy requires a comprehensive framework of conditions that underpin investment. These conditions include accurate and reliable measurements as well as MRV of CO_2 removals for accounting. Approaches to operationalize NDCs require: (1) well-designed targets, with clear outlines of relevant habitats; (2) GHG-mitigation benefits; (3) information on assumptions and methodological approaches; and (4) clarity on complementarities with climate adaptation and sustainable development goals.[169] Aligning research objectives and protocols with policy needs is key to increasing the uptake of BC projects.

Research objectives need to include the measurement of BC stocks and processes, sampling design, modeling for upscaling at multiple spatial and temporal scales, and the incorporation of co-benefits in decision making and voluntary offsetting frameworks.[170] For example, it is much more common for researchers to conduct discrete BC stock assessments as opposed to measuring fluxes and OC accumulation over time.[49,171,172] Discrete sampling of biomass, soil OC stocks, and accumulation rates can provide baseline estimates of BC storage and contribute to deciphering of the potential drivers of change, while periodic sampling over the duration of a BC project is necessary to assess OC stock change and estimate the additional carbon removed by management action based on carbon accounting methodologies.[173,174] This means that researchers need to align their research priorities with policy requirements so that their science can support BC projects throughout. Additionally, the data obtained within BC projects can contribute to increasing scientific knowledge, if made publicly available.

A challenge for researchers attempting to align their research with policy is that carbon standard MRV requirements are constantly evolving, which demands the inclusion of new science within the next generation of standard requirements. For example, *in situ* verification of BC projects is preferable to using global or regional conversion factors linked to avoided emissions and enhanced sequestration, which would increase the uncertainties associated with carbon accounting. In addition, remote sensing can largely contribute to reducing the cost of MRV requirements for BC projects by supporting the monitoring of critical parameters in carbon-offsetting projects (e.g., changes in habitat extent, additionality, leakage, and permanence[175–177]). Furthermore, considering shifting baselines during MRV accounting could improve BC assessment of climate benefits over time. For example, at time 0 the soil OC within the top 1 m is measured, but during monitoring at time 1 the SETs indicate accrual of 10 cm (and no subsidence). In this case, the comparison of soil OC stocks within the top 1 m at time 0 with the stocks within 10–110 cm at time 1 will allow estimation of changes in soil OC within the top 1 m since time 0, whereas the carbon stock within 0–10 cm (and its evolution over time) should be assessed separately. Indeed, comparisons of OC dynamics among restored and non-restored habitats together with habitats under good conservation status can contribute to establishing meaningful assessments of additionality and understanding the dynamics of the habitats in natural conditions.

Recommendations

Effective communication between scientists, managers, and policy makers is required to achieve robust emission reduction and removal mechanisms. The standardization of MRV requirements across regions or the world would contribute to the transparency of carbon accounting.

Involvement of local researchers and coastal communities in the creation of BC science and policy

BC projects should aim toward collaboration between researchers and local communities and thereby contribute to improving the livelihoods of coastal communities through the protection and restoration of BC habitats and the services they provide.[20] Indeed, BC projects and carbon markets are mostly focused on the least-developed countries where benefits for local people are likely to be highest.[178] BC science can benefit from local knowledge, and existing data and projects can be more effective by embedding the understanding and consideration of the demands and values held by local communities as well as the social and economic co-benefits linked to restoration actions.[179] The inclusion of local researchers and communities are already considered in some voluntary carbon programs, such as Plan Vivo, and should be seen as good practice. Citizen science projects can also be a way to engage local communities, prevent leakage activities (such as mangrove harvesting for charcoal), and provide opportunities for large-scale data collection.[88]

International scientific collaborations can help to fill knowledge gaps and can often fast-track BC projects, but it is important to avoid “helicopter research,” which has been pervasive in science[119,180] and is incompatible with international standards.[181] Helicopter research usually refers to the practice of scientists from developed nations flying in and out of countries with less-developed economies with little or no involvement from local scientists and leaving few to no benefits behind.[180] This practice fortifies the power imbalance between scientists and between countries with different economies.[182] Guidelines that advise on good-practice processes to identify and engage with local groups, including universities, non-governmental organizations, indigenous groups, and government bodies, are already available (e.g., ROAM[183,184] and SERA[183,184]). One of the most successful collaborations among scientists and local communities has been the Vanga Blue Forest project in Kenya, which engaged multi-stakeholder collaborations with strong co-management. Indeed, the return of the carbon credit benefits to the community has led to commitment to BC habitat protection and has promoted capacity building activities within the community.[20]

Recommendations

Conducting true collaborations between international and local academia, government, and local stakeholders, that will result in more sustainable BC science and projects with multiple beneficial outcomes for people and nature.

GOOD PRACTICE FOR IMPROVING BC SCIENCE

Through the adoption of good practices, BC science can successfully inform policy to aid the inclusion of BC habitats in national GHG inventories and the implementation of robust BC projects linked to NDCs or other carbon accounting schemes with multiple additional benefits for biodiversity and climate adaptation. The assessment of cumulative biases linked to the use of multiple methodologies in BC science showed up to 10-fold cumulative differences in BC storage assessments, either over- or underestimating BC potential (Table 1).

The recommendations provided in this study aim at strengthening BC research and therefore contribute to the implementation of high-quality BC projects. In all instances, linking BC data to well-documented practices and methods, including limitations and uncertainties associated with the different methods used, is key to advancing BC science. The adoption of good practices and robust BC methods can also help to reduce the risk of overselling the climate-mitigation potential of BC projects.[18,185] Guidelines for good practices are provided for the standardization of robust methods in BC research (Table 1), including enhanced accuracy of BC estimates (recommendations 1, 2, 5, and 6), facilitation of

Table 1. Summary of 14 common research issues and associated basic and gold-standard recommendations for strengthening BC science and policy

Issues related to		Reason for concern	Basic recommendation	Gold-standard recommendation	Potential bias in BC estimates (x-fold difference)
(1)	Local, regional and global data for BC estimates	modeled, global, or regional mean carbon values can cause large uncertainty in BC estimates	stratify over environmental gradients and use global or regional data specific to biological and geomorphic settings	use site-specific BC data stratified over environmental gradients	±5
(2)	Soil OC content in presence of carbonates	presence of carbonates jeopardizes soil OC estimates	calibrate LOI against local or regional EA-measured values and report the uncertainties linked to both methods	use spectroscopy methods (e.g., MIR) in carbonate-rich soils	+0.3
(3)	Coarse plant material within the soil	inclusion or exclusion of living belowground biomass affects the soil BC stock	if possible, exclude living belowground biomass from the soil OC matrix	separate and quantify the density of belowground OC stock (living and dead biomass >2 mm, and soil OC < 2 mm)	+0.5
(4)	Compression of unconsolidated soils	compression leads to an over- or underestimation of soil BC stock	apply linear or exponential decompression factors during coring; increase the diameter of the corers	use coring devices that have no compression (e.g., Russian or piston corer)	+0.4
(5)	Slicing resolution of soil cores	causes uncertainty in soil BC stock estimates	for OC stocks, quantify OC content using one sample for an entire hemi-core	analyze OC in all samples within a core to avoid interpolation	± <0.1
(6)	Standardization of soil depth for carbon stock estimates	extrapolation of soil depths beyond the sampled soil thickness can lead to an overestimation BC stock	apply best-fitted extrapolation method and only extrapolate carbon stocks to known soil depth associated to the BC habitat.	sample soils to the desired depth to calculate carbon stocks	±0.2
(7)	Estimating changes in soil carbon	differences in age-depth models based on the use of MAR or SAR, and direct vs. indirect methods to estimate OC burial can lead to large uncertainties	use MAR for fitting age depth models and deploy rods to estimate changes in soil accrual	short-term measurements are relevant for BC projects when measuring OC gains *in situ* rather than indirect estimates	+3
(8)	Misinterpreting carbon stocks as carbon withdrawal capacity	BC stocks are not sufficient to assess climate change mitigation capacity of BC habitats	estimate CAR using retrospective approaches to evaluate and compare OC withdrawal capacity among BC habitats and avoid linking OC stocks to OC withdrawal capacity	combine direct (e.g., SETs) and indirect (e.g., radioisotopes) approaches to estimate CAR	N/A
(9)	Habitat temporal variability and choice of appropriate baseline reference sites	short-term habitat characteristics are used to infer long-term processes and/or to identify baseline reference sites that can result in misleading outcomes	avoid linking current habitat characteristics to OC storage capacity, including additionality assessments	decipher past habitat conditions for the period of soil carbon accumulation assessed	N/A

(*Continued on next page*)

Table 1. *Continued*

Issues related to	Reason for concern	Basic recommendation	Gold-standard recommendation	Potential bias in BC estimates (x-fold difference)
(10) Provenance of soil carbon and export beyond the habitat	the need of carbon source determination to inform additionality linked to BC projects	use default values to assess the contribution of allochthonous sources in BC soils	use multidimensional fingerprinting tools to assess carbon provenance and fluxes within and beyond BC habitats	±0.5
(11) Soil carbonate precipitation and dissolution	carbonate fluxes can lead to overestimation or underestimation of BC accumulation	when appropriate, acknowledge that the carbonate cycling can play a key role in the capacity of BC habitats to mitigate climate change	account for *in situ* carbonate production and dissolution	±0.9
(12) Greenhouse gas flux estimates	net CO_2 equivalent fluxes are needed to determine the BC sink capacity	when appropriate, acknowledge that CH_4 and N_2O fluxes can impact the capacity of BC habitats to mitigate climate change	include all GHGs and lateral carbon transfer estimates when evaluating BC storage	±0.4
(13) Aligning science with policy criteria	translate the research to fit MRV requirements	collect data linked to MRV criteria when planning research projects	applied BC research should collect and report relevant data to meet MRV criteria	N/A
(14) Engagement with local researchers and stakeholders	avoid helicopter research and lack of co-creation	inform local researchers and stakeholders of the project and invite them to participate as they see fit	actively collaborate with local researchers and stakeholders for planning, implementing, and disseminating activities, embracing their needs and values	N/A

Identified research issues related to planning of projects and field methodologies, analytical and laboratory procedures, and the interpretation and upscaling of results. Potential biases in BC estimates are given as maximum x-fold difference using different methodologies or approaches, whereas the positive (+), negative (−), and plus-minus (±) symbols indicate whether the bias could result in BC overestimates, underestimates, or either way, respectively. BC, blue carbon; CAR, carbon accumulation rate; EA, elemental analyzer; GHGs, greenhouse gases; LOI, loss on ignition; MIR, mid-infrared spectroscopy; MRV, monitoring, reporting, and verification; MAR, mass accumulation rate; N/A, not applicable; OC, organic carbon; SAR, sediment accretion rate; SET, sediment elevation table.

direct comparisons across studies (recommendations 3, 4, and 7), and meaningful interpretations of the data gathered (recommendations 8 and 9). The technical challenges and the cost of some practices highlighted (recommendations 10 and 12) can be bridged through collaboration among scientists and data sharing with stakeholders, with data being published in publicly available repositories. Thus, supporting BC science and project development while reducing costs, together with the co-creation and inclusion of socioeconomic aspects in BC science, policy, and project planning and implementation, could enhance the benefits of BC projects for local communities (recommendations 13 and 14). There are also challenges for BC science that remain unresolved, including how to handle carbonates within the soil matrix when estimating OC content, incorporating CO_2 fluxes linked to carbonate precipitation and dissolution processes, and deciphering the fate of lateral inorganic and organic transport beyond BC habitats (e.g., stored in deep-sea water or sediments)[18] (recommendations 2, 10, and 11). These should be seen as key priorities for future research.

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AUTHOR CONTRIBUTIONS

O.S. conceived the idea. M.D., P.S.L., I.M., J.S.-V., and O.S. designed the research. M.D. and O.S. outlined and wrote the first draft with contributions from P.S.L., I.M., J.S.-V., M.F.A., S.C., C.M.D., D.A.F., D.K.-J., C.L.-D., C.E.L., P.I.M., P.M., and M.A.M.. C.L.-D., I.M., and M.D. provided figures and graphs. All authors reviewed and edited the draft.

DECLARATION OF INTERESTS

The authors declare no competing interests.

SUPPLEMENTAL INFORMATION

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