Title: The Future of Blue Carbon Science

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Abstract

The term Blue Carbon (BC) was first coined a decade ago to describe the disproportionately large contribution of coastal vegetated ecosystems to global carbon sequestration. The role of BC in climate change mitigation and adaptation has now reached international prominence. To help prioritise future research, we assembled leading experts in the field to agree upon the top-ten pending questions in BC science. Understanding how climate change affects carbon accumulation in mature BC ecosystems and during their restoration was a high priority. Controversial questions included the role of carbonate and macroalgae in BC cycling, and the degree to which greenhouse gases are released following disturbance of BC ecosystems. Scientists seek improved precision of the extent of BC ecosystems; techniques to determine BC provenance; understanding of the factors that influence sequestration in BC ecosystems, with the corresponding value of BC; and the management actions that are effective in enhancing this value. Overall this overview provides a comprehensive road map for the coming decades on future research in BC science.

Main

Blue Carbon (BC) refers to organic carbon that is captured and stored by the oceans and coastal ecosystems, particularly by vegetated coastal ecosystems: seagrass meadows, tidal marshes, and mangrove forests. Global interest in BC is rooted in its potential to mitigate climate change while achieving co-benefits, such as coastal protection and fisheries enhancement[1, 2, 3]. BC has attracted the attention of a diverse group of actors beyond the scientific community, including conservation and private sector organizations, governments, and intergovernmental bodies committed to marine conservation and climate change mitigation and adaptation. The momentum provided by these conservation and policy actors has energized the scientific community by challenging them to address knowledge gaps and uncertainties required to inform policy and management actions.

The BC concept was introduced as a metaphor aimed at highlighting that coastal ecosystems, in addition to terrestrial forests (coined as *green carbon*), contribute significantly to organic carbon (C) sequestration[1]. This initial metaphor evolved to encompass strategies to mitigate and adapt to climate change through the conservation and restoration of vegetated coastal ecosystems[1, 2]. As BC science consolidates as a paradigm, some aspects are still controversial; for instance, contrasting perspectives on the role of carbonate production as a component of BC[4] and whether seaweed contributes to BC[5, 6]. We propose an open discussion to refocus the current research agenda, reconcile new ideas with criticisms, and integrate those findings into a stronger scientific framework. This effort will address the urgent need for refined understanding of the role of vegetated coastal ecosystems in climate change mitigation and adaptation.

There is, therefore, a need to establish a comprehensive research program on BC science that addresses current gaps while continuing to respond to immediate policy and managerial needs. Furthermore, this research program can inform policy directions based on new knowledge, thus playing a role in setting the management agenda and not simply responding to it. Here we identify, based on a broad effort by the leading research academics in BC science, key questions and challenges that need to be addressed to consolidate progress in BC science and inform current debate. We do so through three main steps. First, we briefly summarize the elements of BC science that represent the pillar of this research program. Second, we identify key scientific questions by first surveying the scientific community. Then we clustered these questions into common themes, which develop research goals and agendas. Last, we provide guidance as to how these questions can be best articulated into a new research agenda as a path for progress.

Box 1. Evidence underpinning the science

The role of seagrasses and marine macroalgae as major C sinks in the ocean was first proposed by Smith who suggested that seagrasses and marine macroalgae were overlooked C sinks[7]; however, at the time, there was minimal uptake of the concept within climate change mitigation efforts. In 2003 the first global budget of C storage in soils of salt marshes and mangroves brought light to the importance of these coastal ocean sink. By 2005 it was shown that seagrass, mangrove, and tidal marsh sediments represent 50% of all C sequestered in marine sediments[8]. This mounting evidence for such a major role in C sequestration provided the impetus for the Blue Carbon report[1], where the term "Blue Carbon" was first coined, and that led to the development of international and national BC initiatives (e.g., http://thebluecarboninitiative.org). This led to research efforts to propose emissions factors from loss and restoration of BC ecosystems for C accounting[9], provide empirical evidence of emissions following disturbance and removals from restoration[10, 11, 12], map the C density of mangrove soils globally (e.g.[13]), and explore the potential of BC ecosystems to support climate-change adaptation (e.g.[2]).

Scientists' perspectives on the 10 key fundamental questions in BC science

We identified and selected scientists from among the leading and senior authors of the 50 most-cited papers on BC science (ISI Web of Science access date 22 June 2017), together with the participants in a workshop on BC organized at King Abdullah University of Science and Technology, Saudi Arabia, in March 2017. We did not attempt to identify any scientists' area of specialisation to avoid bias. Among these authors, we surveyed those affiliated with academic or research institutions. A group of 50 scientists were asked to contribute from their perspective the top pending questions (up to 10) in BC science. Specifically, the invitees were asked to "Email your ten most important questions (or fewer) relevant to improving our understanding of blue carbon science and its application to climate change mitigation". We did not ask scientists to prioritise their questions, or target any particular geographical area, but we did ask them to focus on mangrove, tidal marsh, macroalgal, and seagrass ecosystems. The answers received (35 total respondents, see Supplementary Information) and were then clustered into ten themes (by grouping questions that were similar) that were subsequently articulated into individual, overarching research questions:

Q1. How does climate change impact carbon accumulation in mature Blue Carbon ecosystems and during their restoration?

The impacts of climate change on BC ecosystems and their C stocks are dependent on the exposure to climate change factors. This is influenced by both the frequency and intensity of stressors, and the sensitivity and resilience of the ecosystem[14]. Question 1 reflects uncertainties associated with the rate and magnitude of climate change[15, 16, 17] as well as uncertainties about the impacts of climate change on current and restored BC ecosystems, their rates of C sequestration and the stability of C stocks, which are likely to vary with past sea level history[18], over geographic locations, among BC ecosystems, and within ecosystems.

BC ecosystems mainly occupy the intertidal and shallow water environments, where their distribution, productivity and rates of vertical accretion of soils are strongly influenced by sea level[19, 20] and the space available to accumulate sediment[21]. Thus, sea level rise ranks among the most important factors that will influence future BC stocks and sequestration. Sea level rise can result in BC gains, with increasing landward areal extent of ecosystems where possible[22], and enhanced vertical accretion of sediments and C stocks[18, 23]; and losses, with losses of ecosystem extent[24], failure of restoration[25], remineralization of stored organic matter[26] that result in greenhouse gas emissions to the atmosphere (Table 1). Intense storms[17], marine heat waves[11, 27], elevated CO_2[28], and altered availability of freshwater[29] have also all been implicated as important factors affecting the distribution, productivity, community composition and C sequestration of BC ecosystems over a range of locations (Table 1). Geographic variation in exposure to climate change is high. Rates of sea level rise and land subsidence[30], which enhances relative rates of sea level rise, vary geographically[18]. Additionally, rates of temperature change and changes in the frequency of intense storms and rainfall vary regionally[15, 16, 17]. Geomorphic models have provided first pass assessments of the global vulnerability of BC ecosystems to sea level rise[20, 31], and for restoration success[32], but local scale descriptors of changes in exposure of BC ecosystems to climate change and impacts on C stocks are often incomplete or missing. For instance, storm associated waves are important for determining the persistence and recruitment of BC ecosystem[33], yet local assessments are not widely available.

Responses of adjacent ecosystems to climate change may influence the exposure and sensitivity of BC ecosystems and their C stocks to climate change. For example, degradation of coral reefs could increase wave heights within lagoons which may lead to losses of seagrass or mangroves within lagoons with rising sea levels as waves increase[34], or decreases of carbonate sediments due to ocean acidification, may reduce the ability of some BC ecosystems to keep up with sea level rise[35]. Additionally, the sensitivity of BC ecosystems to climate change is also likely influenced by human activities in the coastal zone. For example, deterioration in water quality may increase the impacts of sea level rise on seagrass[36] and decreased sedimentation from damming of rivers, hydrological modifications and presence of seawalls may negatively affect BC stocks in mangroves and tidal marshes[20, 31].

Q2. How does disturbance affect the burial fate of Blue Carbon?

The effect of disturbance on BC production and storage has become a topic of intense interest because of an increasing desire to protect or enhance this climate-related ecosystem service. There are three key issues, all beginning to be addressed by BC researchers, but requiring further study: 1) the depth in the soil profile to which the disturbance propagates, 2) the proportion of disturbed C that is lost as CO_2, and 3) the extent to which issues 1 and 2 are context dependent. The first global estimates of potential losses of BC resulting from anthropogenic disturbance combined changes in the global distribution of BC ecosystems with simple estimates of conversion (remineralisation) of stored BC per unit area[37]. The estimated annual CO_2 emission from the disturbance of BC ecosystems was estimated at 0.45 Petagrams CO_2 globally[37]. The generalised assumptions necessary for such global assessments - e.g. remineralization within only the top 1 m of soil, and 100% loss of BC - provide little guidance at a local management scale and gloss over the variability of effects from different disturbance types[38]. This deficiency has led to a more nuanced theoretical framework accounting for the intensity of disturbance, especially whether the disturbance affects only the habitat-forming plant (e.g. clearing, eutrophication, light reduction, toxicity) or whether it also disturbs the soil (e.g. erosion, digging, reclamation)[39, 40]. The duration of disturbance is another important predictor of disturbance effects on BC remineralisation because, over time, more soil BC is exposed to an oxic environment[41].

We have a nascent understanding of the processes by which natural and human disturbances alter C decomposition. Die-off of below-ground roots and rhizomes in tidal marshes, for example, changes the chemical composition of BC and associated microbial assemblages, subsequently increasing decomposition and decreasing stored C (by up to 90%[42]). In seagrass ecosystems, exposing deeply buried sediments to oxygen triggered microbial breakdown of ancient BC[43]. At this stage, there is some evidence that disturbances can diminish BC stocks, for example: oil spills[44], seasonal wrack deposition[42], aquaculture[45], eutrophication[46], altered tidal flows[46], and harvesting of fisheries resources[38, 47]. Such knowledge is key for the construction of Emissions Factors for modelling. But examples in the literature are often specific for a particular disturbance or ecosystem setting, and do not yet offer the generalised understanding necessary to build a comprehensive framework guiding management projects. Finally, although there is widespread agreement that a changing climate directly affects BC production and storage, we recommend a clearer focus on the interacting effects of climate and direct anthropogenic disturbances.

Q3. What is the global importance of macroalgae, including calcifying algae, as Blue Carbon sinks/donors?

Macroalgae are highly productive (Table 2) and have the largest global area of any vegetated coastal ecosystem[48]. Yet only in a relatively few cases have macroalgae been included in BC assessments. Unlike angiosperms, which grow on depositional soils[2], macroalgae generally grow on hard or sandy substrata that have no or only limited C burial potential[6]. However, a recent meta-analysis has estimated that macroalgae growing in soft sediments have a global C burial rate of 6.2 Tg C yr^{-1} [6], which is comparable to the lower range of estimates for tidal marshes. Furthermore, several studies show that macroalgae act as C donors [3, 6, 49, 50, 51], where detached macroalgae are transported by currents, and deposited in C sinks beyond macroalgae habitats. Recent first-order estimates have suggested that up to 14 Tg C yr^{-1} of macroalgae-derived particulate organic C is buried in shelf sediments and an additional 153 Tg C yr^{-1} is sequestered in the deep ocean[6]. These calculations suggest that macroalgae may be supporting higher global C burial rates than seagrass, tidal marshes, and mangroves combined. This research highlights that if we are to incorporate macroalgal systems into BC assessments we need a better understanding of the fate of C originating from these systems. Furthermore, if we are to scale up from local measurements of C-sequestration to the global level, more refined estimates of the global surface area of macroalgal-dominated systems are needed.

Most estimates of C-sequestration by marine vegetated ecosystems refer solely to organic C even though calcifying organisms are also important components of such ecosystems[52]. For calcifying algae, whether they serve as C-sinks or sources is debated[4], especially where calcifying organisms form and become buried within seagrass meadows[4, 5]. Carbonate production results in the release of 0.6 mol of CO_2 per mol of $CaCO_3$ precipitated[53], suggesting that calcifying algae are sources of CO_2 that counteract C-sequestration in these ecosystems. However, co-deposition of organic and inorganic C may also have interacting effects on C-sequestration[4]. Carbonate may help protect and consolidate organic C sediment deposits, and CO_2 release from mineralization of organic matter may stimulate carbonate dissolution and hence, CO_2 removal[48, 53, 54]. Burial of inorganic carbon in seagrass and mangrove ecosystems is also to a large extent supported by inputs from adjacent ecosystems rather than by local calcification. Furthermore, mass balances highlight that such Blue Carbon ecosystems are sites of net $CaCO_3$ dissolution[54]. More studies are needed to assess the net effect of organic and inorganic C deposition on C sequestration in calcifying systems.

Q4. What is the global extent and temporal distribution of BC ecosystems?

Our attempts to upscale BC estimates and model changes across large spatial and temporal scales is hindered by poor knowledge of their current and recent-past global distributions. The best constrained areal estimates exist for mangroves, which occur in tropical and subtropical regions, generally where winter seawater isotherms exceed 20°C [55]. Overall, the global spatial extent of mangroves, and patterns and drivers of their temporal change, are relatively well understood, especially when compared with other BC ecosystems. Still, Giri et al.[56] estimated a global area of mangroves of ca. 140,000 km^2 in the year 2000 and Hamilton and Casey[57] 83,495 km^2 in 2000 and 81,849 km^2 in 2012. Both studies used Landsat data but different methodologies. Mangroves occur in 118 countries worldwide, but ~75% of total coverage is located within just 15 countries, with ~23% found in Indonesia alone[56]. Total mangrove extent during the second half of the 20th century declined at rates 1-3% yr^{-1} mainly due to aquaculture, land use change and land reclamation[58]. There are uncertainties in the area of mangrove that are scrub forms and which are therefore often not considered as forests despite their importance in arid and oligotrophic settings and often their large soil C stocks[59,60]. Since the beginning of the 21st century, mangrove loss rates are 0.16-0.39 % yr^{-1} [57], probably reflecting changes in aquaculture and conservation efforts.

Tidal marshes are primarily found in estuaries along coasts of Arctic, temperate and subtropical coastal lagoons, embayments, and low-energy open coasts, although they also occur in some tropical regions,[61]. Woodwell et al.[62] estimated global tidal marsh extent of 380,000 km^2 using the fraction of global coastline occupied by estuaries and the assumption that ~20% of estuaries supported tidal marshes[48]. However, tidal marsh area has been mapped in only 43 countries (yielding a total habitat extent of ca. 55,000 km^2), which represents just 14% of the potential global area[63]. Tidal marsh extent is well documented for Canada, Europe, USA, South Africa and Australia[63, 64, 65] but remains unknown to a large extent in regions, including Northern Russia and South America. An historical assessment of 12 estuaries and coastal seas worldwide indicated that more than 60% of wetland coverage has been lost[66] mostly due to changes in land use, coastal transformation and land reclamation[61]. The minimum global rate of loss of tidal marsh area is estimated at 1-2% yr^{-1} [67].

Despite the widespread occurrence of seagrass across both temperate and tropical regions, the global extent of seagrass area is poorly estimated[48]. The total global area was recently updated to 350,000 km^2 [68], although estimates range from 300,000[8] to 600,000 km^2 [69], with a potential habitable area for seagrass of 4.32 million km^2 [70]. Available distribution data are geographically and historically biased, reflecting the imbalance in research effort among regions[71], and most data has been collected since the 1980s [72]. The total global seagrass area has decreased by approximately 29% since first reported in 1879 - with ~7-fold faster rates of decline since 1990 [72] - due to a combination of natural causes, coastal anthropogenic pressure and climate change[73].

Producing accurate estimates of the global extent of BC ecosystems is therefore a prerequisite to assess their contribution in the global carbon cycle. In addition, given the fast rate of decline reported for many BC ecosystems, regular revision of these estimates is needed to track any changes in their global extent and importance. Extensive mapping, with particular focus on understudied areas that may support critical BC ecosystems, that combines acoustic (i.e. side scan sonar and multi-beam eco-sounder) and optical (i.e. aerial photography and satellite images) remote sensing techniques with ground truthing (by scuba diving or video images) should be undertaken to map and monitor their extent and relative change over time[74].

Q5. How do organic and inorganic carbon cycles affect net CO_2 flux?

Even though BC ecosystems are significant C_{org} reservoirs, depending on C_{org} and C_{inorg} dynamics they could also be net emitters of CO_2 to the atmosphere through air-water CO_2 gas exchange[75]. For instance, in submerged BC ecosystems (i.e., seagrasses), C_{org} storage is not directly linked with the removal of atmospheric CO_2 because the water column separates the atmosphere from benthic systems. BC science gaps exist in complex inorganic and organic biogeochemical processes occurring within the water column and determining CO_2 sequestration functioning.

Photosynthesis lowers the CO_2 concentration in surface water as dissolved inorganic C (DIC) is incorporated into C_{org} ((1) in Fig. 1), and respiration and remineralization increases the CO_2 concentration ((2) in Fig. 1). Net autotrophic ecosystems would lower surface water CO_2 concentration and be a direct sink for atmospheric CO_2 [76, 77]. Lowering of surface water CO_2 concentration is facilitated if allochthonous C_{org} ((3) in Fig. 1) and DIC inputs ((4) in Fig. 1) are low. Reactions of the inorganic C (C_{inorg}) cycle can also change the CO_2 concentration in surface water and therefore influence net exchange of CO_2 with the atmosphere[4, 5, 78]. Formation of calcium carbonate minerals (calcification) results in an increase of CO_2 in the water column ((5) in Fig. 1) while dissolution of carbonate minerals decreases CO_2 ((6) in Fig. 1). These processes may critically affect air-water CO_2 gas exchange. Although recent studies related to the role of BC in climate change mitigation are beginning to address the abundance and burial rate of C_{inorg} in soils[4, 5, 54, 78, 79, 80], studies investigating the full suite of key processes for air-water CO_2 fluxes, such as carbonate chemistry and C_{org} dynamics in shallow coastal waters and sediments, are still scarce (but see [76, 77, 81, 82]). In particular, relevance of carbonate chemistry to the overall spatio-temporal dynamics of C_{org} and C_{inorg} pools and fluxes (e.g., origin, fate, abundance, rate, interactions) and air-water CO_2 fluxes is largely uncertain for BC ecosystems[4].

Therefore, in addition to C_{org} related processes occurring in sediments and vegetation, future BC science should also quantify other key processes, such as air-water CO_2 fluxes and C_{org} and C_{inorg} dynamics in water, to fully understand the role of BC ecosystems in climate change mitigation[83].

Q6. How can organic matter sources be estimated in BC sediments?

Coastal ecosystems, mangroves, seagrasses and tidal marshes, occupy the land-sea interface and are subject to convergent inputs of organic matter from terrestrial and oceanic sources as well as transfers to and from nearby ecosystems[84]. However, the most basic requirement of quantifying organic matter inputs, and differentiating between allochthonous and autochthonous sources of C_{org}, remains a challenge. This limitation has particular relevance because of interest in financing the restoration of coastal ecosystems through the sale of BC offset-credits[85]. Policy frameworks such as the Verified Carbon Standard Methodology VM0033[86] stipulate that offset-credits are not allocated under the framework for allochthonous C_{org} because of the risk of duplicating C sequestration gains that may have been accounted for in adjacent ecosystems. New methods are emerging that have greater potential to quantify the contribution of different primary producers to sedimentary organic carbon in marine ecosystems[87].

Natural abundance of stable isotopes, most commonly ^{13}C, ^{15}N and ^{34}S, have been used to trace and quantify allochthonous and autochthonous C_{org} sources and their relative contributions to carbon burial. The costs are low, the methodology for sample preparation and analysis is relatively easy and the validity of the technique has been widely, and generally successfully tested[88]. However, the diversity of organic matter inputs can result in complex mixtures of C_{org} that are not well resolved based on the isotopic separation of the sources. Isotopic values of different species may be similar, or may vary within the same species with microhabitats, seasons, growth cycle or tissue type[89, 90].

The use of bulk stable isotopes must be improved by additionally analysing individual compounds with a specific taxonomic origin. Biomarkers such as lignin, lipids, alkanes and amino acids, have proven useful for separating multiple-source inputs in coastal sediments[88, 91]. Leading-edge studies, using compound-specific stable isotopes, employ both natural and radiocarbon analyses, providing the added dimension of age to taxonomic specificity[92, 93]. Oxygen and hydrogen stable isotopes could also be used to improve resolving power, but up to now they have been used mainly in foodweb studies and their utility in determining sedimentary sources in coastal systems still needs to be validated[87]. Studies using both bulk and compound-specific isotopes must consider how decomposition may alter species-specific signatures[89, 90, 94] Other, alternative fingerprinting techniques are emerging. The deliberate stable isotope labelling of organic matter and tracing its fate is a powerful approach that overcomes some of the limitations of natural abundance studies (e.g. source overlap), but has only looked at short-term C_{org} burial to-date[95]. The use of environmental DNA (eDNA) has been used to describe community composition in marine systems, but the potential to quantify the taxonomic proportions of plant sources in sediments has rarely been tested[87, 96].

Overall, projects using ^{13}C and ^{15}N stable isotopes will likely continue to dominate the investigation of organic matter sources, especially in simple two end member systems. While there is a growing suite of organic matter tracers, the ability to distinguish between specific blue carbon sources such as marsh vegetation and seagrass still remains a challenge. Sample size requirement, analytical time and cost implications, will be crucial in the selection of the most appropriate tracers for the characterisation and quantification of the molecular complexity in blue carbon sediments. In general, applications of most compound specific tracers have focused on environments other than those supporting blue carbon ecosystems[88, 93, 97], and more work is needed to apply the same research tools to these systems. We recommend, wherever possible, that complementary methods such as compound-specific isotopes and eDNA that take advantage of methodological advances in distinguishing species contributions, be used in conjunction with bulk isotopes.

Q7. What factors influence BC burial rates?

BC ecosystems have an order of magnitude greater C burial rates than terrestrial ecosystems[3]. This high BC burial rate is a product of multiple processes that affect: the mass of C produced and its availability for burial; its sedimentation; and its subsequent preservation. A host of interacting biological, biogeochemical and physical factors, as well as natural and anthropogenic disturbance (see Q2), affect these processes. With respect to biological factors, it remains unclear how primary producer diversity and traits (e.g. biochemical composition, productivity, size and biomass allocation) influence BC[98, 99]. However, it is likely that the suite of macrophytes present in BC ecosystems is critical to the mass of C available to be captured and preserved (as suggested for tidal marshes[100]). Equally, it is uncertain how fauna influence the production, accumulation or preservation of C_{org} via top-down processes such as herbivory[38, 101, 102, 103]. Similarly, predators can regulate biomass, persistence and recovery of seagrasses, marshes and mangroves by triggering trophic cascades[38]. In addition, the functional diversity and activity of the microbial decomposer community, and how they vary with depth and over time, is only just beginning to be examined[104] and will need to be linked to BC burial rates. Most likely this microbial community will be more important in defining the fate of C_{org} entering BC soils than its production and sedimentation.

The general effects of hydrodynamics on carbon sequestration in BC ecosystems are understood, yet there is much we still do not understand which could explain the variability in sequestration we see across BC ecosystems. We know that hydrodynamics, mediated by biological properties of BC ecosystems (e.g. canopy size and structure), affect particle trapping[105, 106, 107] and, presumably, C_{org} sedimentation rates. For example, increasing density of mangrove stands positively affects affect wave attenuation, enhancing the accumulation of fine grained material[108], which promotes C_{org} accumulation (silts and clays retain more C_{org} than sands[109, 110]. However, significant variation in soil C_{org} has been observed within-meadow[111], pointing to complex canopy-hydrodynamic interactions which we do not understand but which could affect our ability to develop robust estimates of meadow-scale BC burial. For example, a study of restored seagrass meadow found strong positive correlations between C_{org} stocks and edge proximity leading to gradients in carbon stocks at scales of >1 km[112]. Elsewhere, flexible canopies have been shown to interact with wave dynamics, increasing turbulence near the sediment surface[113]. This could explain the loss of fine sediments, and presumably C_{org}, in low shoot density meadows compared to high density meadows[114], with implications for carbon sequestration over time following restoration of BC ecosystems and the development of canopy density. Because these types of hydrodynamic interaction can affect the spatial and temporal patterns in carbon accumulation they need to be better understood in order to design stock and accumulation assessments and to predict the temporal development of stocks following management actions.

The basic biogeochemical controls on C_{org} accumulation within soils are understood (e.g. biochemical nature of the C_{org} inputs which vary among primary producers[115, 116, 117] and the chemistry of their decomposition products)[110], but it remains unclear what controls the stability of stored C_{org} in BC soils and whether these factors vary across ecosystems or under different environmental conditions (incl. disturbance). With the exception of one recent paper[43], we know little about the C_{org} -mineral associations in BC ecosystems, how these affect the recalcitrance of soil C_{org} or whether specific forms are protected more by this mechanism than others, though this is clearly the case in other ecosystems[118, 119, 120]. Undoubtedly the anaerobic character of BC soils places a significant control on *in situ* rates of C_{org} decomposition and remineralisation. However, the time organic materials are exposed to oxygen before entering the anaerobic zone of BC soils will impact the quantity and nature of C_{org} as will the redox potential reached within the soil. The amount of time organic matter is exposed to oxygen explains the observation that C_{org} concentrations in tidal marshes globally are higher on coastlines where relative sea level rise has been rapid compared to those where sea level has been relatively stable[18]. Moreover, exposure of BC to oxygen has been recently shown trigger microbial attack, even ancient (5,000 year old) and chemically recalcitrant BC[43]. Enhancing our understanding of oxygen exposure times and critical redox potentials will help explain variations in C_{org} accumulation rates and preservation within different BC ecosystems.

From the above, there is increasing evidence that we do not understand the complex interactions among influencing environmental factors well enough to predict likely C_{org} stocks in soils, including temperature, hydrodynamic, geomorphic and hydrologic factors that can affect biogeochemical processes or mediate biological processes, and this leads to apparent contradictions. For example, the influence of nutrient availability on C_{org} stocks is unclear with one study reporting an increase in soil C_{org} stocks along a gradient of increasing phosphate availability[121], another reporting no effect[122], and yet others[121, 123] finding that increasing nutrient availability led to lower soil C_{org}. Some empirical studies have examined interactive effects or evoked them to explain difference in C_{org} stock[101, 124, 125]. However, these studies are rare and limited by the complexity or the interactions being examined. We conclude that gaining insights into these interactive effects is more likely to be advanced through modelling approaches.

Q8. What is the net flux of greenhouse gases between Blue Carbon ecosystems and the atmosphere?

BC ecosystems are substantial sources and sinks of greenhouse gases (GHGs) (CO_2, CH_4, N_2O), though we cannot construct accurate global BC budgets due to uncertainties in net fluxes. The C budget is best constrained for mangroves, with mangroves globally taking up 700 Tg C yr^{-1} through Gross Primary Production, and respiring 525 Tg C yr^{-1} (75%) back to the atmosphere as CO_2[126]. However, large uncertainty exists in budgets due to poorly constrained mineralization pathways linked to CO_2 efflux[119].

We lack robust global C budgets for other BC ecosystems due to insufficient empirical evidence[127]. For example, while we have estimated global soil C_{org} stocks[128] and accumulation rates for seagrasses, this is insufficient to create a budget[129] because we lack representative data on community metabolism and GHG fluxes, particularly for CH_4 and N_2O emissions. Thus, we need to better quantify sink/source balances, e.g., the net balance between primary production vs. emissions from ecosystem degradation and pelagic, benthic, forest floor and canopy respiration[126]. We also need to understand how source/sink dynamics change budgets over time and how environmental parameters affect GHG fluxes[129, 130], allowing us to estimate thresholds that flip BC ecosystems from GHG sinks to sources.

Budgets generally focus on CO_2 fluxes, though we must better understand fluxes of other GHGs such as CH_4 and N_2O, and their contribution to the global BC budget[131]. Global estimates show that CH_4 emissions can offset C burial in mangroves by 20% because CH_4 has a higher global warming potential than CO_2 on a per molecule basis[132]. CH_4 emissions may also offset C burial in seagrasses, though these estimates have not been made. In contrast, some mangroves are N_2O sinks[133] which would enhance the value of the C burial as a means to mitigate climate change. Overall, CH_4 and N_2O biogeochemistry is understudied in BC ecosystems.

Finally, we must understand how GHG fluxes change as BC ecosystems replace each other, such as when mangroves expand onto marshes at their latitudinal limits[134], or are planted on seagrass meadows in Southeast Asia. We also need to understand how emissions may change with loss of BC ecosystems. For example, it has been coarsely estimated that a 50% loss of seagrass would result in a global reduction in N_2O emissions of 0.012 Tg N_2O-N yr^{-1} and a 50% loss of mangroves would result in a global reduction in emissions of 0.017 Tg N_2O-N yr^{-1} [130].

Q9. How can we reduce uncertainties in the valuations of Blue Carbon?

Studies into BC increasingly include a valuation aspect, focussed on coastal sites[135] but more recently also including offshore sites[136], showing a range of values for different ecosystems as depicted in Fig. 2. Differences in values are driven by differences in BC sequestration and storage capacity and/or potential avoided emissions through conservation and restoration among ecosystems. There is also variation in BC values due to uncertainties in the calculation of C sequestration and permanence of C storage, as is required for valuation. The wide range of C valuation methods, including social costs of C[111], marginal abatement costs[112], and C market prices, also enhances the uncertainty and variation in valuation estimates.

Valuation of BC enables its inclusion in policy and management narratives[113], facilitating the comparison of future socio-economic scenarios, including mitigation and adaptation interventions[137], and raises conservation interests as an approach to mitigate climate change and offset CO_2 emissions[2]. For example, BC budgets can be incorporated into national greenhouse gas inventories[138]. Alternatively, demonstrable gains in C sequestration and/or avoided emissions through conservation and restoration activities can be credited within voluntary C markets or through the Clean Development Mechanism of the United Nations Framework Convention on Climate Change (UNFCCC)[86]. Voluntary market methodologies for BC ecosystems have been released within the American Carbon Registry[139] and within the Verified Carbon Standard[86], while some countries are developing BC-focussed climate change mitigation schemes that provide economic incentives. However, on the international scale, BC ecosystems have previously not been consistently incorporated into frameworks for climate change mitigation that offer economic reward for the conservation of C sinks, such as the REDD+ program[140], possibly as there was insufficient information for its inclusion. Avoiding degradation of mangroves, tidal marshes and seagrasses could globally offer up to 1.02 Pg CO_2-e yr^{-1} in avoided emissions[37]. Developing countries with BC resources have the opportunity to use BC for the NDC, for example Indonesia, where BC contribution to reduce emissions could be as much as 0.2 Pg CO_2-e yr^{-1} or 30% of national land-based emission while mangrove deforestation only contributes to 6% of national deforestation[141].

To reduce uncertainty in BC values and encourage use of values in future policy and management, we recommend improved interdisciplinary research, combining ecological and economic disciplines to develop standardised approaches to improve confidence in the valuation of BC. Ideally this should be undertaken alongside studies which recognise the additional values of conserving BC ecosystems, for example the benefits generated from fisheries enhancement, nutrient cycling, support to coastal communities and their livelihoods[2] and coastal protection, which is considered a cost-effective method compared to hard engineering solutions[142].

Q10. What management actions best maintain and promote Blue Carbon sequestration?

Research over the past decade has improved estimates of C dynamics at a range of spatial scales. This has enabled modelling of potential emissions from the conversion of seagrass, mangrove and tidal marsh to other uses[41], and estimates of rates of and hotspots for CO_2 emissions resulting from ecosystem loss[13]. The development of policy, implementation of management actions and the demonstration of BC benefits (including payments), however, are still in their infancy.

There are three broad management approaches to enhance C mitigation by BC ecosystems: preservation, restoration and creation. Preserving ecosystem extent and quality – for example, through legislative protection and/or supporting alternative livelihoods - has the two-fold benefit of avoiding the remineralisation of historically sequestered C, while also protecting future sequestration capacity. Preservation may include direct or indirect approaches to maintain or enhance biogeochemical processes, such as sedimentation and water supply[46]. Restoration pertains to a range of activities seeking to improve biophysical and geochemical processes – and therefore sequestration capacity - in BC ecosystems. Examples include passive and/or active reforestation of logged and degraded mangrove forests[143]; earthwork interventions to return aquaculture ponds to mangrove ecosystems[141]; and the restoration of hydrology to drained coastal floodplains[144]. Managed realignment is a particular option for creating or restoring tidal marshes as part of a strategy to achieve sustainable coastal flood defence together with the provision of other services, including C benefits[145]; other similar options include: regulated tidal exchange[131] and beneficial use of dredged material[146]. Although restoration may re-establish C sequestration processes, it is important to note that it may not prevent large amounts of fossil C being lost following future disturbance or intervention. 'No net loss' policies have been now developed and applied to wetland ecosystems in many countries (e.g. USA and EU). These generally imply the creation of BC ecosystems to replace those lost through development. Such approaches should be treated with caution, however, since there is confusion about terminology[141], lack of enforcement and limited capacity to recreate the qualities of pristine sites.

Tools for the accounting and crediting of C payments now exist for coastal wetland conservation, restoration and creation under the voluntary C market[86, 147]. Several small-scale projects (e.g. Mikoko Pamoja in Kenya) are now using these frameworks to generate C credits with others projects in development[148]. Few jurisdictions have adopted their own mechanisms for the accounting and/or trading of BC, though some have undertaken preliminary research to identify BC policy opportunities[149].

Technical, financial and policy barriers remain before local initiatives can be scaled-up to make large impacts – such as through national REDD+ initiatives. Significant barriers include biases in the geographic coverage of data, approaches for robust, site-specific assessment and prediction of some C pools (e.g. below-ground C and atmospheric emissions), high transaction costs and ensuring that equity and justice are achieved. In addition, most demonstrated efforts are recent actions with little quantification of C mitigation benefits (or societal outcomes) beyond the scale of a few years.

Despite such barriers, we now have the fundamental knowledge to justify the inclusion of BC protection, restoration and creation in C mitigation mechanisms. While there remain knowledge gaps – both in science, policy and governance – these will partly be addressed through the effective demonstration, monitoring and reporting of existing and new BC projects.

Toward a research agenda on the role of vegetated coastal ecosystems on climate change mitigation and adaptation

The questions above are not short of challenges and therefore, provide ample scope for decisive experiments to be designed and conducted, current hypotheses to be rejected or consolidated and new ideas and concepts to unfold. Emerging questions that are not yet supported by robust observations and experiments, include, for example: the estimation of allochthonous C (organic and inorganic) contributions to BC, which remains challenging due to availability of markers able to quantitatively discriminate among the different carbon sources; and the net balance of GHG emissions, which remains challenging as it requires concurrent measurements across relevant time and spatial scales of all major GHGs (CO_2, CH_4, NO_2), for which not a single estimate is available to-date. The core questions that capture much of current research efforts in BC science include the role of climate change on C accumulation, efforts to improve the precision of global estimates of the extent of BC ecosystems, factors that influence sequestration in BC ecosystems, with the corresponding value of BC, and the management actions that are effective in enhancing this value. The preceding text provides a summary of current research efforts and future opportunities in addressing these key questions.

Three questions are long-standing, controversial, and need resolution in order to properly constrain the BC paradigm. The first is the effect of disturbance on GHG emissions from BC ecosystems, where the initial assumption, that the top meter of the soil C stock is likely to be emitted as GHG following disturbance[37, 128], continues to be carried across papers without being challenged or verified. The second is whether macroalgae-C can be considered BC. The term BC refers to C sequestered in the oceans[1], and the focus on seagrass, mangroves and tidal marshes is justified by the intensity of local C sequestration these ecosystems support. If macroalgaeprovide intense C sequestration, whether in the ecosystem or beyond, they need to be dealt with in this context. And the third controversy is whether carbonate accumulation in BC ecosystems render them potential sinks of CO_2 following disturbance. It is clear that there are far too many key uncertainties[4] to resolve this at the conceptual level, since empirical evidence to provide a critical test is as yet lacking. We propose that a research program including key observational and experimental tests designed to resolve the mass balance of carbonate (e.g. balance between allochthonous and autochthonous production and dissolution) - and then the coupling between BC ecosystems and the atmosphere - is needed. In the case of all three controversies, we believe that the positive approach to address these questions, is to pause the current discussion, which are largely rooted in the lack of solid, direct empirical evidence, and recognize that further science is required before any conclusion can be reached.

In summary, the overview of questions provided above portrays BC science as a vibrant field that is still far away from reaching maturity. Apparent controversies are a consequence of this lack of maturity and need to be resolved through high quality, scalable and reproducible observations and experiments. We believe the questions above inspire a multifarious research agenda that will require continued broadening the community of practice of BC science to engage scientists from different disciplines working within a wide range of ecosystems and nations.

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Tables

Table 1. Examples of gains and losses for BC stocks with a range of climate change factors. Green text indicate potential positive effects on BC stocks, red text negative effects with black text indicating where effects could be positive or negative.

Ecosystem	**Sea level rise**	**Extreme storms**	**Higher temperatures**	**Extra CO_2**	**Altered precipitation**
Mangrove	Landward expansion increases area and C stocks; Losses of low intertidal forests and coastal squeeze could reduce C stocks. Increasing accommodation space increases C sequestration.	Canopy damage, reduced recruitment and soil subsidence resulting in losses of C stocks; Soil elevation gains due to sediment deposition increasing C stocks and, reducing effects of sea level rise.	Minimal impacts anticipated, although increased decomposition of soil C possible; Poleward spread of mangrove forests at expense of tidal marshes increases C stocks; Change in dominant species could influence C sequestration.	An increase in atmospheric CO_2 benefits plant productivity of some species which could alter C stocks.	Canopy dieback due to drought; Losses of C stocks due to remineralization and reduced productivity. Increased rainfall may result in increased productivity and C sequestration.
Tidal Marsh	Landward expansion increased area and C stocks;	Loss of marsh area and C stocks; Enhanced sedimentation	Increased temperatures may increase decomposition of soil organic matter, but	An increase in atmospheric CO_2 benefits plant productivity of some	Reduced above and belowground production due to drought reducing C sequestration;

	Losses of low intertidal marsh and coastal squeeze could reduce C stocks; Increasing accommodation space increases C sequestration.	and soil elevation increasing C stocks and, reducing effects of sea level rise.	offset by increased productivity of tidal marsh vegetation; Poleward expansion of mangroves will replace tidal marsh and increase C storage; Poleward expansion of bioturbators, may decrease soil C stocks.	species which could alter C stocks.	Possible losses of C stocks due to remineralization; Impact could be greater in areas that already have scarce or variable rainfall.
Seagrass	Loss of deep water seagrass; Landward migration in areas where seawater floods the land (into mangrove or tidal marsh ecosystem).	Some extreme storms cause the erosion of seagrasses and loss of seagrass C stocks but some seagrass species are resistant to these major events. Flood events associated with extreme rainfall may result in mortality, but could also	Thermal die-offs leading to losses of C stocks; Species turnover. Colonization of new poleward regions Increased productivity.	An increase in dissolved inorganic C benefits plant productivity increasing C stocks; Ocean acidification leads to loss of seagrass biodiversity, decreasing C stocks.	Most seagrasses are tolerant of acute low salinity events associated with high rainfall, but some are negatively affected and potential interactions with disease may lead to losses of C stocks; Reduced rainfall increases light availability

		increase sediment accretion and C sequestration.			which increases productivity and C sequestration.
Seaweed	Seaweeds are expected to colonise hard substrata that become flooded, increasing C stocks.	Reduces seaweed cover, but could lead to sequestration of C stocks as detritus sinks.	Major retraction in kelp forest C stores at non-polar range edges; Expected expansion at polar range edges.	Increased biomass and productivity of kelp where water temperatures remain cool enough.	Little effect overall; Regional effects on seaweed flora in areas with high land run off/rivers.

Table 2. Estimates of global net primary productivity, CO_2 release from calcification and C sequestration (Tg C per year) for three benthic marine systems

System	Global CO_2 (as C) fixation in NPP	Global CO_2 (as C) Release from calcification, assuming 0.6 CO_2-C per $CaCO_3$-C produced	Global net organic C assimilation = NPP minus C as CO_2 produced in calcification	Global C sequestration	References
Benthic Macroalgae (calcified and uncalcified)	960 - 2000	?	?	60– 1400	Charpy-Roubard & Sournia (1990); Krause-Jensen & Duarte (2016); Duarte (2017); Raven (2017)
Calcified coralline red algae	720	120	600	?	Van den Heijden & Kamenos (2015), who do not mention CO_2 release from $CaCO_3$ formation
Coral reefs	0	84- 840	--84- -840	0[2]	Ware et al. (1991); Smith & Mackenzie (2015);

[1] See Figure S1.

[2] Assuming $CaCO_3$ ultimately sinks below the lysocline, where $CaCO_3$ dissolves, and upwelling ultimately (10^2-10^3 years) brings the resulting HCO_3^- back to the sea surface.

Figures

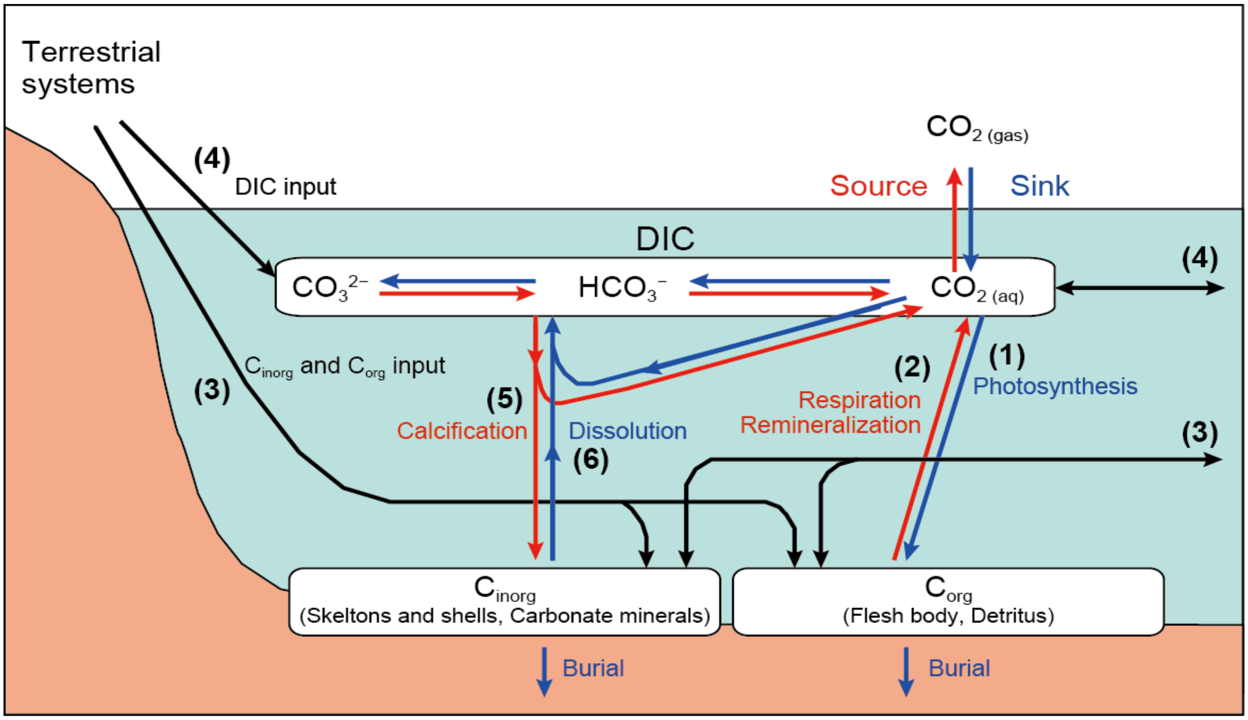

Figure 1. Conceptual diagram showing the biogeochemistry of carbon associated with air-water CO_2 exchanges. Blue lines indicate the processes that enhance the uptake of atmospheric CO_2, and red lines indicate those that enhance the emission of CO_2 into the atmosphere. The CO_2 concentration in surface water is primarily responsible for determining the direction of the flux. The concentration of surface water CO_2 is determined by carbonate equilibrium in dissolved inorganic carbon (DIC) and affected by net ecosystem production (the balance of photosynthesis, respiration, and remineralization), which directly regulate DIC (1 and 2), allochthonous particulate and dissolved organic carbon (C_{org}), particulate inorganic carbon (C_{inorg}), and DIC inputs from terrestrial systems and coastal oceans (3 and 4), net ecosystem C_{inorg} production (the balance of calcification and dissolution), directly regulating both DIC and total alkalinity (TA) (5, 6), and temperature (solubility of CO_2). Calcification produces CO_2 with a ratio (released CO_2/precipitated C_{inorg}) of approximately 0.6 in normal seawater[53].

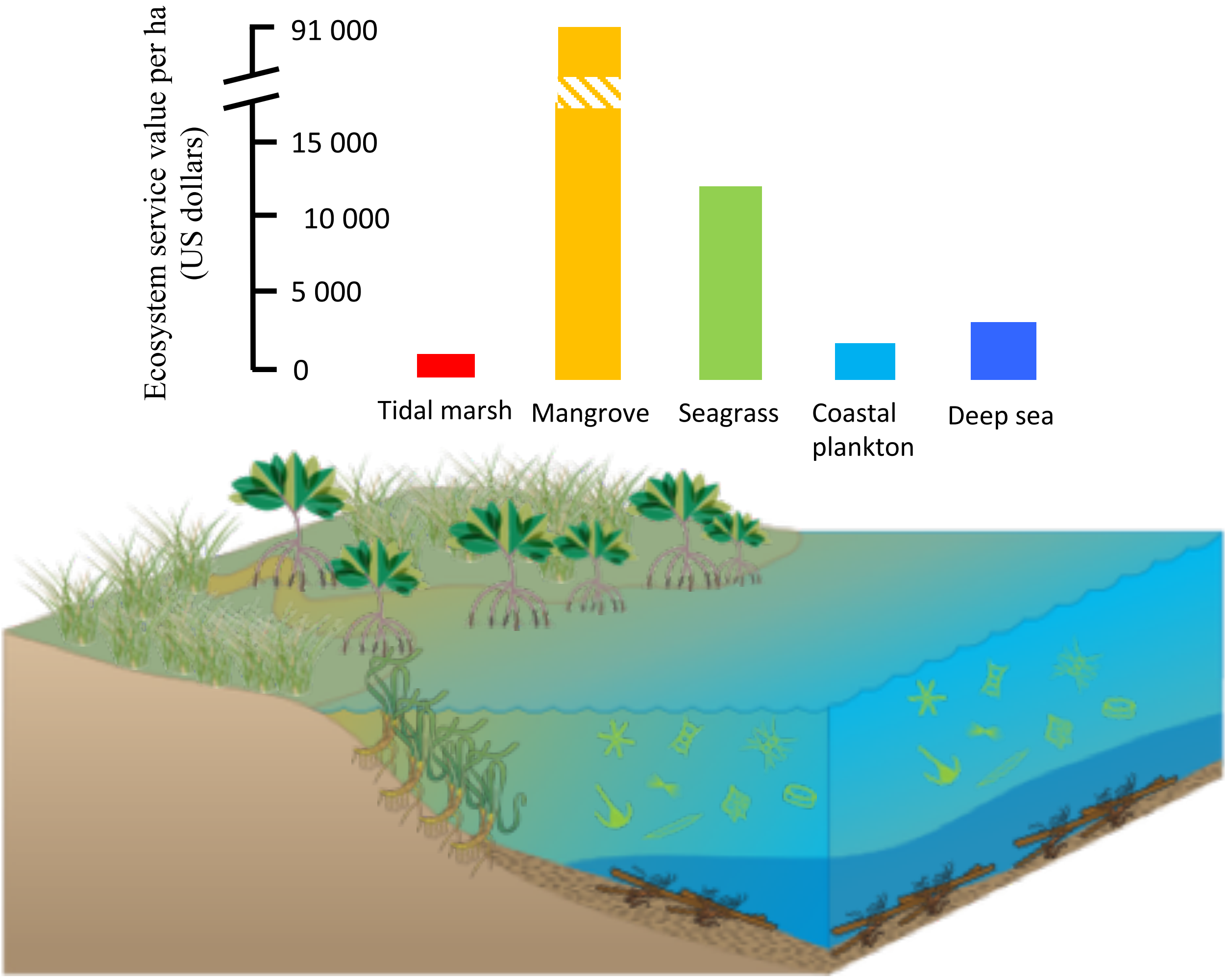

Figure 2. Estimated valuation of Blue Carbon sink per hectare. Adapted from[1]. Symbols and images are a courtesy of the Integration and Application Network, University of Maryland Center for Environmental Science (ian.umces.edu/symbols/).

Supplementary Information

List of the questions submitted by co-authors identifying perceptions of key questions in Blue Carbon science

Andrea Anton

- What are the global areas of the main Blue Carbon habitats (seaweeds, mangroves, seagrasses, and saltmarshes)?
- What are and where are the main carbon sinks for macroalgae?
- What are the carbon storage rates for macroalgae in the deep sea?

Bayden Russell

- The fate of C sequestered by macroalgae which then die on short time scales. Many are annual to less than a decade in life span and the lost carbon can then potentially re-enter the carbon system;
- Fate of C which is lost as tissue from macroalgae. Unlike terrestrial biomes where any shed carbon (e.g. leaves, other biomass) can be incorporated into the soil and therefore "locked away", the fate of this biomass is relatively unknown for macroalgal stands.
- Realistic predictions of our ability to restore habitats in the face of ongoing and persistent pollution (local to regional discharges) and increased temperatures.
- The trade-off between ongoing aquaculture development in Asia and Africa and Blue Carbon stores – currently practices are generally in conflict
- Can aquaculture be used as a Blue Carbon? What is the fate of the carbon along the consumption chain? Does this actually count towards C reduction?

Bradley Eyre

- CH_4 and N_2O offsets to Blue Carbon burial
- Carbonate burial offsets to Blue Carbon burial
- Autochthonous versus allochthonous carbon source contributions to Blue Carbon burial
- Area estimates of Blue Carbon burial habitats, particularly at the species level (e.g. Zostera vs Halophila) and sub-type level (e.g. river vs ocean mangroves).
- How do you upscale areas. Lots of different ways.

- Lack of burial data for Blue Carbon burial habitats, particularly replicated burial rates and at the species level (e.g. Zostera vs Halophila) and sub-type level (river vs ocean mangroves)

Brian Silliman

- How does the increasing rate of disturbance in coastal wetlands impact Blue Carbon?
- How do habitat cascades impact spatial variation in Blue Carbon storage?
- How do filter feeding bivalves regulate carbon sequestration in vegetated coastal wetlands?
- How do different types of development (reclamation, shrimp farming etc) impact Blue Carbon in mangroves?
- How does Blue Carbon storage vary with time since restoration in restored wetlands?
- What is the density-dependent impact of grazers on Blue Carbon storage?
- How do predators indirectly control Blue Carbon, and how does that vary with predator identity and density?
- How does frequent drought impact carbon storage in coastal wetland?
- How does sea level rise impact carbon storage?
- How does loss of Blue Carbon storage vary with length of disturbance event?

Carlos Duarte

- What is the area covered by seagrass and how is it distributed globally? (As the areas for mangroves and salt-marshes are now relatively well constrained).
- What is the global distribution of organic carbon density, burial rates and stocks in BC habitats? (As estimates published thus far may have been biased towards particular regions or, in the case of seagrass, upper estimates).
- What is the net balance between emissions of greenhouse gases and organic carbon burial in Blue Carbon habitats?
- How do macro algae contribute to carbon sequestration?
- What is the fate of exported production from Blue Carbon habitats, including macroalgae, where do these stocks accumulate?
- What is the role of carbonates in Blue Carbon sediments and how does it affect greenhouse accounting and organic carbon preservation?

- What is the best approach to fingerprint the contributions of different sources to Blue Carbon organic stocks?
- How should allochthonous contributions be considered in terms of greenhouse accounting?
- Does climate change affect the stability of Blue Carbon CO2 sequestration and stocks?

Catherine Lovelock

- Are Blue Carbon ecosystems "safer" or more prone to disturbance than terrestrial carbon sinks?
- What happens to Blue Carbon stocks with sea level rise?
- What is the shape of the trajectories of C sequestration upon restoration – what should those models look like? Linear for soil; exponential for biomass? How many years to reach targets?
- What is the cost/benefit of Blue Carbon projects – are they really more expensive than terrestrial ones? Which ones are and which ones are not?

Dan Friess

- Can we better quantify dissolved carbon fluxes in mangroves? A large part of the global mangrove carbon budget is unaccounted for. This may be because we have poor knowledge of dissolved flux pathways for DIC and DOC, particularly sub-surface tidal pumping and groundwater fluxes.
- What are the carbon links between Blue Carbon ecosystems? We need a better understanding of how Blue Carbon ecosystems exchange carbon between them, both spatially and through time.
- How can we better quantify the spatial distribution of soil carbon at multiple scales? This is a potential constraint to Blue Carbon Payments for Ecosystem Services (PES), and it would better incentivize conservation if we could include soil carbon stocks. However, this needs us to develop better methods to quantify soil carbon at scales larger than plot measurements.
- How can we accurately upscale estimates of soil carbon accretion? Some studies have linked measurements of soil carbon with sediment accretion rates to understand soil carbon accumulation over time. However, sediment accretion and surface elevation processes are hugely variable across a site due to geomorphology, microtopography, disturbance etc. Our

inability to measure the spatial variation of accretion constrains our current estimates of soil carbon accumulation.

- What time scales are required for restored mangroves to attain natural carbon cycling function? Through studies of forestry plantations we have an idea of how much time is required to restore some parts of the carbon budget (e.g., above-ground biomass) to a predisturbance state. However, the same cannot be said for dissolved and gaseous fluxes, and to a lesser extent soil carbon stocks.
- Can we better constrain emissions factors during land cover conversion? We now have quite a solid picture of Blue Carbon stocks in many parts of the world. However, we rarely measure the carbon stocks of alternative land uses. This information is required if we are to more accurately quantify Blue Carbon loss during habitat conversion. Emissions factors for mangroves and alternative land uses are urgently needed.
- What are the emissions from degraded mangroves? We need a better understanding of the disturbance thresholds that flip mangroves into carbon emitters, particularly soil gaseous fluxes.
- What are the governance and implementation challenges to Blue Carbon PES? Despite years of research and discussion, Blue Carbon PES is still at an embryonic stage. We need to better understand the socio-economic constraints to Blue Carbon PES implementation, how it differs between countries, and how it differs from terrestrial PES mechanisms.

Dan Laffoley

- How do Blue Carbon habitats respond to a changing terrestrial environment? (Craig Smeaton/William Austin)
- Within the sediment stores associated with Blue Carbon habitats, how should we account for terrestrial Carbon subsidies? (William Austin/Craig Smeaton)
- What role will future sea level rise play in the potential of coastal Blue Carbon habitats to sequester and store Carbon? (William Austin)
- How significant are Blue Carbon habitats in subsidizing Carbon to subtidal sediments? (William Austin)

- To what degree and geographical extent does sea grass influence the carbonate chemistry of the surrounding waters including carbon absorption as well as locally buffering ocean acidification scenarios (Dan)
- Quantification and timescales for the carbon re-release pathways for subtidal sink habitats such as sea grass and maerl as a result of impacts and damage from human activities including trawling (Dan)
- Does having a local profusion of subtidal carbon pools and sinks confer any buffering advantages down the line from effects of progressive ocean acidification (Dan)
- How does subtidal carbon pools and sinks stability interact with a warming and deoxygenating ocean? (Dan)

Daniel Smale

- What is the spatial distribution (at local to global scales) of Blue Carbon source and sink habitats and what environmental factors drive their distributions?
- What is the standing stock (above and below ground) of organic carbon (at local to global scales) in Blue Carbon habitats and what environmental factors drive variability in standing stock?
- What is the burial rate and long-term storage capacity of organic carbon (at local to global scales) within Blue Carbon habitats and what environmental factors drive variability in storage capacity?
- What is the significance of carbon donors (e.g. macroalgae) for Blue Carbon ecosystem services?
- How interconnected are Blue Carbon habitats and what processes determine transport pathways of organic carbon and source-sink connectivity?
- What is the contribution of allochthonous organic carbon (i.e. from terrestrial sources and macroalgae) to total carbon storage in Blue Carbon habitats and how does this vary spatio-temporally?
- How will climate change (i.e. ocean warming, sea level rise, increased storminess) alter the assimilation, transport, burial and storage of organic carbon in Blue Carbon habitats?
- How will climate change-carbon cycle feedbacks/interactions influence Blue Carbon services?

- How will local/regional anthropogenic stressors (e.g. physical disturbance from fishing/shipping practises, decreased water quality, coastal development and land use) alter the assimilation, transport, burial and storage of organic carbon in Blue Carbon habitats?
- What are the implications of rapid ice loss in the Arctic and Antarctic for the expansion of Blue Carbon habitats and natural carbon sequestration?
- What management actions/approaches (e.g. MPAs, fishing restrictions, land use management) best maintain and promote natural carbon sequestration? Can or should international policy frameworks be expanded to include carbon donor habitats (e.g. kelp forests) within the context of natural carbon sequestration?

Dorte Krausse-Jensen

- What is the contribution of macroalgae to carbon sequestration? - there is a need of field data on the contribution of macroalgae to sediment carbon stocks, estimates of carbon export from macroalgae etc.
- To what extent is macroalgal carbon preserved in sediments? - differences between species, habitats.
- To what extent does DOC emitted from macroalgae forests and seagrass meadows contribute to carbon sequestration?
- What is the carbon emission from eroded seagrass sediments?
- To what extent does macroalgal cultivation contribute to carbon sequestration, - e.g. to what extent and how can the seaweed biomass that is currently discarded from production be used in carbon sequestration?

Eugenia Apostolaki

- Expand the data-set of carbon sequestration, burial and storage of Blue Carbon ecosystems (different vegetation type, species and biogeographic regions)
- Assess the carbon sequestration, burial and storage of mixed vs. monospecific seagrass meadows
- Identify the environmental variables that are responsible for the variability in the carbon sink capacity of seagrass ecosystems (e.g. hydrodynamic regime, depth, temperature, sediment granulometry)

- Study the effect of direct anthropogenic impacts [e.g. eutrophication, fish farming, coastal development, mechanical damage (trawling, dredging, anchoring)] on the carbon sink capacity and burial rate in seagrass ecosystems
- Study the effect of climate change on the carbon sink and burial in seagrass ecosystems (e.g. warming, acidification, alien species invasion)
- Assess and quantify the sources of organic matter (carbon and nutrients) stored in Blue Carbon ecosystems
- Assess and quantify the fate of organic matter released after the carbon sinks get impacted or destroyed
- Evaluate the organic matter (carbon and nutrients) transferred/ exchanged between adjacent Blue Carbon ecosystems extending at different zones (e.g. supralittoral to intertidal to subtidal and salt marsh to seagrass or mangroves to seagrass)

Gail Chmura

- What is the alternate fate (in open ocean, estuaries, tidal flats) of allochthonous carbon trapped in restored salt marshes and mangroves?
- What is the rate of loss of OC or IC when BCE's are drained?
- What role does tidal amplitude play in rates of OC accumulation during restoration?
- What role does climate play in C accumulation in mature BCE's and during their restoration?

Hilary Kennedy

- Does allochthonous and autochthonous organic carbon have equal validity in assessing C stocks and accumulation?
- How important is it that coastal ecosystems store terrestrially derived soil?
- What variables need to be included to predictively model OC accumulation and storage across different environmental settings?
- How can modelling help in scaling up from local measurements to the global scale?
- What is the most effective way to measure baselines on which to base temporal (or spatial) change?
- What is the fate of autochthonous organic carbon in natural settings and soil C after vegetation loss in degraded ecosystems?

- How can we effectively map submerged C stores?
- How does carbonate production and dissolution affect carbon fluxes and storage in the short and longer term?
- When should we be measuring gas (carbon dioxide, methane and nitrous oxide), rather than solid phase, fluxes?
- How can we improve both, identification of anthropogenic from natural change, and quantification of the impact of converted, disturbed and degraded ecosystems?

Iris Hendricks

- Carbonate Question: isn´t this really a matter of time scales, whether carbonate production is a source or sink of CO2. Wouldn´t it be fascinating to determine the kind of scale that is relevant and specifically see if we can get to a working definition of when we call it sink (cliffs of Dover? - if a calcified organism is deposited and buried) or source (calcification in the water column and/or in this very moment), like a threshold time period.
- Related: how would we denominate calcifying algae? Sources or sinks? Should we measure net fluxes per species (but see next whether algae are even relevant)
- Related: should we include calcifying epiphytes in our calculations of carbon accounting?
- The Macroalgae question: eligible for carbon accounting or not? If we focus on carbon deposits no (or yes? if material gets transported to the deep sea - too early to say) but focussing on air-sea fluxes yes.
- Are points measurements of fluxes sufficient with the huge seasonal/daily variations of NPP? Are we over/underestimating fluxes this way? Again if we only focus on burial capacity less relevant
- Why does carbon need to be deposited on "millenary" scales for carbon accounting schemes? That sounds absolutely irrelevant seeing we cannot even predict how the earth will be in 100 years (i.e. changing IPCC predictions).
- How relevant is horizontal advection in carbon transport from/to vegetated ecosystems? Can we pool it as "continental shelf area"/"coastal ecosystem" and assume the transport between patches of vegetation are not relevant or is hydrodynamic transport (i.e. between coral reefs and seagrass) actually very relevant? Should the scale of the Blue Carbon initiative and regional hydrodynamics determine the importance and how to treat differences between Blue

Carbon projects of the same scale in energetically different areas (or changing wave regimes with global change - regional differences).

- Should we actively seek to sequester carbon by artificially enhancing oceans´ capacities to take up CO2 like by olivine addition (mineral stone weathering) - much like iron fertilization in limited areas? and should this be an alternative to Blue Carbon (loss of co-benefits of vegetation) or be discouraged in favor of Blue Carbon

Jason Hall-Spencer

- How will ocean acidification and warming affect photoautotrophs and their role in the marine carbon cycle?
- Can we expect more or less carbon sequestration by marine algae and plants as CO2 levels rise?
- What proportion of oil, gas and coal reserves has been created by each of the following - seagrasses, salt marshes, mangroves, seaweeds and phytoplankton?
- Is growing seaweeds for food a good way of taking nutrients and carbon out of waters that are polluted with fertilizers and CO2?

Jeff Baldock

- What controls the stability of organic carbon in the soil under Blue Carbon ecosystems (Mangroves, tidal marshes, seagrasses) and do they vary across habitats or with differences in environmental conditions?
    - Input chemistry – chemical nature of the organic inputs
    - Chemistry of products of decomposition – do changes in chemical composition during decomposition infer stability
    - Decomposer community variations – does the capability exist to decompose a wide range of forms of organic matter.
    - Mineral association – how does association with minerals impact on the decomposability of organic materials in soils, does this vary with different mineralogies or surface areas, are specific forms (chemistries) of OC protected more by this mechanism than other forms.

  - Environment - O2 exclusion (biological oxygen demand, oxygen exposure time) and temperature effects as modifiers of process rates (biological and chemical)
- Rates of organic carbon input into the systems.
- Differentiating autochthonous from allochthonous contributions – probably more important in the carbon accounting realm. As far as the atmosphere is concerned, if the carbon is stabilised the atmosphere does not see it, so it should not matter what the initial source is. This then really only becomes a question associated with our attempts to ensure proper C mass balance in C accounting exercises.
- How to effectively sample to measure current stocks and stock change (issues: depth of sampling, minimising the impact of spatial variance through sampling designs to allow better isolation and detection of the temporal change).
- Development of predictive models for OC cycling in Blue Carbon systems – although understanding all the above would be required, we could get something started and modify it as understanding improves.

Jeffrey Kelleway

- What will be the fate of BC habitats and existing BC stocks under SLR?
- What will be the fate of BC habitats and existing BC stocks under warming and enhanced atmospheric CO2?
- What are the most promising restoration/creation options for C abatement and how do these vary among jurisdictions
- Can we accurately predict BC stocks, accumulation rates and/or emissions with remotely sensed data?
- What are the remineralisation rates of mangrove, tidal marsh and seagrass soils?
- What are the drivers of Blue Carbon remineralisation?

Jim Fourqurean

- what is the fate of stored Corg upon disturbance of Blue Carbon habitats?
- how important are the macrophytes in Blue Carbon habitats in the accumulation and retention of Corg in the sediments?

- how does the inorganic C cycle interact with net ecosystem metabolism to influence flux of C from Blue Carbon habitats to the atmosphere?
- will active creation or restoration of Blue Carbon habitats lead to a net increase in C uptake and storage in blue carbon ecosystems
- under what circumstances are the plant communities necessary for the retention of C in Blue Carbon ecosystems (a slight variation on my question #2)
- does disturbance of Blue Carbon habitats influence the lability of Corg stored in them?
- how much of a threat is sea level rise and climate change to the storage of C in Blue Carbon habitats?
- can planning and management ameliorate the threat that climate change presents to Blue Carbon stores?
- do Blue Carbon habitats reduce the lability (and therefore increase storage) of terrestrial Corg from the watersheds?
- how can we include seagrass Blue Carbon into national inventories, given the need to redefine the land area of nations to include subtidal habitat?

John Raven

- What are the implications of changes in global cover of the coastal macrophytes on DMS and halocarbon release with direct and indirect effects on radiative forcing?
- Are there any long-lived biomarkers from coastal macrophytes (or other sources) in organic carbon deposits that can help with determining the source of the organic carbon and its radiocarbon age, using techniques pioneered by Tim Eglinton?

Karen McGlathery

- What are the sources of sediment organic carbon in seagrass meadows? How much is allochthonous vs. autochthonous? What is the important of in situ, non-seagrass productivity (i.e., benthic micro algae) to carbon storage in seagrass sediments? How do the source contributions vary spatially with meadow size/configuration and proximity to adjacent ecosystems (e.g., marshes)?   How can this information inform policies on carbon accounting?

- How can restoration reinstate carbon storage/sequestration capacity? What is the time frame over which this occurs? Are the "best practices" that can be recommended for seagrass restoration projects that focus on carbon sequestration? Can we manage ecosystems to sequester more carbon?
- How does nutrient enrichment affect metabolism and carbon sequestration in seagrass biomass and sediments? How do the source contributions vary with nutrient enrichment?
- What is the resilience of buried carbon to climate change? For example, how does temperate effect carbon metabolism and storage, especially in the context of temperature-related seagrass die-offs?
- How important is carbonate chemistry to net CO2 fluxes in seagrass meadows in temperate and tropical regions?

Kuwae Tomohiro and Kenta Watanabe

- Tradeoffs (dilemma) between carbon storage and CO2 emission caused by carbonate production and organic matter decomposition in coastal BC ecosystems (e.g., Kuwae et al., 2016)
- Extension of BC studies to seaweed ecosystems (Krause-Jensen and Duarte, 2016) and coral reefs
- Synergies and tradeoffs between BC functioning (mitigation and adaptation) and other ecosystem services (fisheries, recreation, water quality improvement)
- Tradeoffs between CO2 emission (negative for mitigation) and land formation (positive for adaptation) by calcifiers

Mark Huxham

- What is the total quantity of carbon stored in the various key Blue Carbon sinks?
- What are the rates of loss and degradation of Blue Carbon habitats?
- How does loss and degradation affect carbon storage in Blue Carbon habitats?
- What are the rates of re-oxidation of carbon (or carbon loss) from Blue Carbon sinks following habitat loss or degradation?
- What are the key drivers of habitat loss and degradation in different areas of the world?

- How can we best communicate to the public and to policy makers the importance of Blue Carbon habitats? (this includes the secondary question of whether an emphasis on carbon implicitly devalues the other ecological services and the intrinsic beauty and value of these habitats).
- What management interventions have been shown to work and what are the local contexts in which they best succeed?
- What are our best predictions for the effects of climate change on carbon dynamics and persistence of these systems? For example, under what conditions may sinks become sources or sulphate reduction no longer limit methanogenesis?
- Does the use, promotion and expansion of payments for ecosystem services schemes (particularly carbon offsetting) involving Blue Carbon habitats lead to perverse outcomes such as 'moral hazard'; a failure to deal with the larger structural and behavioural changes need to tackle climate change?
- Can we develop relatively simple protocols, measurements and tools to allow non-specialists and local groups to assess and communicate the value of their Blue Carbon ecosystems and integrate these into international processes such as IPCC?

Nicola Beaumont

- How do we define permanence in carbon storage? For example do we consider permanent storage to be 100 years, or a millennia?
- How do we include risk in the estimates of permanence of storage? For example we may know a seagrass bed stores 100tonnes of carbon per year and this will be permanent if conditions remain the same. However, it is possible that changes may occur (port development, pollution, significant storms) which will remove or destroy the seagrass bed, possibly also releasing the carbon stored. Including this risk element in our estimates of carbon storage is critical to managers.
- How do we handle spatial boundaries in Blue Carbon science? I have seen many studies that report export of carbon from a given system with no consideration of what will happen next. We need more joined up thinking to understand how carbon moves between systems.
- How do we include uncertainty in our estimates of Blue Carbon sequestration and storage? These are critical to policy makers and managers but are rarely reported in a consistent or

clear fashion. I would advocate a move towards standardised approaches to documenting uncertainty.

- How do we monetarily value Blue Carbon in a meaningful way? There are a variety of monetary values which we can associate with Blue Carbon and this can be done relatively easily to provide a value, but little research has been undertaken to investigate the validity of these values. For example: which monetary value is most applicable to which environment? - the values vary by more than an order of magnitude, so the value you choose makes a significant difference to the final value. Which discount rate should be applied? There have been no detailed studies into methodological and conceptual development of valuing Blue Carbon and this is a real gap in the research.
- What options are there to value Blue Carbon beyond monetary estimates? There are a host of difficulties in monetising Blue Carbon (as above) so what other approaches can we take?

Nuria Marba

- global current extent of seagrass meadows, salt-marshes, macroalgae
- thickness of carbon stores that can act as C source in degraded seagrass meadows
- magnitude of carbon emissions from degraded seagrass meadows
- creation of new BC carbon sinks (e.g. macroalgae farming; seagrass carbon sinks in new suitable areas as e.g. sub-Arctic and Arctic)
- co-benefits of BC

Oscar Serrano

- Should allochthonous C be accounted for in BC accounting?
- How to estimate allochthonous C robustly in BC ecosystems?
- what’s the change in Corg stock and acc rates after habitat loss?
- what’s the fate of Corg stock loss after habitat loss?
- What’s the role of BC ecosystems in climate change mitigation and adaptation over different time-scales? from present to geological scales.
- Area of BC ecosystems (particularly critical for seagrass and tidal salt marsh)?
- Produce a global, robust, standard dataset that could assist NGO, Industry etc to establish policy and crediting schemes

- Create BC data to fulfil gaps from underrepresented areas/regions
- Involve industry into BC initiatives (e.g. BC international workshop)
- Carbonate accounting in CO2 cycling and fluxes
- What is autochthonous C? Everything that happens in the area boundaries occupied by BC ecosystems
- Macroalgae and standing stocks in living BC biomass are BC sinks? Depends on the fate of biomass or the C footprint of e.g. Food and other bioproducts
- Biochar/fertilisers from wrack is a friendly solution for managing wrack waste and reduce emissions
- Estimate the export of BC biomass into other ecosystems (beach wrack, deep ocean, adjacent ecosystems, etc.)
- Evaluate cost/benefit (feasibility) of BC projects: need to incorporate the $value of additional ecosystems services (and create markets for them if don't exist).
- Role of BC ecosystems in keeping pace with SLR: need to estimate soil accretion but also their role in supporting calcifying organisms and export of biogenic sands

Patrick Megonigal

- How do biogeochemical, geomorphic and hydrologic factors interact to preserve carbon, and how does the relative importance of these factors vary spatially? The basic controls are well known, but there is increasing evidence that we do not understand the interactions well enough to develop spatial maps from databases and remote sensing products.
- How do biogeochemical, geomorphic and hydrologic factors interact to control the fate of carbon exported from intact or disturbed Blue Carbon ecosystems? Again, we understand the basic processes, but are far from having coupled wetland-estuarine models that can predict the outcome of an erosion event (for example).
- Considering the fact that carbon sequestration and methane emissions are biogeochemically linked processes, under what circumstances are climate benefits maximized when protecting, restoring and creating Blue Carbon ecosystems?

Paul Lavery

- Emissions factors for different ecosystems in both baseline and disturbed conditions. This needs to encompass N oxides and methane as well as CO2. It also needs to take into account the different biogeochemical settings and the the time-course of responses following restoration or management interventions aimed at reducing emissions.
- Carbonate production – exactly how important is this, in what ecosystems is it important and what is the geographical distribution of those ecosystems. How do we factor this into our estimates of net C accumulation in BC ecosystems. This needs serious attention from geochemists that that consider the simultaneous precipitation and dissolution processes occurring in ecosystems.
- Macroalgae – it is currently a theoretical contribution, and maybe a big one, but we need to get empirical evidence. We need a global network on this to establish how significant it is and which factors in the variability that may be associated with the distribution of major macroalgal production hotspots.
- Allochthonous: Autochthonous ratio – this is still relevant to Corg but is likely to be even more so for carbonate
- Extent of BC habitats – definitely not sexy, but it remains a critical knowledge gap. All our efforts to reduce the errors in stocks estimates by refining carbon density measures can be easily undone by the very poor estimates of BC habitat extent.
- Climate change impacts – in particular, there is uncertainty about how changes such as sea level rise will affect BC ecosystems. The effects may not be consistent across all situations so we need to get a better conceptual framework for assessing this. Another critical aspect is how tropicalisation, resulting from climate change, may affect BC ecosystems. The expected shifts in BC primary producers and their grazers could have complex, interactive effects on BC stocks and accumulation rates.
- Filling in the geographical gaps in stock – Coral triangle is woefully under-represented in our global syntheses and saltmarshes are poorly captured compared to the other ecosystems.
- What are the impediments to uptake/incorporation of BC into carbon crediting schemes and how can these be overcome. This is more of an economic/socio-ecological question, but one which needs to be addressed if we are to get traction in the crediting community.
- How can we value the carbon sequestration service of BC ecosystems? Currently we rely on fairly simple estimates based on anticipated C-trading scheme values. but in the same way

that fisheries values are much more extensive than the direct sale price of the fish, are there other aspects of valuation that we need to take into account?

Pere Masque

- Relevance of CO2 released by carbonate sediment production
- Adequate assessment of net Corg burial rates at various time scales: year, decades and centuries
- Assessment of remineralisation rates of Corg in the soils attending to its various types
- Assessment of spatial coverage of vegetated coastal habitats at regional and global scales, particularly for seagrass meadows
- Fate of Corg after disturbance of vegetated sites: remineralisation vs redistribution
- Assessment of macroalgae in carbon sequestration: where does the Corg go? (i.e. build on Krause-Jensen and Duarte)

Rod Connolly (with comments on the table)

- What generalised models best predict spatial variation in rates of BC production?
- How can the fate of C produced in wetlands be more rigorously allocated to BC vs other routes (e.g. grazing, decomposition, export)?
- How does seascape influence BC production?
- How does BC valuation for CC mitigation compare with valuation of labile C supporting seafood production?
- How will current and future climate feedbacks affect BC production?
- How do different disturbances, from temporary shallow to permanent deep, affect the amount of existing and future BC production?
- What is the impact of ocean sprawl on BC production?
- How can urbanised and industrialised wetlands be managed (modified) to maximise BC production?
- Is widespread eutrophication of coastal waters stimulating or stymying BC production?
- How can frequency and extent of inundation of mangroves be managed to optimise BC production?

Rui Santos

- What is the proportion of autochthonous versus allochthonous carbon that is sequestered into the sediments of mangrove, tidal marsh and seagrass ecosystems?
- What is the role of water flow (and turbulence) on allochthonous blue C sequestration (as mediated by the sediment grain size)?
- What is the natural turnover time of Blue Carbon sequestered in the sediments of mangrove, tidal marsh and seagrass ecosystems?
- How do sediment properties and microbiota affect this turnover?
- How do anthropogenic disturbances affect the release of Blue Carbon back to the atmosphere?
- What is the proportion of organic carbon exported from mangrove, tidal marsh, macroalgal, and seagrass ecosystems that is sequestered?
- How much carbon is sequestered by fleshy macroalgal beds (and marine algal crops)?
- Are rhodolith beds sources or sinks of carbon? Will OA alter their role by increasing dissolution versus precipitation?
- How does calcification offsets the C sequestration by seagrasses? How will OA and temperature affect this balance?
- Will Blue Carbon sequestration increase in a high CO2 future?
- What is the C sequestration potential of reconstructed ecosystems? How much time do they need to equal natural ecosystems?
- How relevant is Blue Carbon sequestration of reconstructed ecosystems for climate change mitigation?
- How relevant is Blue Carbon sequestration versus other ecosystem services provided by mangrove, tidal marsh, macroalgal, and seagrass ecosystems?

Thomas Bianchi

- How deep to we really need to core to get the best long-term rates of sequestration and how do they differ across BC habitats?
- How important is it to determine other sources of carbon (e.g., algal or seagrass) when estimating the carbon stores of a particular habitat (e.g. mangroves)?

- How the rates of decay vary with depth and what are the controlling mechanisms across different BC habitats and regions?
- What are the GHG emissions from these systems?
- How important is later import and export of allochthonous OC material from and to these systems?
- What is the impact of relative sea-level rise and global warming on C sequestration rates in BC habitats, and can they be separated?
- What is the fate of eroding BC in coastal systems?
- Can we establish a universal worldwide system for carbon trade on preservation of these systems?
- How is global warming change the composition of coastal BC habitats (marsh to mangrove) and what are the benefits or losses from this transition.
- How can coastal plans for river diversion in regions experiencing high land loss (e.g., Mississippi, Shanghai, etc.) be combined with the added value of wetland services performed BC C sequestration to enhance the efficacy of coastal planning and management.

Tiziana Luisetti

- What are the functioning requirements of coastal Blue Carbon (e.g. mangrove, tidal marsh, macroalgal, and seagrass ecosystems) to be economically valued?
- What is the cost to society of losing Blue Carbon, or the gain for restoring it?
- How much carbon is released back into the atmosphere following anthropogenic disturbance on coastal 'blue' carbon?
- What is the cost to society of re-emitted carbon from coastal Blue Carbon stocks/sinks?
- What are the bio-physical and economic requirements needed to include coastal Blue Carbon in a global carbon permit trading market?
- What international agreements are needed to allow coastal Blue Carbon permits to be traded?
- What policies are needed to protect coastal Blue Carbon?

Trisha Atwood

- What role do macroalgal systems play in long-term carbon storage?

- How, and to what extent, do above-ground processes like herbivory influence carbon accumulation and retention in Blue Carbon and macroalgal ecosystems?
- To what degree does adjacent land use influence sources of carbon and sedimentation rates to these systems?
- How do above- and below-ground plant traits influence carbon accumulation and retention?
- Can we make generalizations about the fate (transported or transformed) of disturbed soil C
  - How does disturbance type influence the fate of disturbed soil C
  - What is the magnitude of loss (transformed or transported) and how deep in the soil matrix does that loss occur.
  -

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