TECHNICAL MEETING ON NUCLEAR AND ISOTOPIC TECHNIQUES IN BLUE CARBON HABITATS AS A NATURE-BASED SOLUTION FOR CLIMATE CHANGE

2021 2030 United Nations Decade of Ocean Science for Sustainable Development

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Foreword

Welcome to the first science technical working group output from the United Nations Ocean Decade Programme for Blue Carbon in the Global Ocean (GO-BC)! Our programme launched at the UN Ocean Conference in Lisbon, Portugal in June 2022, and we are delighted to have been invited to partner with the International Atomic Energy Agency (IAEA) for our very first science technical working group in-person meeting, which was hosted at the IAEA headquarters in Vienna, Austria, in November 2023. This partnership of two UN programmes has been supported and encouraged by the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO), highlighting to all of us who assembled in Vienna that multilateralism in the ocean sciences is alive and well!

As workshop meeting convenors, we are acutely aware that our blue carbon science community will benefit from greater diversity in the co-ordination of international scientific networks, and we are indebted to the IAEA for the exemplary approach adopted to ensure that workshop participants, while first and foremost being blue carbon experts, were selected to reflect an appropriate balance of gender, geography, and career stage. We have more to do, but GO-BC is now actively building a global blue carbon initiative which seeks to support UN Sustainable Development Goal 17 – *Partnerships for the Goals* – and this first report captures aspects of data sharing and capacity building which GO-BC will champion to meet the objectives of the Ocean Decade, namely to deliver *The Science We Need For The Ocean We Want*.

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Meeting outcomes

Day 1: Emerging Blue Carbon Ecosystems

(Chair: Bill Austin)

The group agreed that there is a need to improve recognition of emerging BCEs, so that they can be incorporated, alongside 'classical' BCEs, into national policy and BC stocktakes. It was also highlighted that these emerging BCEs should be prioritized for research that focuses on clearly quantified understanding of additionality and permanence, as well as the stacking of blue carbon alongside multiple other ecosystem benefits.

Day 2: Global Blue Carbon Database

(Chair: Pat Megonigal)

The group identified the Coastal Carbon Atlas as an essential repository for BC data. There was a collective drive to incentivise funding and collaboration between the CCA and national repositories 'to accelerate the pace of discovery', which will help address SDG goal 17 "Partnerships for the goals". It was agreed that data generation needs to adhere to CARE (Collective benefit, Authority to control, Responsibility, Ethics) and FAIR (Findability, Accessibility, Interoperability, and Reusability) principles.

Day 3: Capacity Building Materials for Blue Carbon Scientists and Practitioners

(Chair: Inés Mazarrasa)

GO-BC plans for capacity building were discussed and aligned specifically with SDG's 13, 14, and 17. Capacity building activities associated with GO-BC aim to engage with various stakeholders to boost BC research, through developing standardised methodologies, increasing data availability in under-researched regions, and building regional hubs and global networks.

Day 4: GO-BC Science Technical Working Group

(Chairs: Miguel Cifuentes-Jara & Bill Austin)

The GO-BC science technical working group discussed the current state of BC research and took part in a priority science questions exercise which aimed at identifying the most pressing questions in BC science. Over 130 questions were anonymously submitted prior to the meeting, and then collectively whittled down to the 20 most pressing questions, addressing themes of: emerging BCEs; co-benefits of BCEs; crediting, reporting, and standardisation; measurements and methodologies; prediction; rights, policy, and equity; and finance and marketability. These findings will inform the future research priorities and directions of GO-BC and will be shared through UN Ocean Decade channels.

Meeting programme

Day 1

Session 1

09:00 Opening remarks by the IAEA deputy director *(Najat Mokhtar)*

09:05 Welcome to the IAEA *(Pere Masque)*

09:20 Introduction to Emerging Blue Carbon Ecosystems and Objective Setting *(Bill Austin)*

09:30 Round-table introductions *(All participants)*

10:00 Tidal freshwater forested wetlands (upper tidal estuary) as a novel BC ecosystem *(Ken Krauss)*

Session 2

11:00 Macroalgae and carbon subsidies into marine sediments *(Dorte Krause-Jensen)*

11:30 Challenges of measuring CDR by seaweed systems (natural and farmed) *(Catriona Hurd)*

Session 3

13:30 Seaweed BC & other potential BC projects beyond wetlands – knowledge gaps *(Ana Queiros)*

14:00 Breakout Discussion Groups *(All participants)*

Session 4

15:30 Plenary Discussion and Scope of the Science Technical Working Group on Emerging BCEs
(Chairs: Bill Austin & Miguel Cifuentes-Jara)

Day 2

Session 1

09:00 The Coastal Carbon Library and Atlas *(Pat Megonigal)*

09:30 Data synthesis Tools to Support Blue Carbon Actions *(Miguel Cifuentes-Jara)*

10:00 Engaging different data sharing cultures *(Hannah Morrissette)*

Session 2

11:00 Quantifying Opportunities for Blue Carbon Actions *(Peter Macreadie)*

11:20 Discussion *(All participants)*

11:30 Moderated Discussion on Pre-Planned Topics *(Chair: Pat Megonigal)*

Session 3

13:30 Curating Data on Methane Emissions for Synthesis *(Ariane Arias-Ortiz)*

14:00 Sampling Geomorphic Features for Synthesis *(Andre Rovai)*

14:30 Curating Literature for Synthesis of Land Use Impacts *(Sigit Sasmito)*

14:50 Discussion *(All participants)*

Session 4

15:30 Remote Sensing data for Seagrass Blue Carbon *(Milica Stankovic)*

16:00 Federated data for ocean acidification and oxygen *(Kirsten Isensee)*

16:30 Moderated Discussion on Pre-Planned Topics *(Chair: Pat Megonigal)*

Day 3

Session 1

09:00 Welcome to the session. Introduction to the GO-BC & IAEA Capacity Building Goal *(Inés Mazarrasa)*

09:15 Review of previous experiences in Blue Carbon training *(Anna Lafratta)*

10:00 Introduction to the Ocean Teacher Global Academy (OTGA) *(Kirsten Isensee)*

Session 2

11:00 Ongoing efforts on online training by the Blue Carbon Initiative *(Miguel Cifuentes-Jara)*

11:20 Discussion on the structure and content of IAEA & GO-BC training materials I *(Inés Mazarrasa)*

Session 3

13:30 Discussion on the structure and content of IAEA & GO-BC training materials II *(Inés Mazarrasa)*

Session 4

15:30 Coordination for the development of training materials *(Inés Mazarrasa)*

Day 4

Session 1

09:00 GO-BC as a Blue Carbon science programme within the Ocean Decade *(Bill Austin)*

09:15 Reflections on the status of Blue Carbon Initiatives *(Miguel Cifuentes-Jara)*

09:30 "Speed-talks" on regional/topical blue carbon science initiatives *(All participants)*

Session 2

11:00 "Speed-talks" on regional/topical blue carbon initiatives *(All participants)*

Session 3

13:30 Breakout Discussion Groups – Priority Science Questions *(Chair: Peter Macreadie)*

Session 4

15:30 Plenary – Priority Science Questions Report *(Chair: Peter Macreadie)*

16:15 GO-BC Next steps *(Miguel Cifuentes-Jara & Bill Austin)*

16:25 Closing comments *(Pere Masque)*

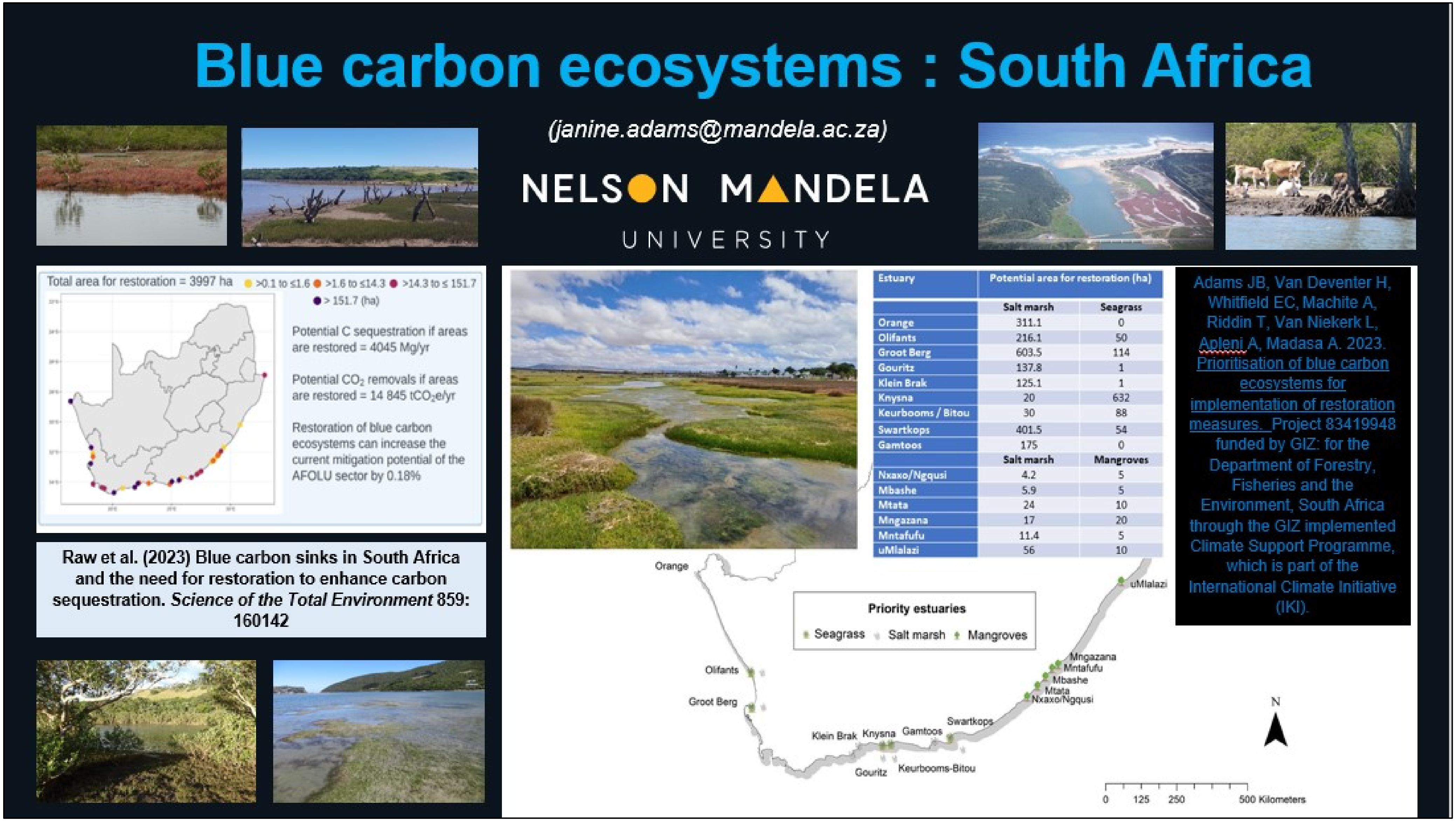
Red mangrove (Rhizophora Mangle L.) in Isla Verde, Gulf of Nicoya, Costa Rica: Photo by Andre Rovai

Abstracts

All abstracts are listed alphabetically according to surnames, and presented in the same order below.

1. Blue carbon ecosystems : South Africa **(JA)**
2. Curating Data on CH_4 Emissions for Synthesis **(AAO)**
3. The United Nations Ocean Decade Programme for Blue Carbon in the Global Ocean (GO-BC): A brief introduction **(WA)**
4. Mangrove carbon sequestration observation network from site to regional scales in China **(LC)**
5. Data Synthesis Tools to Support Blue Carbon Actions **(MCJ)**
6. Blue Carbon Training **(MCJ)**
7. Evolution of Blue Carbon Initiatives **(MCJ)**
8. Enhancing understanding of organic carbon stocks and accumulation rates in blue carbon ecosystems in the Southern Atlantic, with emphasis on Brazil **(VH)**
9. Blue carbon is more than stocks **(JHS)**
10. Challenges of measuring carbon dioxide removal (CDR) by seaweed systems **(CH)**
11. Experiences with aligning metadata and data for ocean acidification and ocean oxygen data – one stop shops for the respective information **(KI)**
12. Drivers of carbon sink function in tropical seagrass beds **(RI)**
13. Two newly funded blue carbon science projects from the UK and EU **(HK)**
14. Macroalgal and Carbon Subsidies into Marine Sediments **(DKJ)**
15. Tidal freshwater forested wetlands as a BC ecosystem **(KK)**
16. Capacity building within the Global Ocean decade on Blue Carbon **(IME, AL, KI, MCJ)**
17. Quantifying Opportunities for Blue Carbon Action **(PM)**
18. The Coastal Carbon Library and Atlas **(PM)**
19. Engaging different data sharing cultures **(HM)**
20. Seaweed Blue Carbon (& other potential Blue Carbon) projects beyond wetlands? Knowledge gaps **(AQL)**
21. Blue Carbon science in Panama **(TRG)**
22. Mangrove blue carbon: Sampling geomorphic features for syntheses **(AR)**
23. Blue Carbon is declining at some Caribbean meadows due to excessive grazing while we are just learning about seagrass carbon pools in the East Tropical pacific **(JSV)**
24. Curating Literature for Synthesis of Land Use Impacts **(SS)**
25. Remote Sensing Data for Seagrass Blue Carbon **(MS)**
26. Blue Carbon science topics in Japan **(KW)**

Janine Adams (Nelson Mandela University, South Africa)

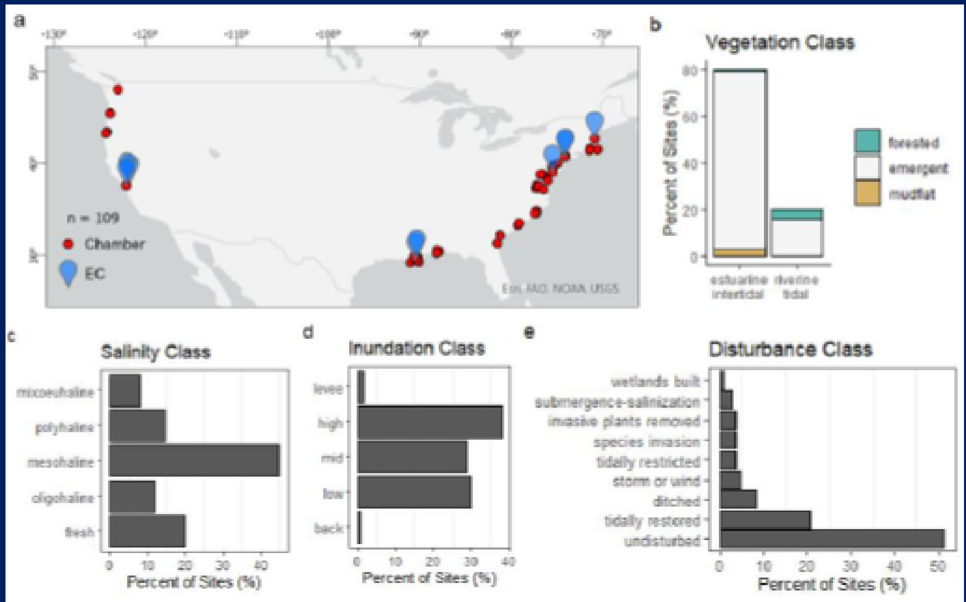


Estuary	Potential area for restoration (ha)	
	Salt marsh	Seagrass
Orange	311.1	0
Olifants	216.1	50
Groot Berg	603.5	114
Gouritz	137.8	1
Klein Brak	125.1	1
Knysna	20	632
Keurbooms / Bitou	30	88
Swartkops	401.5	54
Gamtoos	175	0
	Salt marsh	Mangroves
Nxaxo/Ngqusi	4.2	5
Mbashe	5.9	5
Mtata	24	10
Mngazana	17	20
Mntafufu	11.4	5
uMlalazi	56	10

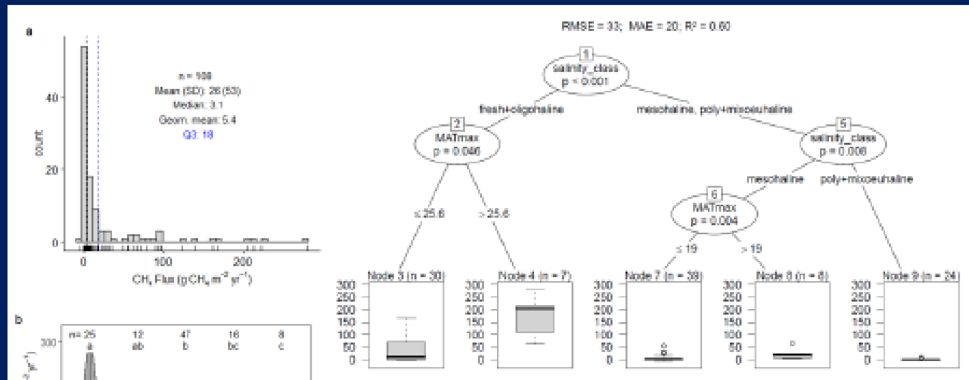
Ariane Arias-Ortiz (Universitat Autònoma de Barcelona)

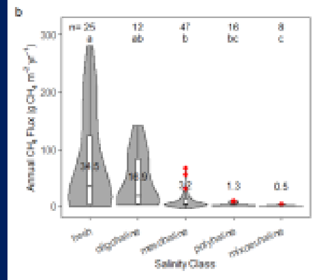
Curating Data on CH_4 Emissions for Synthesis

Tidal Marsh CH_4 Flux Database: Chamber-based flux measurements represent most available CH_4 flux data from tidal wetlands, yet they remain widely dispersed and frequently unavailable. We compiled > 8500 chamber-based across 100 tidal marsh sites in the conterminous United States. We conducted an in-depth analysis of tidal marsh CH_4 fluxes and predictors of CH_4 flux variability across salinity, inundation, and impact classes. This effort resulted in the creation of an open-source database of chamber-based GHG flux measurements disaggregated by sampling event doi.org/10.25573/serc.14227085



Annual CH_4 fluxes and Predictors of CH_4 Flux Magnitude: Annual fluxes averaged 26 ± 53 g CH_4 m^{-2} yr^{-1} across all sites, with a median of 3.1 g CH_4 m^{-2} yr^{-1}. Only 25% exceeded 18 g CH_4 m^{-2} yr^{-1}. Flux magnitudes and variability increased with decreasing salinity. The highest fluxes were observed at fresh-oligohaline sites with maximum annual temperature normals (MATmax) > 25.6ºC, followed by mesohaline sites with MATmax > 19ºC. This lends support to refining Tier 1 emission factors for fresh/oligohaline and mesohaline tidal marshes.





The database allows:

- Exploration of scaling factors for upscaling discrete chamber measurements to annual estimates.
- Identification of dominant covariates of CH_4 flux in tidal marshes and their hierarchical importance
- Improving monitoring and predictions of CH_4 emissions in tidal marshes

Ariane Arias-Ortiz*, Jaxine Wolfe, Scott Bridgham, Sara Knox, Gavin McNicol, Brian Needleman, Julie Shahan, Ellen J. Stuart-Haëntjens, Lisamarie Windham-Myers, Patty Y. Oikawa, Dennis Baldocchi, Joshua Caplan, Margaret Capooci, Kenneth Czapla, Robert K. Derby, Heida L. Diefenderfer, Inke Forbrich, Gina Groseclose, Jason Keller, Cheryl Kelley, Amr Keshta, Helena Kleiner, Ken W. Krauss, Robert Lane, Sarah Mack, Serena Moseman-Valtierra, Thomas Mozdzer, Peter Mueller, Scott C. Neubauer, Genevieve Noyce, Karina V.R. Schäfer, Rebecca Sanders-DeMott, Charles Schutte, Rodrigo Vargas, Nathaniel Weston, Benjamin Wilson, James R. Holmquist, Patrick Megonigal

Coastal Carbon Research Coordination Network

The United Nations Ocean Decade Programme for Blue Carbon in the Global Ocean (GO-BC): A brief introduction

William Austin (University of St Andrews, Scotland, UK)

GO-BC is championing a new dialogue to promote the fundamental values of science which are increasingly required to deliver the evidence that underpins policy change, supports a just transition, and creates the credible and globally connected blue carbon science community necessary to achieve meaningful and lasting ocean solutions. GO-BC's deep commitment to ocean science is reflected through an evidence-based approach that seeks to demonstrate, promote, and encourage improved international scientific collaboration in blue carbon research, knowledge, and data sharing. The science technical working group is being solicited widely to ensure that GO-BC captures and articulates the ethos and values of a diverse blue carbon research community. GO-BC will highlight the need to support (and fund) blue skies research; the value of investment in early career researchers as future ocean leaders; the opportunities and added value of engaging local communities (and youth) as meaningful project research partners; the need for regional knowledge hubs to be established and to share best practice and scientific skills to build in-country capacity and knowledge; and the growing need for an ocean science community who understand and are prepared to engage with policy makers and others to effect fundamental changes in the management of our seas which are always informed by the best scientific evidence.

Group photo from the IAEA meeting, Vienna

Mangrove carbon sequestration observation network from site to regional scales in China

Luzhen Chen (Xiamen University, China)

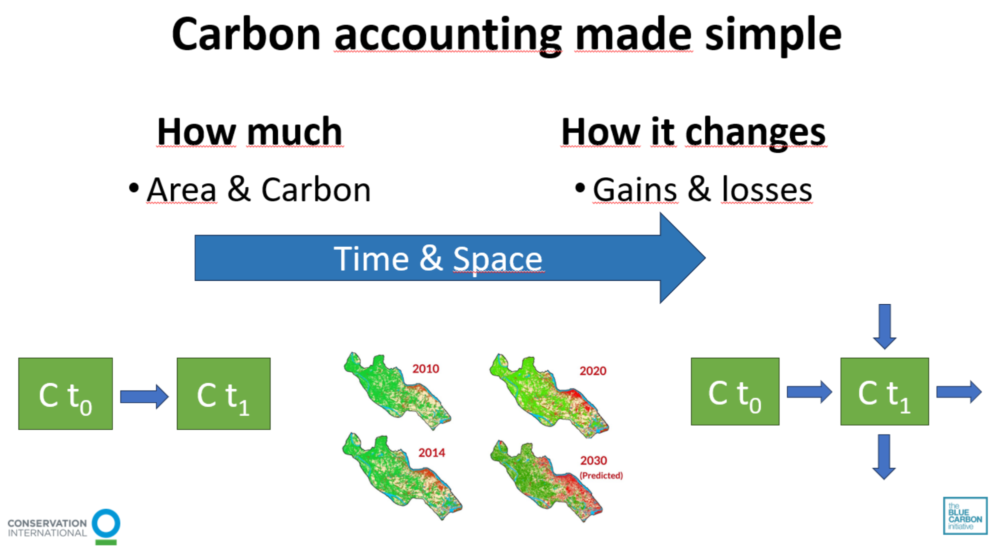
Accurate assessment of mangrove blue carbon (BC) sequestration is crucial for revealing their climate mitigation potential. Traditional forest inventory methods through field observation systems provide a critical data base for mangrove BC budget in China. We systematically sorted out key parameters such as biomass, carbon sequestration rate and carbon accumulation rate (CAR) in a case study at the Zhangjiang Station, aiming to provide a site-scale systematic solution for BC inventory compilation. Permanent plots based on vegetation and sediment carbon gain were established for annual carbon sequestration. A new technique for stem sap flow monitoring was applied to obtain the carbon sequestration of individual trees, reducing the uncertainty in carbon budget calculations. Sediment CAR was generally derived from isotopic dating for a century-scale average or from surface elevation tables (SETs) for annual changes. Observations were conducted to integrate greenhouse gas (GHG) emission from various components using static or dynamic chambers. An eddy covariance tower was installed on the forest canopy to obtain ecosystem carbon exchange at the site scale. This system has conduct scientific and precise observation for ten years in Zhangjiang Station, resulting in a site-scale mangrove blue carbon budget. However, it is extremely challenging to observe carbon flux with eddy due to the sieve coastal condition and the expense, limiting its applicability. A regional scale observation network for mangrove BC inventory in China was established based on permanent plot setting and SETs, utilizing the stock-difference method for carbon assessment.

Mangroves, Celestún, Mexico: Photo by Andre Rovai

Data Synthesis Tools to Support Blue Carbon Actions

Miguel Cifuentes-Jara (*Conservation International, Costa Rica*)

High quality blue carbon data is needed as part of our efforts to provide society with foundational science and knowledge to improve how our world works in bring the tangible and intangible values of nature to the forefront of global conservation and restoration. These data also inform global and local decision-making, for management and policy. Importantly, blue carbon data contribute to assessing progress towards national and global climate goals. IPCC-based standardized carbon accounting can be done by combining knowledge of changes in area of land use categories ("activity data") and how much carbon has been lost or gained due to those land use transitions ("emission factors"). Spatially explicit data, time series and modeling tools can be used to make these calculations and project them into the future and analyse management scenarios.



Researchers and decision makers should first determine who are the users of the data and what will they use. This determines the level of detail, effort and investment that will be needed, and the types of products and inferences that might be possible. For Tier 2, countries will need local to national baselines of land use/land cover and spatially explicit time series for activity data and emission factors. These data can be generated from national forest or research inventories, and will need standardized methods, allometric equations and calculation factors (wood specific gravity, C% by species, etc.). I used the example of a Central American data platform to show how forest carbon data can be collected, synthesized and made useful for countries to aid them in carbon accounting and international emissions reporting. For discussion, I posed the following questions: What is the minimum set of data countries need to collect for basic BC accounting? What strategies and actions might we need to build to promote standardized data entry, processing and sharing (through a centralized location)? How might we promote and ensure long-term stability and regular updating of data platforms? How might we ensure democratization of data access for developing countries and/or governments with low BC capacities?

Miguel Cifuentes-Jara (*Conservation International, Costa Rica*)

I shared three elements to consider while designing and executing any training: scope and topics, the type and size of the audience and the facilities/venues and length of the training. I also provided an overview of a blue carbon training course the Blue Carbon Initiative (BCI) has been working on. It is web-based and consists of three levels of increasing complexity in terms of the breadth and depth of the topics shared. The final version of the course will be available via the Ocean Teacher Platform.

The basic level provides an overview of climate change, the dynamics of land use and emissions from the three blue carbon ecosystems, and current management options to conserve, restore and protect these ecosystems. The content is directed at protected area managers, local communities, and government conservation representatives or other general audiences. The intermediate level is designed for institutional (government and NGO) leaders and policy makers. It builds on the first level and provides an overview of “high quality blue carbon principles” for developing such projects, an introduction to blue carbon policy within the UNFCC and national contexts, and details on climate finance architecture for blue carbon. This level ends with the participants being asked to develop a blue carbon initiative.

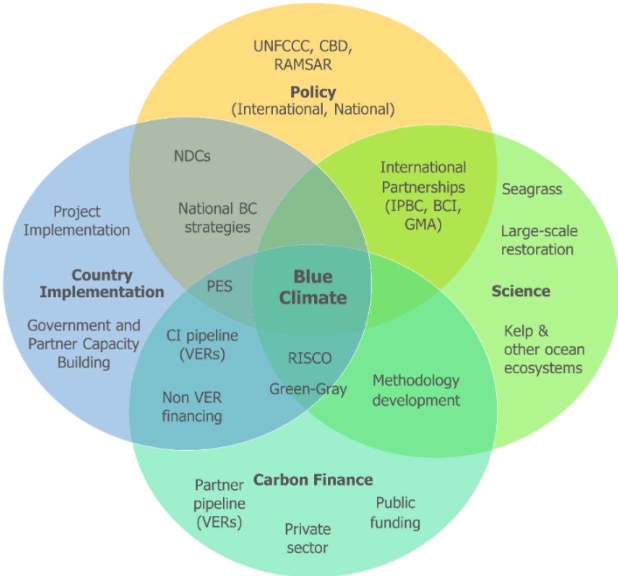
The advanced level has three tracts, focusing on blue carbon practice, policy and crediting. The first one goes into the minutiae of carbon inventory and monitoring (including remote sensing, mapping, data management, etc.), GHG accounting and the basics of blue carbon project design. Under the policy tract, participants will learn about enabling conditions, international frameworks and policy instruments (e.g., NDCs, NBSAPs, SDGs, Ramsar) and the basic dynamics behind nature climate solutions and carbon markets. Finally, the crediting tract focuses on carbon project standards, the project development “cycle”, and blue carbon finance.

Evolution of Blue Carbon Initiatives

Miguel Cifuentes-Jara (*Conservation International, Costa Rica*)

Conceptually, we might organize the blue carbon “space” into overlapping science, policy, finance and implementation “realms”. Blue carbon work is relatively nascent and is experiencing rapid growth between 2009, when the concept was first presented, following larger global interest in the topic. Research areas and methods, as well as policy and finance are growing in depth and breadth. There is now a myriad of relevant actors, with varying outlooks on the subject, organizing themselves into different partnerships, platforms and working groups.

With this growth and the sometimes divergent interests, there is a need for some level of cohesiveness and collaboration, at least within organizations working towards the conservation, restoration and 16protection of these ecosystems at global and national levels. Key questions posed are: What do we want to achieve? What are the specialized niches we can recognize (and nurture to collaborate)? How do we seek synergies and avoid duplication among organizations, working groups and initiatives? How might we link national to global institutions and organizations towards a common blue carbon goal of conserving, restoring and protecting blue carbon ecosystems.



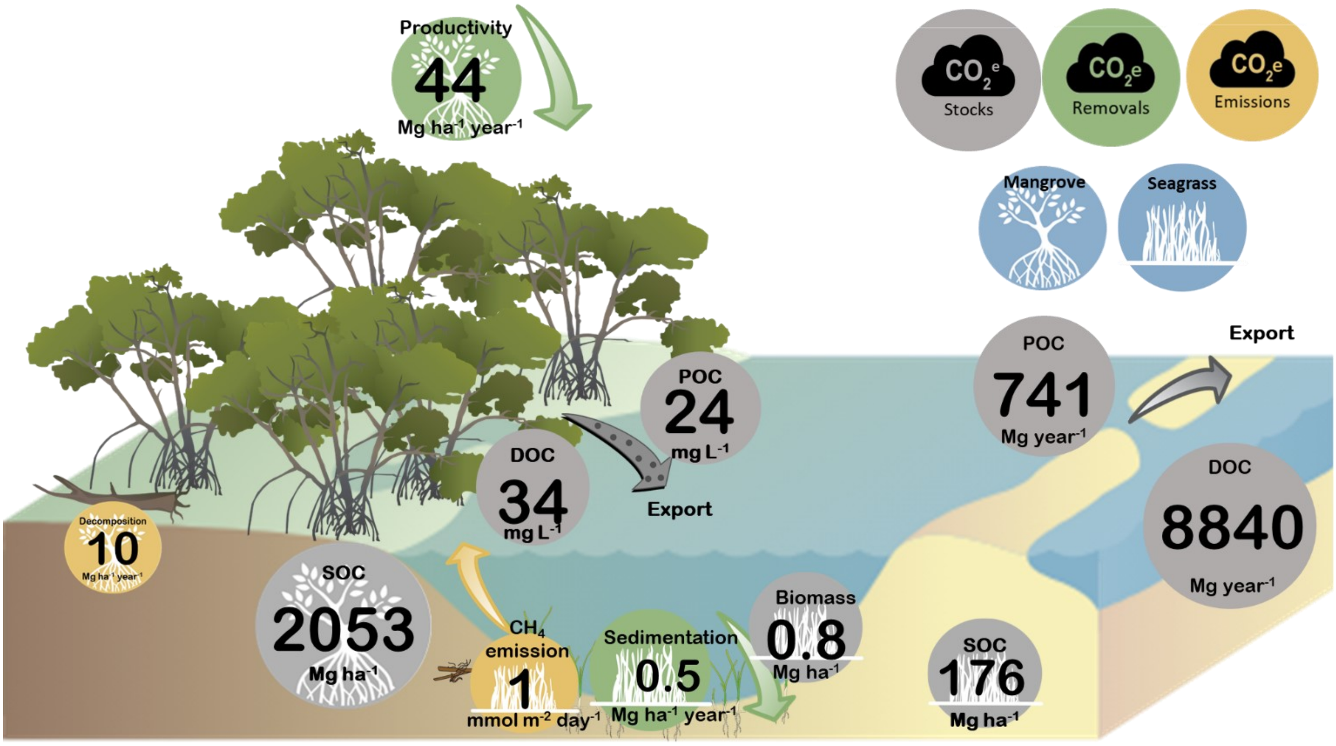
Enhancing understanding of organic carbon stocks and accumulation rates in blue carbon ecosystems in the Southern Atlantic, with emphasis on Brazil

Vanessa Hatje (Federal University of Bahia, Brazil)

The quantification of regional carbon inventories, sequestration rates, and the potential of Blue Carbon (BC) ecosystems as natural climate change mitigation strategies remains inadequately characterized in the Southwestern Atlantic, notably in Brazil. Mangroves, comprising the most extensive coverage among BC ecosystems, significantly contribute to annual organic carbon accumulation, with Brazil accounting for approximately 95% of mangrove stocks in the region (Hatje et al., 2023). However, despite estimates suggesting organic carbon accumulation in the region representing between 0.7 to 13% of global rates in BC ecosystems, significant large data gaps persist, necessitating further attention (Hatje et al., 2023). To address these gaps, our ongoing research focuses on comprehensive sampling across the Brazilian coastline to minimize geographical biases in BC data coverage, specifically within mangrove ecosystems. Presently, we are examining the impacts of anthropogenic disturbances - such as shrimp farming and sewage inputs - on carbon stocks and accumulation rates along the Brazilian coast. Our group also assesses carbon fluxes from sources to sinks across the porewater-mangrove-estuary-ocean continuum at key areas along the Brazilian coast. Additionally, our initiatives involve evaluating the influence of ecosystem connectivity along salinity gradients (including freshwater tidal forests, marshes, mangroves, and tidal flats) on the quality and lability of organic matter, alongside investigating organic carbon stocks and accumulation rates. Furthermore, our study investigates the environmental context of seagrass meadows and their role in determining seagrass organic carbon stocks and accumulation rates. Collectively, this ongoing research aims to provide robust datasets essential for integrating blue carbon into climate change mitigation policies.

Jorge A. Herrera Silva, **Helena Huechacona, Tania Cota, Siuling Cinco** Castro (CINVESTAV-IPN, Mexico)

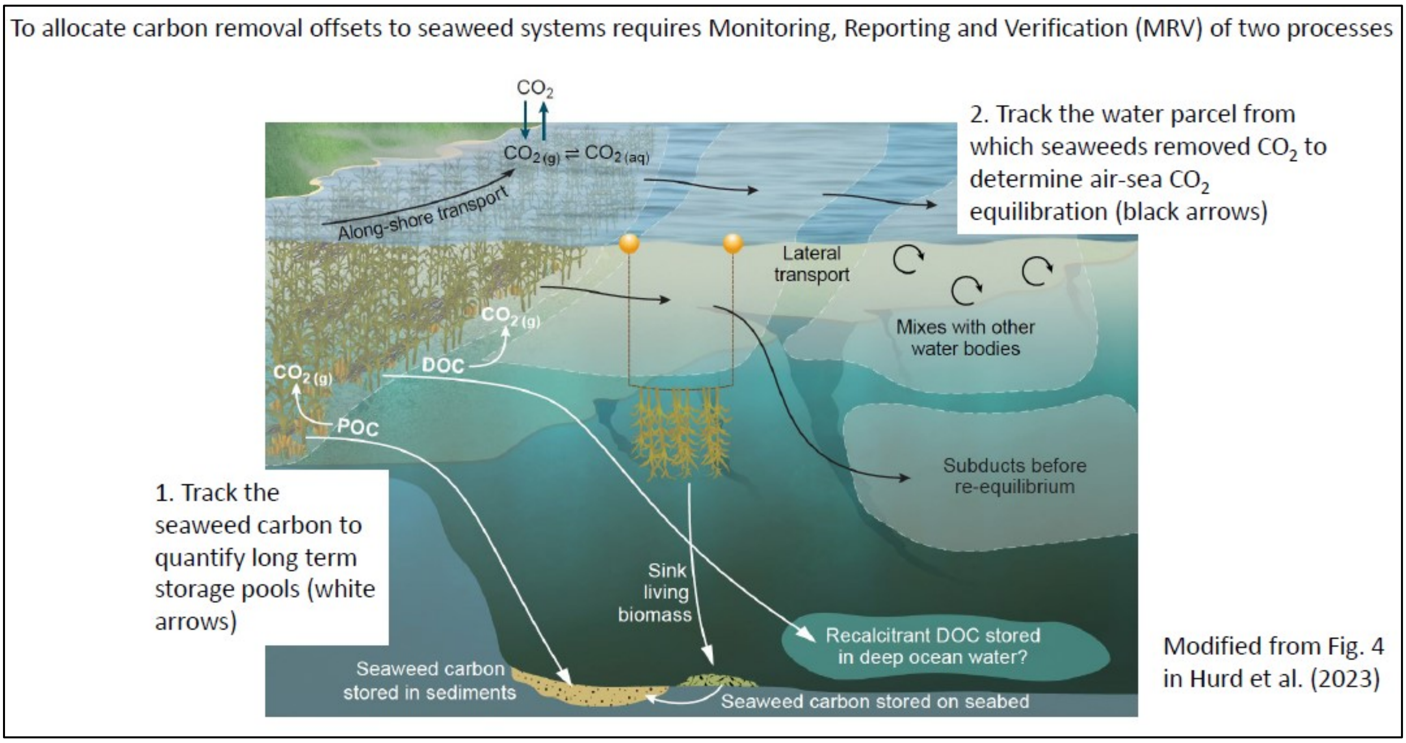
Coastal ecosystems play a crucial role in climate change mitigation through their role as carbon sinks and facilitating CO_2 sequestration through coastal vegetation (blue carbon). While preserving these ecosystems is a valuable strategy to counteract the impacts of climate change, information is still insufficient to determine whether these ecosystems function strictly as carbon sinks or sources. In a study focused on a tropical coastal lagoon in the SE Gulf of Mexico, the integration of data on carbon fluxes and stocks in mangroves and seagrasses was carried out; factors of geomorphology, hydrology and long-term climate seasonality were considered. The carbon budget revealed that the largest carbon storages are in mangroves, the dominant flows are DOC+POC export; that both are dependent on climatic controls and are related to productivity, connectivity, decomposition, and sedimentation processes. These findings represent an initial step to address local and regional scale uncertainties in coastal ecosystem carbon stocks and fluxes. More research on fluxes and their relationship with geomorphology, hydrology and climate are required to better understand their role in the processes of mitigation and adaptation to the effects of climate change.



Challenges of measuring carbon dioxide removal (CDR) by seaweed systems

Catriona Hurd (University of Tasmania, Australia)

To keep ocean warming at <2 °C by 2100, we must remove 100-900 Gt CO_2 from the atmosphere (carbon dioxide removal, CDR) in addition to drastically reducing emissions. Seaweeds have been proposed as a safe, reliable method of CDR via the expansion of aquaculture including into the open ocean, and the restoration of coastal seaweed beds. Forensic Carbon Accounting is a framework for Monitoring, Reporting and Verifying (MRV) that CO_2 removed by seaweeds from seawater via photosynthesis results in measurable, durable, and verifiable CDR. The photosynthetic uptake of CO_2 from seawater occurs on a timescale of seconds; the majority of resulting seaweed biomass is recycled and a fraction (~16%) enters storage pools in the sediments. The uptake of CO_2 by seaweeds from seawater creates a CO2-deficit in the water surrounding the seaweeds and CO_2 from the atmosphere must then enter seawater via diffusion to replace that removed by photosynthesis (termed CO_2 equilibration): this process occurs on a timescale of weeks-years depending on location. For MRV of an individual seaweed bed or farm, we need to track and quantify 1. how much seaweed organic carbon enters long term storage pools in the sediments and 2. the extent of CO_2 equilibration in the water parcel that bears the CO_2 deficit, using methods such as eddy-diffusivity. Methods to quantify seaweed carbon storage pools are progressing well, and the next challenge for MRV is to link these pools to the magnitude of CO_2 drawn down from the atmosphere via CO_2 equilibration.



Modified from Fig. 4 in Hurd et al. (2023)

Loch Fyne: Photo by Bill Austin

Experiences with aligning metadata and data for ocean acidification and ocean oxygen data – one stop shops for the respective information

Kirsten Isensee (IOC-UNESCO, France)

Ocean and coastal data collection are key to advance in ocean science and so in blue carbon science. To conduct regional and global assessments it is indispensable to have some knowledge about the quality of data used. The Coastal Blue Carbon Atlas will be a great tool to facilitate this. IOC-UNESCO is involved in similar efforts for ocean acidification and deoxygenation data at the global level and shared some lessons learned over the past years. While blue carbon measurements might involve different stakeholders and scientists the steps to develop a globally relevant blue carbon data portal are similar, e.g., establishment of community agreed minimum metadata, application of controlled vocabularies, identification and implementation quality control mechanisms, in addition to establishing partnerships with and National Oceanographic Data centres, regional data centres and international data bases, which might be holding complementary data.

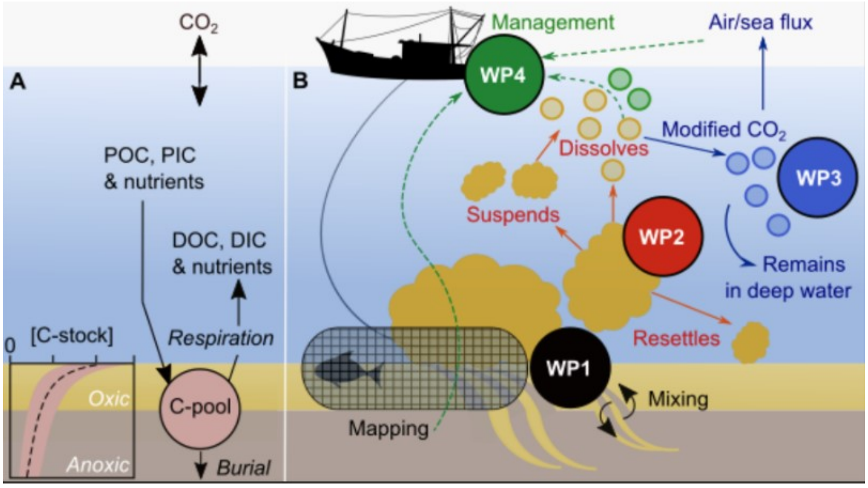
Drivers of carbon sink function in tropical seagrass beds

Rashid Ismail (University of Dar es Salaam, Tanzania)

Seagrass meadows are effective carbon sinks, sequestering atmospheric CO_2 and capturing allochthonous organic material, storing organic carbon in their sediments, so called Blue Carbon. In tropical areas, seagrass meadows have a high number of calcareous organisms, which can offset carbon sequestration by releasing CO_2 through their calcification. Human activities such as urbanization and land-use change with inadequate management of blue carbon ecosystems are causing fast degradation of tropical blue carbon ecosystems, particularly mangroves and seagrasses. We studied the carbon sequestration process and the impact of marine protected areas (MPAs) on organic carbon conservation in the blue carbon ecosystems of the western Indian Ocean (WIO) region. This was accomplished by examining the air-water CO_2 flux in different plant community compositions (i.e., seagrass and calcifying macroalgae), as well as factors driving air-water CO_2 flux and the assessment of organic stocks within and outside MPAs in tropical and subtropical areas of the WIO. We found that, the sum of the fluxes showed a net efflux of CO_2 over the meadows. The CO_2 fluxes changed both in rate and direction over the day, and were significantly related to plant community composition and environmental conditions such as pH and CO_2 partial pressure, where pH had the strongest influence on CO_2 fluxes. Influxes were found only over vegetation with high proportion of seagrass and in the afternoon, whereas calcifying algae appeared to reverse the flow. We found that highly productive seagrass meadows can generate a net CO_2 from the water to the atmosphere as plants' demand for CO_2 to a large extent is covered by internal cycling of CO_2, both from degradation of autochthonous and allochthonous material and calcification. We found that accumulation of organic carbon in seagrass meadows is larger than the flow to the atmosphere, indicating that these systems can still be carbon sinks. It was found that tropical and subtropical blue carbon ecosystems store a significant amount of carbon in their sediments, but that many carbon storage hotspots are entirely/partially outside MPAs. This masks their influence on blue carbon conservation. MPAs can still be used to conserve blue carbon if carbon hotspots are properly located and managed. Our studies contribute knowledge of important determining factors influencing primary pathways of tropical coastal ecosystem carbon sequestration and are critical for identifying hotspots of carbon storage to generate conservation prioritizations. Future research should focus on conservation prioritizations that will limit the unsustainable use of coastal resources.

Two newly funded blue carbon science projects from the UK and EU

Hillary Kennedy (University of Bangor, Wales, UK)



Understanding how the disturbance associated with bottom trawling modifies C-storage, -cycling and air/sea CO_2 fluxes. It has been suggested that benthic trawling has the potential to impact organic carbon storage on the seafloor, causing carbon dioxide to be emitted to the atmosphere. The aim of the project, funded by NERC and led by Bangor University, UK, is to provide data to evidence these potential impacts.

C-BLUES, a European funded project (14 European and 3 Chinese partners). The aim of the project, led by NIVA, is to advance knowledge and understanding of Blue Carbon to secure and promote Blue Carbon Ecosystems, including emerging ecosystems, as Nature Based Solutions and enable key gaps in current reporting of national Greenhouse Gas inventories to be filled.

Macroalgae and Carbon Subsidies into Marine Sediments

Dorte Krause-Jensen (Aarhus University, Denmark)

Macroalgae dominate hard-bottom habitats, which do not sequester carbon but act as carbon donors to sinks beyond their habitats. The decoupling between the macroalgal source and sink makes quantification and documentation of their contribution to C-sequestration difficult as it requires quantification of macroalgal production/detritus-production, export pathways, fingerprinting of the macroalgal carbon and its relative contribution and permanency at the sink. A first order estimate has suggested a substantial role of macroalgae in the global marine carbon cycle (avg. 173 TgC yr^{-1}) but highlighted the need for more evidence. We provide an overview of results from group efforts conducted over the past few years to further explore the evidence and address knowledge gaps.

We made a first data-driven assessment of global extent and production of macroalgae, which is fundamental for quantifying their importance. Based on modelled and observed distributions and net primary production (NPP) across habitat types, we quantified the global macroalgal area at 6.06-7.22 million km^2 and the production at 1.32 Pg C annually, matching the extent and production of the Amazon rainforest. A review of detritus production indicates that on average 61% of the kelp production is exported as particulate organic carbon.

The potential for the macroalgal carbon to be sequestered depends on the lability of the organic matter as well as the transport time to reach a carbon sink beyond the habitat in either fjord- or shelf sediments or in the deep sea. By combining global maps of potential macroalgal production with a global ocean model, we provide an estimate of the amount of exported particulate macroalgal carbon reaching deep sea sinks. We also provide examples of fingerprinting methods (eDNA, stable isotopes) to document macroalgal origin of carbon and discusses potentials and limitations of these.

Given the role of macroalgae in the carbon budget, management actions to protect and restore these habitats and associated C-sinks may support C-sequestration in addition to supporting biodiversity. However, restoration of macroalgal habitats have, so far, only been demonstrated at small scale and even global net losses of kelp forests were restored, climate change mitigation benefits would be minor in relation to the gigantic global emissions of greenhouse gasses, which must be reduced at the source. Moreover, quantification & verification of the climate benefits are hugely challenging.

Tidal Freshwater Forested Wetlands as a Blue Carbon Ecosystem

Ken W. Kraus (U.S. Geological Survey, USA) & **Gregory B. Noe** (U.S. Geological Survey, USA)

The science of blue carbon has advanced tremendously over the past decade. From this, guidance for including additional ecosystems as blue carbon communities has been developed, offering opportunity for expanding the definition to include novel ecosystems. Here, we propose that tidal freshwater forested wetlands (TFFW) be included globally. Based on currently available research, TFFW meet all criteria for classification as blue carbon, and their inclusion may enhance the potential to connect restoration and rehabilitation to actionable blue carbon projects within this generally unrecognized tidal zone. Specifically, blue carbon criteria include marine and coastal ecosystems that remove or emit significant amounts of greenhouse gases, can store carbon from CO_2 over long time periods, have adverse human impacts that can be ameliorated, can be managed for increased carbon sequestration, have intervention options that do not cause additional harm, and align with current policies for mitigation and adaptation.

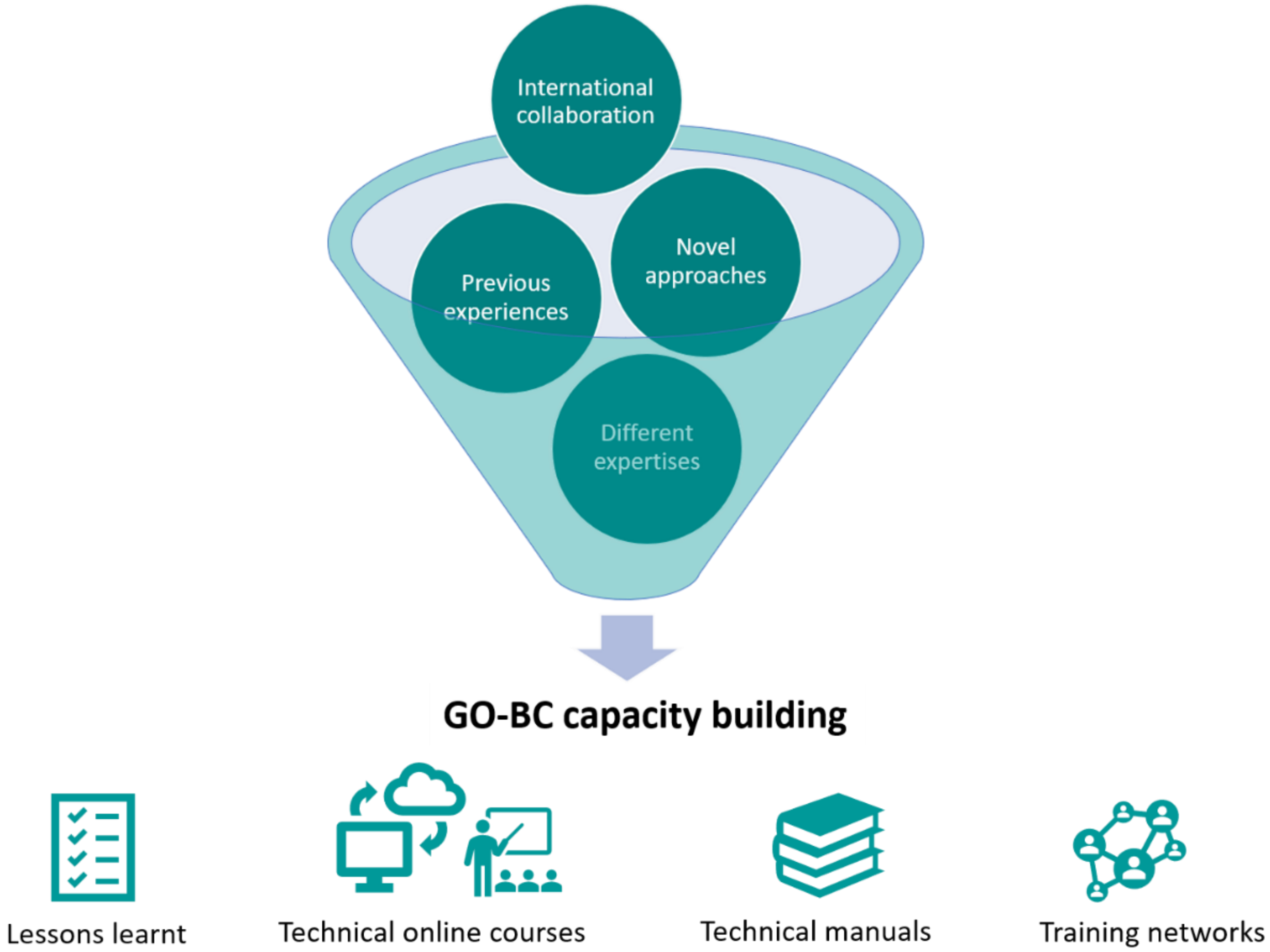
For these reasons, we suggest that criteria be expanded to consider all ecosystems with tidal influence. Among all criteria, the balance of methane from TFFW needs the most attention; however, research to date finds no distinction between methane emissions from TFFW and mangroves, which are considered sentinel blue carbon wetlands. Other forested wetland types that occur along the upper tidal estuary are currently included as blue carbon ecosystems. For example, Australia's blue carbon legislation recognizes their supratidal, upper estuarine forests as blue carbon ecosystems. Evidence to date suggests that globally all forested wetlands along the upper tidal estuary meet the blue carbon criteria when flooded by frequent-to-infrequent tides. TFFW have the potential to add considerably to global blue carbon sequestration through management actions, adding further legitimacy to the suggested use of blue carbon ecosystems for atmospheric carbon drawdown.

Tidal freshwater forested wetland, St. Johns River, Florida, USA: Photo by Ken Krauss

Capacity building within the Global Ocean decade on Blue Carbon

Inés Mazarrasa (University of Cantabria, Spain), **Anna Lafratta** (Edith cowan University, Australia), **Kirsten Isensee** (IOC-UNESCO, France), & **Miguel Cifuentes-Jara** (Conservation International, Costa Rica)

Capacity building is key to address some of the barriers that constraint the successful implementation of Blue Carbon (BC) strategies and to support the development of the robust science needed to inform adequate policies and to boost BC to the frontiers of knowledge. During the 1st meeting of the science technical group of GO-BC, a session was dedicated to defining the capacity building pathway of the GO-BC programme. Based on past and ongoing experiences in capacity building shared by some of the participants and group discussions, different actions to support capacity building in BC were defined. Those include: 1) conducting a review paper to understand the impact of capacity building in the implementation of BC initiatives and to identify best practices as well as challenges to overcome to make training useful in the long-term; 2) developing a comprehensive and high-quality body of technically focused online courses and manuals to complement in person training and address some of its limitations (e.g., limited number of people); and 3) the creation of a training network that supports *in situ* capacity building offering specific expertise and technical skills. By learning from and building on previous and on-going efforts, we expect GO-BC to significantly contribute to make capacity building in BC more useful, applicable, and available to a wider audience.



Tall mangrove canopy, Isla Verde, Gulf of Nicoya, Costa Rica: Photo by Andre Rovai

Peter Macreadie (Deakin University, Australia)

Peter Macreadie, on behalf of Blue Carbon Lab and partners

This talk explores how blue carbon opportunities are quantified, and situations where access to organised existing data could accelerate progress towards on-ground action – i.e., conservation and restoration of blue carbon ecosystems. The talk includes: a review and observations of commercial blue carbon projects globally; frameworks used for estimating blue carbon opportunities; approaches to quantifying co-benefits including new technologies; knowledge gaps for operationalising marketable blue carbon; and suggestions for fair and marketable blue carbon projects.

Photo by Alisdair O'Dell (SAMS)

The Coastal Carbon Library and Atlas

Pat Megonigal (Smithsonian Environmental Research Center, USA)

The Smithsonian Institution seeks to lower barriers impeding the pace of meaningful action to protect and restore coastal ecosystems for their many benefits to climate, people, and oceans. At the core of the Smithsonian effort is the Coastal Carbon Library (Figure 1), the largest collection of carbon data in the world for vegetated coastal ecosystems, with over 10,000 coastal wetland soil profiles from 64 countries, synthesized from 48,870 samples and 126,629 physical and chemical observations. This unique database was built over decades in collaboration with a global network of scientists and institutional partners using FAIR principles and building trust with colleagues that the Smithsonian will curate their data, respect intellectual property, and guarantee free public access. Our goal is to transform the world's largest collection of blue carbon data into a high-impact source of knowledge, data-analytics, and expertise in service of the global community inspired to preserve marine ecosystems, and to expand it to encompass biodiversity, fisheries, and the many other co-benefits they give to people.

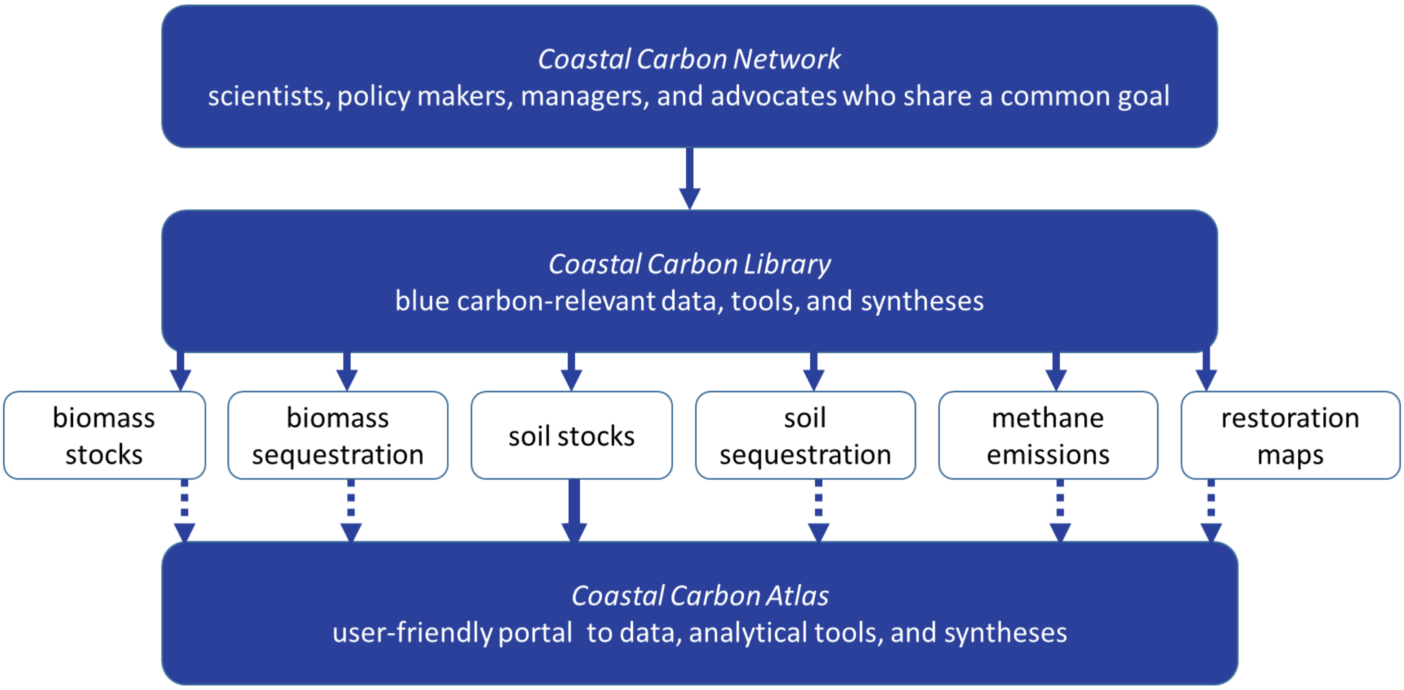
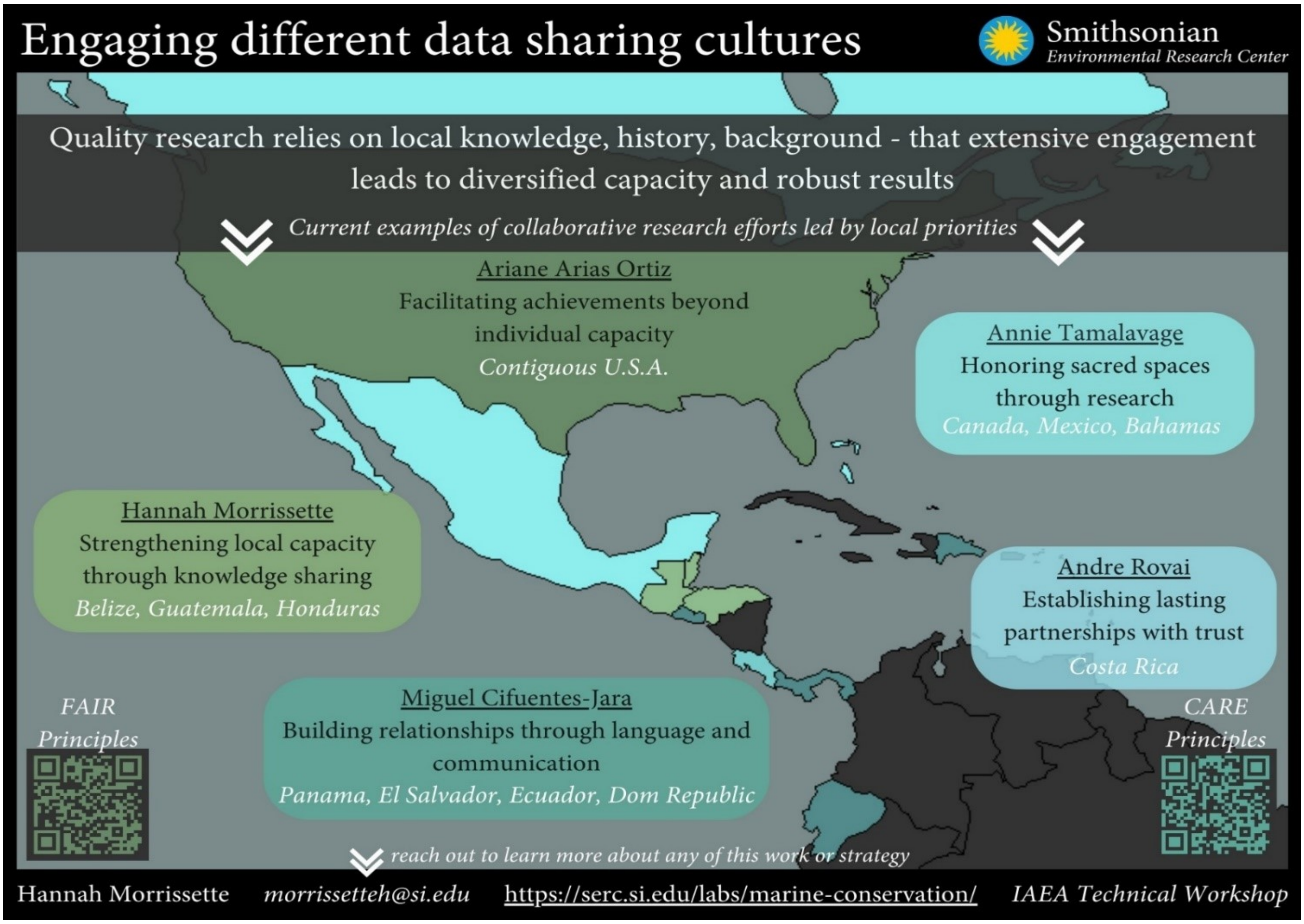


Figure 1. The Coastal Carbon Network maintains a library of data and analytical tools to support blue carbon science and applications. The Coastal Carbon Atlas is a graphical interface that simplifies data access. Currently the Atlas provides access to soil stock data. Our goal is to link and integrate all of the data resources and analytical tools of the Library to the Atlas.

Hannah Morrissette (Smithsonian Environmental Research Center, USA)

Sharing data across stakeholders is a fairly regular practice in today's environmental research as the FAIR standards for data accessibility become more commonplace (**F**indability, **A**ccessibility, **I**nteroperability, **R**euse; Wilkinson et al., 2016). However, the process is far from perfect, often neglecting key aspects of collaboration that need to occur before a project begins. *Engaging different data sharing cultures* was a presentation describing a few steps further in research collaboration - not just data sharing after work is complete, but involving multiple cultures and stakeholder groups from a project's conception to application of results - described as the CARE principles (**C**ollective benefit, **A**uthority to control, **R**esponsibility, **E**thics; Carroll et al., 2020). This process of extensive engagement is of particular importance in the blue carbon field. As the quantity of blue carbon projects rapidly expands, many coastal communities around the world are at risk of exploitation by outside scientists, investors, etc. that speed up the timeline without regards to the affected parties. From a research perspective, it is our obligation to utilize "...culturally relevant methods to produce respectful research outcomes in support of local priorities". Examples of this collaborative research that prioritizes responsible data stewardship in the blue carbon field are few, but increasing. Some work highlighted in this talk included Ariane Arias Ortiz, who incorporates a host of individual capacities and strengths to perform multifaceted global syntheses; Miguel Cifuentes-Jara, who works across entire regions with adaptive communication; Andre Rovai, who continues partnerships beyond projects to encourage lasting trust; and Annie Tamalavage, who follows indigenous methods to accomplish research goals in sacred spaces.



Seaweed Blue Carbon (& other potential Blue Carbon) projects beyond wetlands? Knowledge gaps

Ana Queirós Langley (Plymouth Marine Laboratory, University of Exeter, UK)

There is growing recognition that carbon fluxes across the coast to the sea may represent important blue carbon capability, beyond vegetated coastal habitats. Several such "emerging blue carbon ecosystems" have thus been identified, with much research effort, policy and finance development focused on seaweed (i.e., macroalgae) conservation and farming. Whilst modelling evidence suggests that seaweed may have an ample global biome, and field data demonstrate they have very high net primary productivity rates, the observational data basis remains exceptionally sparse with regard to the location and rates of potential long-term (>100 yrs) storage of the carbon seaweed fix, which is largely exported into the coastal and deep ocean though detrital pathways. Conserving seaweed blue carbon thus requires a much-improved understanding of these detrital pathways, and of the connectivity between seaweed habitats and their long-term carbon stores. Less than 10 years ago questions remained about whether any seaweed carbon was assimilated into the seabed. Recent studies employing stable isotope modelling, coupled with benthic-pelagic process measurements, have provided initial field-based estimation of seaweed particulate organic carbon sequestration rates into sediments, but such studies remain exceptionally rare. Such studies are necessary to estimate the present-day contribution of seaweed to sequestration rates in sediments in a blue carbon sense (i.e., additionality), and the seabed may be the seaweed carbon sink most amenable to MMRV. Applications of hydrodynamic modelling techniques (e.g., Lagrangian particle tracking) are beginning to be emerge, which (pending field validation) may enable the identification of such sedimentary sinks for seaweed particulate organic carbon. Longer-lived tracers such as ^{210}Pb can then provide additional, necessary information about the historical, long-term value of such sink sites (i.e., avoided emissions). Other long-term sinks for seaweed carbon in the ocean include the uptake into the dissolved organic carbon pool, and the alkalinity pool (for re-mineralised seaweed organic carbon fractions) but our understanding of these rates remains largely understudied. Outstanding issues for seaweed blue carbon potential include our limited knowledge of the methane, nitrous oxide and halocarbon production in seaweed ecosystems, all of which have been identified and may offset (some of) the value of seaweed habitats with regard to climate change mitigation. Such questions are the center of ongoing research in the UK and around the world, which will be much enriched by the coordinating efforts of GO-BC.

Blue Carbon science in Panama

Tania Romero Gonzalez (Smithsonian Tropical Research Institute, Panama)

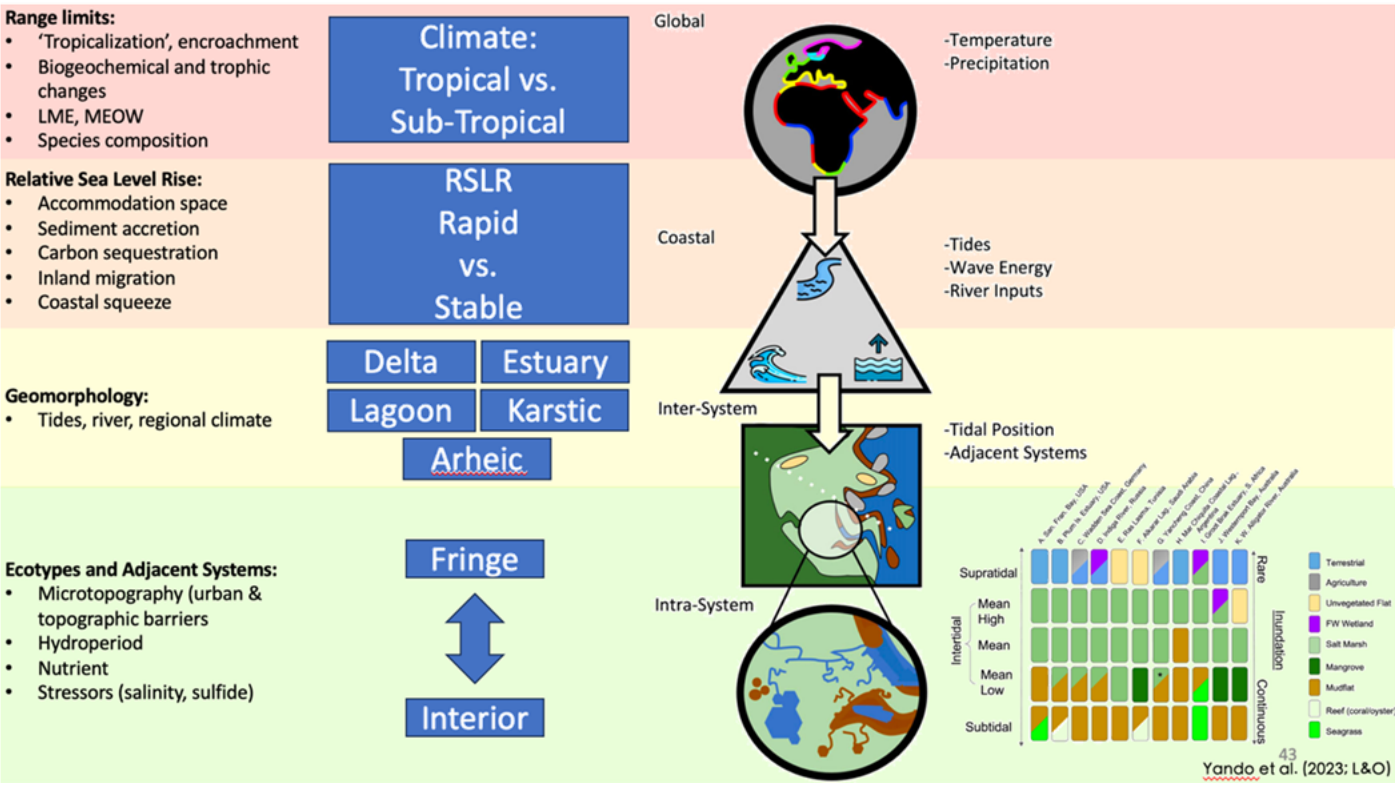
While the Central American region has a small proportion (2%) of the total global mangrove cover (Spalding, 2010), Panama is ranked 23th globally (Jia et al. 2023) and the has the greatest mangrove extent in Central America. Over recent years, Panama's mangrove ecosystem has been the focus of several internationally collaborative studies, such as, OIMT & ANAM (2009); Romero (2018).These efforts were developed to answer questions on extension, impact of use, economic value, fisheries, tenure, REDD+, blue carbon, and carbon fluxes. A first estimate total ecosystem carbon stock of 328.12 ± 108.03 MgC ha^{-1} (restricting soil depth to 1m for IPCC standard) was made in 2016. Previous literature estimates the values for aboveground biomass at 176 Mg ha^{-1} (Gross et al., 2014) and up to 1730 MgC ha^{-1} for the soil carbon down to 3 m (Costa et al., 2022). This information is relevant to understanding the country's potential for emission reduction through the conservation and restoration of mangroves. Furthermore, these data will help Panama comply with commitments of several international agreements such as the Global Biodiversity Framework and the Nationally Determined Contributions of the Paris Agreement. Even though data are available, it has been a challenge to combine existing data from several sources to inform these policy commitments. We have begun a project that will collate these data using the Coastal Carbon Atlas, to enhance the data availability on carbon stock and fluxes generated by local science community, and build blue carbon capacity across local, regional, and national organizations. The project will ultimately update the mangrove carbon baseline and inform national policy and management.

Coastal mangroves: Photo by Hannah Morrissette

Mangrove blue carbon: Sampling geomorphic features for syntheses

Andre Rovai (U.S. Army Engineer Research and Development Center, USA)

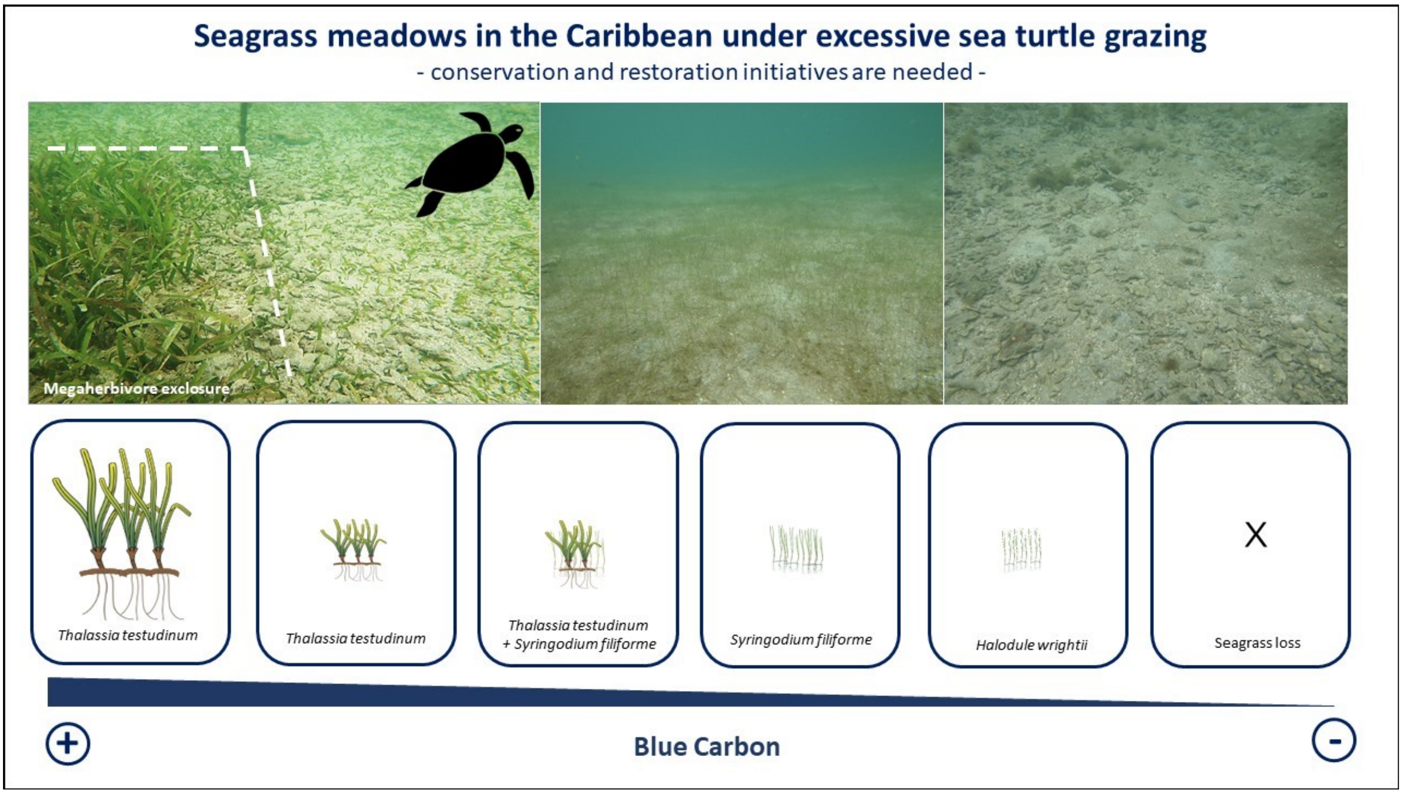
Mangroves thrive along nearly all the world's tropical and subtropical coastlines. This pantropical distribution spanning broad geographical gradients – climate, sea level rise, geomorphology – has shaped the diversity and plasticity of mangrove forests as we know today. Understanding how these drivers interact in time and space to control mangroves' physical environments and ecological feedbacks is fundamental to account for present and future carbon dynamics along ever-changing coastlines. Here, we review process-based concepts and map data available on carbon fluxes and stocks across the world's mangroves to ask: This review is a first step in reconciling cross-scale uncertainties with geographical sampling bias and drafting a roadmap towards a 'global mangrove observatory network' to address both ecological and social inclusion gaps.



Blue Carbon is declining at some Caribbean meadows die to excessive grazing while we are just learning about seagrass carbon pools in the Eastern Tropical Pacific

Jimena Samper-Villareal (Universidad de Costa Rica, Costa Rica)

Long-term seagrass monitoring in the Wider Caribbean has revealed a marked decline and loss of seagrasses at some sites. The largest seagrass species in the Caribbean has declined in size and dominance, most recently linked to excessive sea turtle grazing. Recent Blue Carbon studies on the Caribbean coast of Costa Rica revealed that meadows composed of larger species and with longer and wider leaves store more carbon and show increased relative sediment size compared to meadows of smaller canopy sizes and composed of pioneer/opportunistic species. A new initiative, the Caribbean Carbon Accounting in Seagrass (CariCAS) program, is currently underway at many sites in the Caribbean in an effort to quantify seagrass Blue Carbon and map seagrasses in this region. In contrast, seagrasses studies in the Eastern Tropical Pacific (ETP) have been limited. Recently however, seagrasses and their ecological dynamics have been reported at many new locations in Costa Rica. Multiple recent studies have also quantified the sediment and biomass carbon pools in these meadows, revealing that seagrasses contribute as much as 51% to the carbon in associated sediment within the ETP. These recently published values represent the only information to date on blue carbon for seagrasses in the ETP and should be included in global Blue Carbon analyses. Meanwhile, seagrass loss has also been reported at two locations on this coast thus highlighting the fragility of ETP seagrasses. A site where seagrasses disappeared in the mid-1990s has shown no recovery to date, and the first seagrass restoration project for this region is currently underway at this site. A regional network on seagrass and mangrove restoration was also recently consolidated, the Tropical Restoration Network (TRN). This is a regional initiative to facilitate collaboration on ecological restoration capacity building of Blue Carbon habitats in the region.



Curating Literature for Synthesis of Land Use Impacts

Sigit Sasmito (NUS Environmental Research Institute, Singapore)

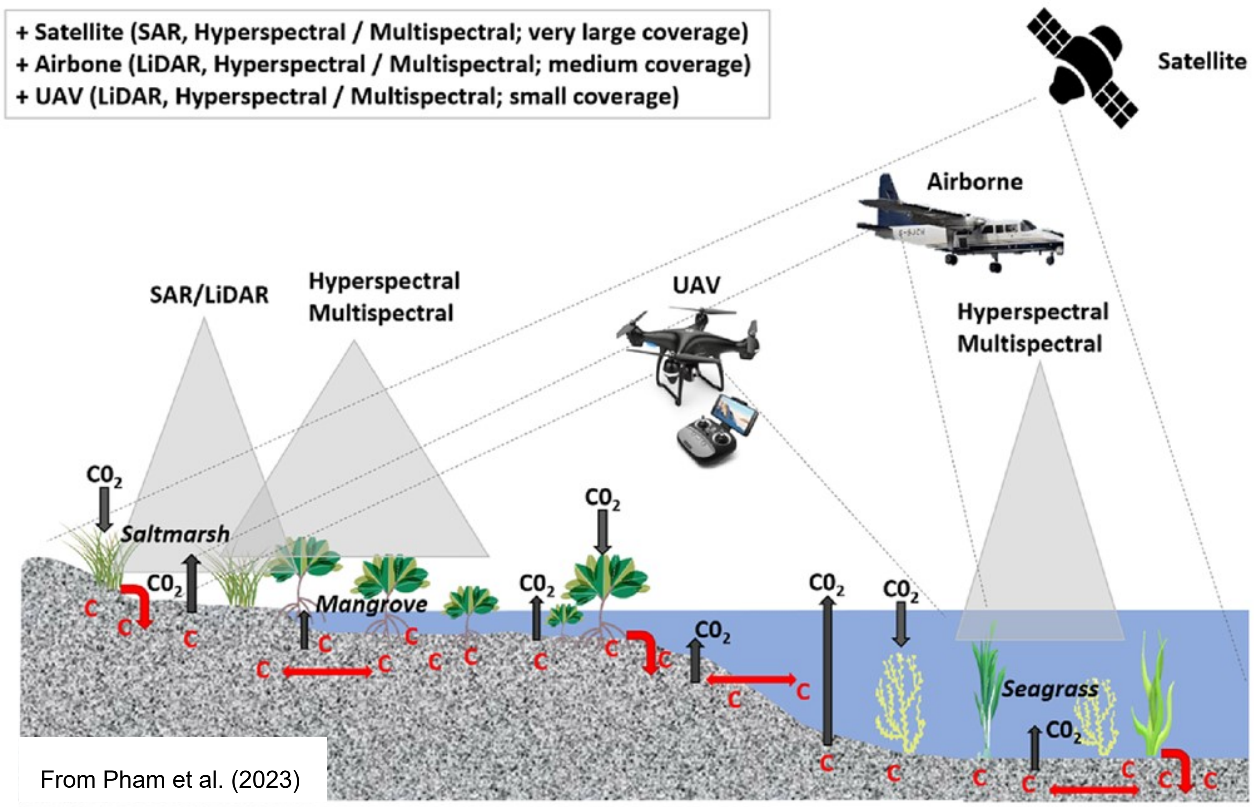
More countries are interested in including blue carbon ecosystems (mangroves, saltmarshes, and seagrasses) in their Nationally Determined Contributions (NDCs) as part of their commitment under the 2015 Paris Agreement and in line with the Sustainable Development Goals (SDG 13 on climate action). Mangroves can play a significant contribution to national emissions reduction targets, particularly for the land-based sector, in addition to the climate adaptation component. In this presentation, a literature systematic review and meta-analysis approach to assess the effects of land-use and land-cover changes were described. Two systematic review studies were discussed, with the first study highlighting the impacts of LULCC on mangrove blue carbon stocks and fluxes at the global scale, while the second study highlighted similar components at the national scale with the Indonesia study case. Several scale-up studies and analyses from previous and ongoing assessments were also discussed highlighting more field-based blue carbon assessment data. Challenges for assessing carbon emissions from blue carbon ecosystems exist, including the suitability and applicability of the stock-different and gain-loss approaches for organic soils in the tropics.

Remote Sensing Data for Seagrass Blue Carbon

Milica Stankovic (Prince of Songkla University, Thailand)

The remote sensing technologies have been used to obtain various information related to the seagrass ecosystems as well as secondary data (environmental variables) that can contribute towards better understanding the ecosystems such as sea surface temperature, salinity, sea level rise, pollution, total suspended solids etc. Currently there are many available methodologies to assess seagrass extent, coverage, discrimination of the species, biomass, growth patterns and more recently carbon within the ecosystem. A wide range of the remotely sensed datasets, including underwater photography and videography, laser scanners, sonars and radars, airborne imagery such as multispectral and hyperspectral data and LiDAR, unmanned aerial vehicles (UAVs), spaceborne imagery through various satellites are available and have been used in the seagrass research in the last several decades.

However, there is still lack of the updated global distribution of the seagrass and many countries are using rough outdated estimates. There are advancements in seagrass distribution in several regions of the world using Allen Coral Atlas (https://allencoralatlas.org/) and more recently Global Seagrass Watch (https://www.linkedin.com/company/global-seagrass-watch). Furthermore, several studies used airborne and satellite technology to map blue carbon within the seagrass meadows through correlation of the aboveground carbon and the satellite bands, transformation from leaf area index to aboveground organic carbon and the use of decision trees for classification and regressions of multiple satellite bands to obtain sedimentary carbon data within the seagrass meadows.

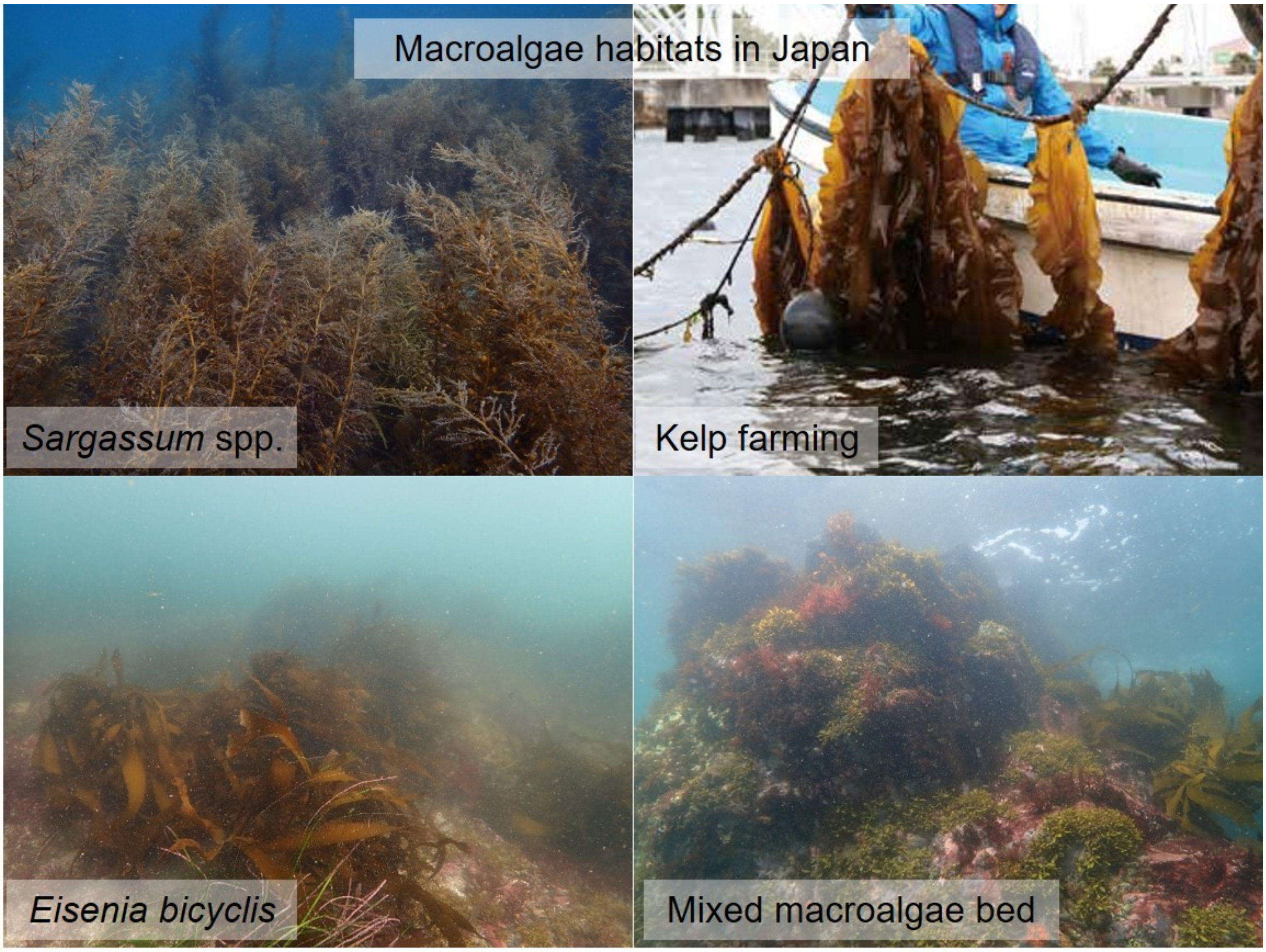


From Pham et al. (2023)

Blue Carbon science topics in Japan

Kenta Watanabe (Port and Airport Research Institute, Japan)

In this presentation, I introduced current topics related to Blue Carbon sciences in Japan. Japan has begun reporting GHG inventory of mangrove in April 2023 as a first step towards national BC accounting. The government intends to incorporate other BC ecosystems including seagrass and macroalgae beds in the inventory in the future. Nationwide estimates of the habitat area of seagrass and macroalgae beds using remote sensing, AUV, and modelling are in progress. Also, we are estimating carbon storage rates for multiple seagrass and macroalgae species inhabiting in Japan. Japan Blue Economy association (JBE) operated credit standard which certificates credits specializing in Blue Carbon. In 2022, 21 projects were certified with J Blue Credits covering approximately 1100 ha in Japan.



Mangroves, Celestún, Mexico: Photo by Andre Rovai