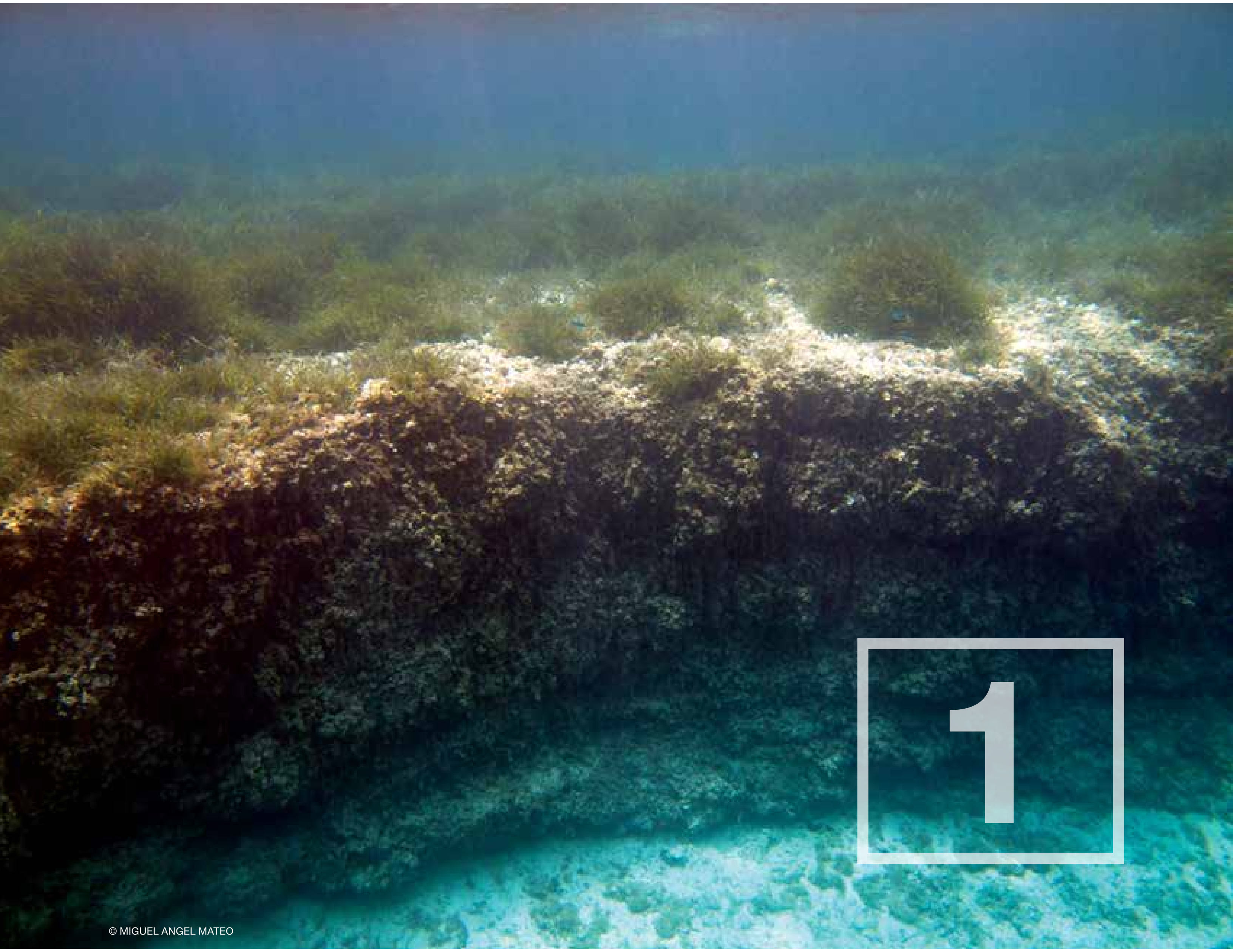

Why Measure Carbon Stocks

1

BACKGROUND AND CONTEXT

Coastal ecosystems are critical to maintaining human well-being and global biodiversity. In particular, mangroves, tidal salt marshes, and seagrasses provide numerous benefits and services that contribute to people's ability to mitigate and adapt to the impacts of climate change (**Fig. 1.1**). Many of these services are essential for climate adaptation and resilience along coasts, including protection from storm surge and sea level rise, erosion prevention along shorelines, coastal water quality regulation, nutrient recycling, sediment trapping, habitat provision for numerous commercially important and endangered marine species, and food security for many coastal communities around the world (Kennedy 1984; Robertson & Alongi 1992; King & Lester 1995; Hogarth 1999; Beck *et al*. 2001; Kathiresan & Bingham 2001; Saenger 2002; Mumby 2006; Gedan *et al*. 2009; Barbier *et al*. 2011; Sousa *et al*. 2012; Cullen-Unsworth & Unsworth 2013). In addition, these ecosystems help mitigate climate change by sequestering and storing significant amounts carbon, known as coastal blue carbon, from the atmosphere and oceans (Duarte *et al*. 2005; Bouillon *et al*. 2008; Lo Iacono *et al*. 2008; Duarte *et al*. 2010; Kennedy *et al*. 2010; Donato *et al*. 2011; Mcleod *et al*. 2011; Fourqurean et al. 2012a; Pendleton *et al*. 2012; Chmura 2013; Lavery *et al*. 2013).

Figure 1.1 Blue carbon ecosystems: mangroves (top left, © Sterling Zumbrunn, CI), seagrasses (bottom left, © Miguel Angel Mateo), and tidal salt marshes (right, © Sarah Hoyt, CI)

Despite their benefits and services, coastal blue carbon ecosystems are some of the most threatened ecosystems on earth, with an estimated 340 000 to 980 000 hectares being destroyed each year (Murray *et al*. 2011). Although their historical extent is difficult to determine due to dramatic losses which occurred before accurate mapping was possible, it is estimated that up to 67% of the historical global mangrove range, 35% of tidal salt marshes, and 29% of seagrasses have been lost. If these trends continue at current rates, a further 30–40% of tidal marshes and seagrasses and nearly all unprotected mangroves could be lost in the next 100 years (Pendleton *et al*. 2012).

Increasingly, coastal ecosystems are being recognized for their important role in carbon sequestration and, when degraded, their potential to become sources of carbon emissions. Progress has been made to include these systems in international and national policy and finance mechanisms, but full integration of coastal management activities as part of countries' portfolio of solutions to mitigate climate change has not yet been realized. This opportunity to incorporate coastal blue carbon into policies and management could lead to additional coastal ecosystem conservation (restoration and protection) worldwide, which would preserve and enhance the multiple benefits these ecosystems provide to humans.

NEED FOR THE MANUAL

There is a rapidly growing body of scientific knowledge on the direct and indirect effects of climate change and human development on coastal ecosystems. Increased attention is being paid to mangroves, tidal salt marshes, and seagrasses for their carbon sequestration capabilities, as well as other important ecosystem services. If properly planned and managed, coastal blue carbon could function as a potential funding mechanism for coastal ecosystem conservation and restoration. To achieve this goal, managers need to be able to assess carbon stocks (total amount of carbon stored within a distinct area) and monitor changes in carbon stocks and greenhouse gas (GHG) emissions over time. Until recently, coastal ecosystem managers and other stakeholders interested in quantifying blue carbon have lacked practical tools and guidance to allow for proper carbon analyses. This is particularly true in developing countries where there may be large data gaps and a lack of technical and financial resources to carry out complex analyses. New guidelines and methodologies have begun to emerge in the last few years, all of which refer to the need for internationally accepted measuring and monitoring procedures for carbon accounting (Appendix A: Additional Guidance Documents). This guide will provide managers, scientists, and field practitioners with standardized recommendations and techniques for carbon measurement and analysis in blue carbon systems and directly support the assessment and accounting of blue carbon globally.

OBJECTIVE OF THE MANUAL

The objective of this manual is to provide standardized methods for field measurements and analysis of blue carbon stocks and flux in coastal ecosystems. The manual is designed to provide users with relevant background information on key concepts, and guide them in a step-by-step process, pointing out stages where expert advice or additional technical data may be required. The goal is to utilize these assessments to support improved conservation and restoration of coastal ecosystems through various management and policy approaches, regulatory frameworks, and participation in voluntary carbon markets.

WHO IS THE MANUAL FOR?

The manual has been designed to be used by a wide range of stakeholders, including natural resource managers, scientists, community groups, and local and national government agencies interested in assessing blue carbon stocks. It can be implemented in a range of situations, with a focus on developing country contexts, and can be tailored to the needs of specific areas according to resource availability. The manual has been designed for users with local knowledge about the system being assessed, but without necessarily a detailed technical knowledge of how to conduct blue carbon measurements.

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MANUAL STRUCTURE

The manual outlines the rationale and project design for measuring blue carbon in the field and approaches for data analysis and reporting. Effort was made to ensure consistency with international standards, the Intergovernmental Panel on Climate Change (IPCC) guidelines, and other relevant sourcebooks.

The manual is structured as follows:

Chapter 1: Introduces the role of blue carbon in climate change mitigation and outlines the manual's purpose and objectives;

Chapter 2: Outlines the main steps to prepare a robust field measurement plan;

Chapter 3: Provides protocols and guidance for measuring organic carbon stocks found in the soils of all three ecosystems;

Chapter 4: Provides protocols and guidance for measuring organic carbon stocks, found in above- and belowground biomass, with specific protocols designed for each ecosystem;

Chapter 5: Highlights methods for determining the changes in carbon stocks over time and monitoring greenhouse gas emissions;

Chapter 6: Gives an overview of remote sensing options and applications;

Chapter 7: Provides guidance on managing large data sets and data sharing; and

Appendices: There are several appendices; they contain supplementary information, worked through examples, lists of equations, and more.

WHAT IS BLUE CARBON

Blue carbon is the carbon stored in mangroves, salt tidal marshes, and seagrass meadows within the soil, the living biomass aboveground (leaves, branches, stems), the living biomass belowground (roots), and the non-living biomass (e.g., litter and dead wood) (Mcleod *et al*. 2011). Similar to the carbon stored in terrestrial ecosystems, blue carbon is sequestered in living plant biomass for relatively short time scales (years to decades). Unlike terrestrial ecosystems, carbon sequestered in coastal soils can be extensive and remain trapped for very long periods of time (centuries to millennia) resulting in very large carbon stocks (Duarte *et al*. 2005; Lo Iacono *et al*. 2008). The difference in soil carbon accumulation in terrestrial versus coastal systems is that potential carbon storage in upland soils is limited by high availability of oxygen, allowing for aerobic microbial carbon oxidation and release back into the atmosphere (Schlesinger & Lichter 2001). In blue carbon systems, however, the soil is saturated with water keeping it in an anaerobic state (low to no oxygen), and it continually accretes vertically at high rates resulting in continuous build-up of carbon over time (Chmura *et al*. 2003). Some of the largest examples of carbon stocks in coastal sediments include the *Posidonia oceanica* seagrass meadows in Portlligat Bay, Spain, and mangroves in Belize which have accreted carbon-rich soils more than 10 meters thick and are more than 6000 years old (McKee *et al*. 2007; Lo Iacono *et al*. 2008; Serrano et al. 2014). Similarly, tidal salt marsh sediments in northern New England are 3–5 meters thick, 3000–4000 years old, and are composed of up to 40% organic carbon (Johnson *et al*. 2007).

Figure 1.2 Tidal salt marsh soil sample, Beaufort, NC (© Jennifer Howard, CI)

The carbon found in blue carbon ecosystems can be classified as either autochthonous or allochthonous and depending on the project, may need to be assessed separately (Middelburg *et al*. 1997; Kennedy *et al*. 2010).

- **Autochthonous Carbon**: This type of carbon is produced and deposited in the same location. Plants remove carbon dioxide (CO_2) from the atmosphere/ocean through photosynthesis (primary production) and convert it for use by plant tissue (such as leaves, stems, roots/rhizomes) to increase plant biomass. A large portion of plant biomass is allocated to the roots where it decomposes very slowly in anaerobic conditions, thus storing the carbon within the sediments (**Fig. 1.2**) (Middelburg *et al*. 1997; Kennedy *et al*. 2010).
- **Allochthonous Carbon**: This type of carbon is produced in one location and deposited in another. Blue carbon ecosystems exist in very hydrodynamically active settings; they are constantly battered by waves, tides, and coastal currents that transport sediments and associated organic carbon from adjacent ecosystems (offshore or terrestrial). The plants found in these systems have complex root structures and canopies that are efficient at trapping sediment as it moves through the system, adding to the local carbon stock as a result (**Fig. 1.2**).

The ratio of carbon originating within the ecosystem to that trapped from external sources varies between blue carbon systems. In seagrass meadows, an estimated 50% of carbon stored in soils can be of external origin (allochthonous) (Kennedy *et al*. 2010), while most of the sequestered carbon in mangrove and tidal salt marsh systems is directly produced by the plants within the system (autochthonous) (Middleton & McKee 2001). However, in some settings there are significant allochthonous contributions found in mangroves and marshes, derived from adjacent terrestrial or marine ecosystems (Middelburg *et al*. 1997; Bouillon *et al*. 2003; Adame *et al*. 2012).

WHY MANAGE FOR BLUE CARBON

Globally, numerous policies, coastal management strategies, and tools designed for conserving and restoring coastal ecosystems have been developed and implemented. Policies and finance mechanisms being developed for climate change mitigation may offer an additional route for effective coastal management. Blue carbon now offers the possibility to mobilize additional funds and revenue by combining best-practices in coastal management with climate change mitigation goals and needs.

Mangroves, tidal salt marshes, and seagrasses are under high levels of pressure from coastal development and land-use change (Alongi 2002; Gedan *et al*. 2009; Saintilan *et al*. 2009; Waycott *et al*. 2009). When vegetation is removed and the land is either drained or dredged for economic development, (e.g., mangrove forest clearing for shrimp ponds, draining of tidal marshes for agriculture, and dredging in seagrass beds—all common activities in the coastal zones of the world), the sediments become exposed to the atmosphere or water column resulting in the carbon stored in the sediment bonding with the oxygen in the air to form CO_2 and other GHG that get released into the atmosphere and ocean (Yu & Chmura 2009; Loomis & Craft 2010; Donato *et al*. 2011; Kauffman *et al*. 2011; Lovelock *et al*. 2011; Ray *et al*. 2011; Callaway *et al*. 2012; Fourqurean *et al*. 2012a) (**Fig. 1.3**). Not only do these activities result in CO_2 emissions but they also result in losses of biodiversity and critical ecosystem services.

Coastal blue carbon ecosystems offer coastal protection through wave attenuation and erosion prevention (King & Lester 1995; Gedan *et al*. 2011). These services are already recognized as a vital function of mangroves (Mazda *et al*. 1997; Massel *et al*. 1999; McIvor *et al*. 2012a; McIvor *et al*. 2012b), but they gained more prominence in the aftermath of the December 2004 Indian Ocean tsunami (Danielsen *et al*. 2005; Kathiresan & Rajendran 2005; Alongi 2008), the November 2013 typhoon Haiyan that hit the Philippines (Gross 2014), and other recent destructive cyclones and hurricanes (Tibbetts 2006; Williams *et al*. 2007; Das & Vincent 2009). These systems also regulate water quality, serve as critical habitats for many fish and shellfish species, provide wood and other products to local populations, and host

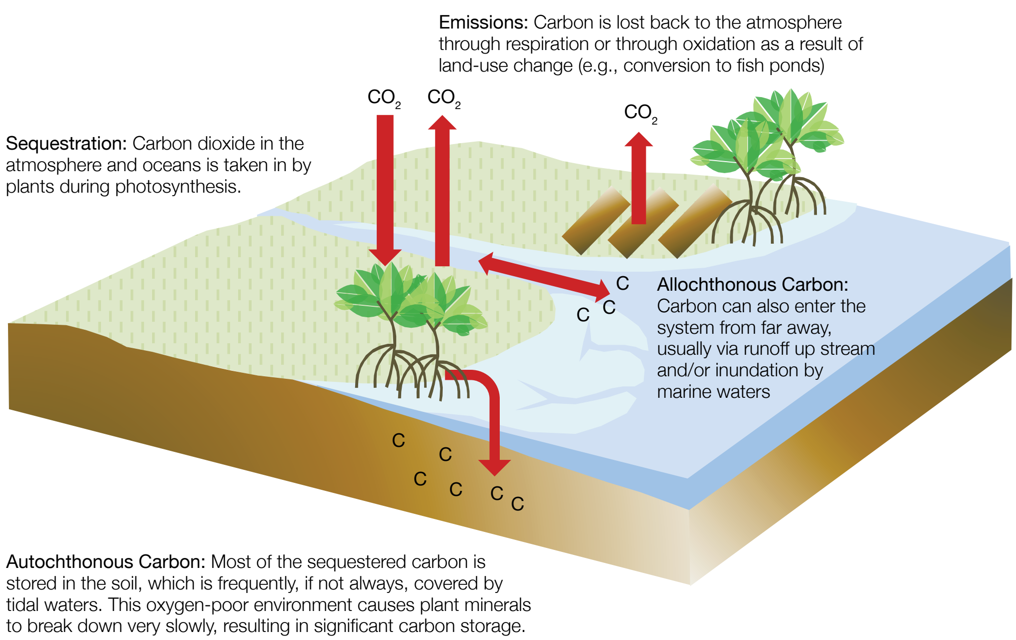

Figure 1.3 Mechanisms by which carbon moves into and out of tidal wetlands

a diverse array of rare and endangered species (Valiela & Teal 1979; Beck *et al*. 2001; Duke *et al*. 2007; FAO 2007; Barbier *et al*. 2011; Cullen-Unsworth & Unsworth 2013). They are a source of nutrients to adjacent ecosystems, provide sheltered living space for economically important species, and are valued for aesthetics and ecotourism (Barbier *et al*. 2011).

While this manual is focused on the evaluation of carbon stocks as a tool for conservation of coastal vegetated ecosystems, it is important to remember that actions to conserve the carbon stocks also ensure the preservation of these and other critical ecosystem services.

KNOWLEDGE GAPS

Despite the wealth of research that has been conducted, knowledge gaps still exist. Continued work in the areas outlined below will help to further refine current estimates and evaluations.

- **Geographical extent**: While mangroves are fairly well mapped, large areas containing seagrass meadows remain largely unsurveyed, (e.g., Southeast Asia, eastern and western South America and the west coast of Africa). Similarly, the global extent of tidal salt marsh and rates of marsh and seagrass meadow loss are currently undocumented.
- **Sequestration and storage**: Limited data are available in the scientific literature on the carbon sequestration and storage rates of blue carbon ecosystems in Africa, South America, and Southeast Asia.
- **Emissions and removals:** Additional mapping of converted, and degraded and revegetated blue carbon ecosystems and the quantification of emissions from exposed organic soils, and from disturbed or degraded seagrass meadows as well as quantification of removals to restored coastal ecosystems, is needed to enable inclusion in relevant databases (e.g., the IPCC Emission Factor Database).
- **Human drivers**: Emission rates associated with specific human activities over time for various drivers of ecosystem degradation, or loss (e.g., drainage, burning, harvesting, or clearing of vegetation at different intensity levels) are limited at the moment, especially for seagrasses. Removal rates to restored coastal ecosystems are also currently lacking.
- **Coastal Erosion**: A significant amount of eroded coastal carbon is thought to be dissolved in the ocean water where it enters the ocean-atmosphere system. The remaining eroded carbon is deposited in offshore sediments and sequestered. The fate of carbon eroded from blue carbon ecosystems is an ongoing topic of scientific research.

BLUE CARBON INVENTORIES

To explicitly address the role of blue carbon ecosystems in climate change mitigation and human wellbeing through policy, regulatory, finance, or other mechanisms, the carbon stock in these ecosystems and the existing or potential carbon emissions resulting from changes to those ecosystems must be quantified. This process is referred to as creating a carbon inventory. Carbon inventories can be undertaken at site-level, regional, national, and global scales. Specific examples of activities that require a blue carbon inventory include quantifying the total GHG emissions that result from land use changes, and estimating the avoided carbon emissions and the resulting climate change mitigation potential of a given coastal conservation project or activity.

1

Creating a carbon inventory for a given area requires understanding 1) the past and present distribution of coastal vegetated ecosystems linked to the human uses of the area, 2) the current carbon stock within the project area and rate of carbon accrual, and 3) the potential carbon emissions that will result from expected or potential changes to the landscape. Carbon emissions are normally expressed in megagrams (Mg) or metric tons[1] of carbon (C) per hectare (ha), for a given change in land use in a given time frame. Results can also be reported in tons of CO_2 per ha. To convert Mg C/ha to Mg CO_2/ha, multiply the Mg C/ha by 3.67 (the molar ratio of CO_2 to C). CO_2 equivalents (equiv) per hectare is a metric used to express carbon emissions produced by non-CO_2 emissions (e.g., methane) and allows for comparability between GHG.

The IPCC guidelines identified “activity data” and “emission factors” as being required to calculate the carbon emissions or removals for a given area. Those two distinct types of data are described here:

- **Activity data**: This term refers to geographical data showing the types of land coverage and use in a given area such as pristine mangrove forest, degraded tidal marsh, agricultural land, grassland, or aquaculture ponds. These data also include the expected rates of change in land uses over time—for example the rate of conversion of mangrove areas to shrimp ponds. Remote sensing is commonly used to classify land-use types and to track changes between different land uses over time. However, additional field assessments and mapping are often necessary, especially in coastal environments where accurate remote imaging may be challenging (Chapter 6: Remote sensing methods).
- **Emission factors**: Emission factors: This term refers to changes (loss or gain of carbon) the investigated area that has resulted from changes in land coverage and use (e.g., loss of carbon due to conversion of mangrove to aquaculture, and tidal marsh to agricultural land or gain of carbon through revegetation or restoration of coastal ecosystems. Positive values for emission factors indicate loss of carbon from biomass and soil, to the atmosphere and negative values indicate removal of carbon from the atmosphere to the biomass and soil (sequestration). Accurate quantification of emission factors requires ground-based measurements of ecosystem carbon stocks and their change over time, (Chapters 3: General principles of field sampling soil carbon pools and Chapter 4: General Principles of field sampling vegetative carbon pools for relevant methods for measuring carbon stocks in mangroves, tidal marshes, and seagrasses meadows) or direct measurement of how much carbon is emitted or sequestered over time (Chapter 5).

TIERS OF DETAIL IN CARBON INVENTORIES

There is a clear need to align methods with international standards such as those described by the IPCC’s 2013 Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands (IPCC 2013) and other relevant sourcebooks. According to the IPCC, carbon inventories can be achieved at various levels of detail or certainty, often determined by the purpose of the inventory and the resources available. The IPCC has identified three tiers of detail in carbon inventories that reflect the degrees of certainty or accuracy of a carbon stock inventory (or assessment) (**Table 1.1**).

1 A metric ton is the same as a mega gram (Mg) or 1 000 000 grams.

The methods described in this manual are relevant to achieving the highest level of assessment of carbon stocks in ecosystems—Tier 3. The IPCC recommends that countries aspire for Tier 3 for the measurement of key carbon stocks/sources/sinks. However, Tier 3 assessments are more costly to implement, require higher levels of technical resources and capacity, and are not always possible.

Table 1.1 Tiers that may be used to assess carbon emission factors (GOFC-GOLD 2009).

TIER	REQUIREMENTS	COMMENTS
1	IPCC default factors	Tier 1 assessments have the least accuracy and certainty and are based on simplified assumptions and published IPCC default values for activity data and emissions factors. Tier 1 assessments may have a large error range of +/- 50% for aboveground pools and +/- 90% for the variable soil carbon pools.
2	Country-specific data for key factors	Tier 2 assessments include some country or site-specific data and hence have increased accuracy and resolution. For example, a country may know the mean carbon stock for different ecosystem types within the country.
3	Detailed inventory of key carbon stocks, repeated measurements of key stocks through time or modelling	Tier 3 assessments require highly specific data of the carbon stocks in each component ecosystem or land use area, and repeated measurements of key carbon stocks through time to provide estimates of change or flux of carbon into or out of the area. Estimates of carbon flux can be provided through direct field measurements or by modelling.

GLOBAL BLUE CARBON STOCKS

When Tier 2 or 3 estimates are not possible, Tier 1 estimates can be performed. The globally averaged estimates, shown in **Table 1.2**, can be used to give a Tier 1 estimate of carbon stocks within any given area if site-specific data does not exist. They are based on globally averaged carbon stock estimates for mangroves, tidal marshes, and seagrass meadows according to current literature. However, these estimates have a high degree of uncertainty.

Table 1.2 Mean and range values of soil organic carbon stocks (to 1 m depth) for mangrove, tidal marsh, and seagrass ecosystems and CO_2 equivalents. Examples of how carbon is distributed amongst the different ecosystems and the variation within each ecosystem (IPCC 2013)

ECOSYSTEM	CARBON STOCK Mg/ha	RANGE Mg/ha	CO_2Mequiv/ha
Mangrove	386	55 – 1376	1415
Tidal salt marsh	255	16 – 623	935
Seagrass	108	10 – 829	396

A Tier 1 assessment of a carbon stock within a project area can be achieved by multiplying the area of an ecosystem by the mean carbon stock for that ecosystem type.

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FOR EXAMPLE

Questions being asked:

- How much carbon is stored in the biomass and top 1 m of soil in 564 hectares of mangrove forests on your project site?
- And how does that relate to CO_2 emissions if all the organic carbon in the upper 1 m of sediment is oxidized to carbon dioxide?

Total Carbon (MgC/ha) * Area (ha) = Tier 1 total carbon stock for the project site (Mg)

- Where Total Carbon = the mean carbon stock for a given ecosystem (from **Table 1.2**)
- Area = the area of the ecosystem being investigated

Answer to the first question

- *386 MgC/ha * 564 ha = 217 704 Mg of Blue Carbon in the study area*

Total potential CO_2 emissions per hectare (Mg CO_2/ha) = Conversion factor for the CO_2 that can be produced from the carbon present in the system * carbon in the system

- Conversion factor = 3.67, the ratio of the molecular weights of CO_2 (44) and carbon (12)
- Carbon in the system = the mean carbon stock for a given ecosystem

Answer to the second question

- *217 704 Mg of Blue Carbon * 3.67 = 798 974 Mg CO_2 in the study area*

CONCLUSION

This manual provides specific instructions for the field collection and laboratory analysis of carbon pools in mangrove, tidal salt marsh, and seagrass systems and some additional guidance for measuring GHG emissions, such as CO_2 and methane, which may be appropriate for some projects. Depending on the level of detail and the accuracy of the measurements used, this manual should be able to provide estimates that meet the IPCC standards for Tiers 2 and 3. It should be noted that the technical aspects of quantifying coastal ecosystem carbon and removals described in this guide are only one of several elements of complete carbon accounting. Other important elements including social, political, and economic factors—for example, addressing permanence, leakage, and governance—are not covered here. Definitions and information on those topics can be found in the IPCC guidelines (IPCC 2007) and associated sourcebooks (GOFC-GOLD 2009).