CHAPTER 4

COASTAL WETLANDS

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4.1 INTRODUCTION

This chapter provides guidance on estimating and reporting anthropogenic greenhouse gas (GHG) emissions and removals from managed coastal wetlands. Coastal wetlands hold large reservoirs of carbon (C) in biomass and especially soil [global stocks: mangroves, ~8 Pg C (Donato *et al*., 2011); tidal marshes, ~0.8 Pg C (midrange; Pendleton *et al*., 2012); and seagrass meadows, 4.2 – 8.4 Pg C (Fourqurean *et al*., 2012)]. Soil carbon originates largely *in situ*, from root biomass and litter, and can result in a significant pool in coastal wetlands, especially when compared with terrestrial forests (Pidgeon, 2009).

Coastal wetlands generally consist of organic and mineral soils that are covered or saturated, for all or part of the year, by tidal freshwater, brackish or saline water (Annex 4A.1) and are vegetated by vascular plants. The boundary of coastal wetlands may extend to the landward extent of tidal inundation and may extend seaward to the maximum depth of vascular plant vegetation. Countries need to develop a nationally appropriate definition of coastal wetland taking into account national circumstances and capabilities. This chapter refers specifically to tidal freshwater[1] and salt marshes, seagrass meadows, and mangroves. For non-tidal inland mineral wetland soils, refer to Chapter 5, this supplement.

TABLE 4.1
SPECIFIC MANAGEMENT ACTIVITIES IN COASTAL WETLANDS

Activity	*Subactivity*	*Vegetation types affected*
Activities relevant to CO_2 emissions and removals		
Forest management practices in mangroves	Planting, thinning, harvest, wood removal, fuelwood removal, charcoal production[1]	Mangrove[2]
Extraction	Excavation to enable port, harbour and marina construction and filling or dredging to facilitate raising the elevation of land	Mangrove, Tidal marsh, Seagrass meadow[4]
	Aquaculture (construction)	Mangrove, Tidal marsh
	Salt production (construction)	Mangrove, Tidal marsh
Drainage	Agriculture, forestry, mosquito control	Mangrove, Tidal marsh
Rewetting, revegetation and creation[3]	Conversion from drained to saturated soils by restoring hydrology and reestablishment of vegetation	Mangrove, Tidal marsh
	Reestablishment of vegetation on undrained soils	Seagrass meadow[4]
Activities relevant to non-CO_2 emissions		
Aquaculture (use)	N_2O emissions from aquaculture use	Mangrove, Tidal marsh, Seagrass meadow
Rewetted soils	CH_4 emissions from change to natural vegetation following modifications to restore hydrology	Mangrove, Tidal marsh

[1]Including conversion to Forest Land or conversion from Forest Land to other land uses.

[2] It is *good practice* to report mangroves in the appropriate national land-use category according to the national forest definition and to consider when forest management practices may occur on mangroves classified under land-use categories other than Forest Land (similar types of examples in inventory reporting include wood harvest from orchards or other perennial Cropland or harvest of trees from Wetlands).

[3]The term revegetation is used to refer to practices within the framework of UNFCCC reporting.

[4]Countries need to report on emissions from extraction and revegetation only if necessary data are available.

[1]At the present time, insufficient data are available to provide generic default data for C pools in tidal freshwater swamps.

It is *good practice* that inventory compilers determine a country-specific definition of coastal wetlands, recognizing national circumstances. Having applied the country-specific definition, the specific management activities (Table 4.1) need to be identified and emissions and removals reported using the methodologies provided in this chapter. When identifying the nature and location of these activities, inventory compilers need only report GHG emissions or removals for activities where the anthropogenic contribution dominates over natural emissions and removals. Management activities resulting in extraction of soils, such as construction of aquaculture ponds, can result in large carbon dioxide (CO_2) emissions in mangroves and tidal marshes. Nitrous oxide (N_2O) emissions can be significant from aquaculture activities. Rewetting increases methane (CH_4) emissions from drained freshwater tidal systems and increases carbon accumulation in mangrove biomass, dead wood and soils.

Coastal wetlands can potentially occur in any land-use category defined in Chapter 3, Volume 4 of the *2006 IPCC Guidelines* and the management activity may or may not result in a land-use change (see Box 4.1). Regardless of whether a land-use change occurs, it is *good practice* to quantify and report significant emissions and removals (Table 4.1) resulting from management activities on coastal wetlands in line with the country-specific definition. To cover all potential reporting options, new Wetland subcategories *Other Wetlands Remaining Other Wetlands* and *Land Converted to Other Wetlands* are included. Coastal wetlands can also occur on areas that are not part of the total land area of the country. Emissions and removals from these areas should be reported separately under the relevant land-use category, however the associated land areas should be excluded from the total area of the land-use category (refer to Chapter 7, this supplement). In this way, countries need not be concerned with areas of coastal wetland, with small impacts on carbon stock changes and emissions of non-CO_2 gases, which are not included in the total land area.

Readers are referred to Volume 4 of the *2006 IPCC Guidelines* for many of the basic equations to estimate GHG emissions, and new guidance is provided in this chapter, as necessary. The decision tree (Figure 4.1) guides the inventory compiler to the appropriate estimation methodology for each of the specific management activities covered in this chapter.

COVERAGE OF THIS CHAPTER

This Chapter updates guidance contained in the *2006 IPCC Guidelines* to:

- provide default data for estimation of carbon stock changes in mangrove living biomass and dead wood pools for coastal wetlands at Tier 1.

This Chapter gives new:

- guidance for CO_2 emissions and removals from organic and mineral soils for the management activities of extraction (including construction of aquaculture and salt production ponds), drainage and rewetting, revegetation and creation;
- default data for estimation of anthropogenic CO_2 emissions and removals for soils in mangrove, tidal marsh and seagrass meadows;
- guidance for N_2O emissions during aquaculture use;
- guidance for CH_4 emissions for rewetting, revegetation and creation of mangroves, tidal marshes and seagrass meadows.

The Appendix to this Chapter provides the basis for future methodological development to address:

- Anthropogenic emissions and removals associated with dissolved or particulate organic carbon (DOC, POC) loss during drainage as affected by tidal exchange.

For constructed wetlands that occur in coastal zones that are modified to receive and treat wastewater, refer to Chapter 6 (this supplement). Chapter 6 also covers semi-natural treatment wetlands, which are natural wetlands where wastewater has been directed for treatment but the wetland is otherwise unmodified.

While countries will follow their own national definitions of coastal wetlands, some general features that may help in consistent identification can be found throughout this guidance. It is *good practice* to maintain consistent identification of lands for the purpose of reporting.

BOX 4.1

THE FOLLOWING EXAMPLES ILLUSTRATE DIFFERENT MANAGEMENT PRACTICES WHICH MAY RESULT IN A CHANGE OF A LAND-USE CATEGORY DEPENDING ON HOW COUNTRIES DEFINE MANGROVES AND OTHER COASTAL WETLANDS

For Land remaining in a Land-use category (i.e. no change in land-use category), when:

Seagrass meadows or tidal marshes classified as Wetlands remain reported as Wetlands following introduction of aquaculture activity.

Mangroves classified as Forest Land according to the national forest definition undergo selective harvesting or biomass clearing remain reported as Forest Land unless they undergo a land-use change.

Mangroves, which do not meet all thresholds of a country's definition of forest, but are coastal wetlands with trees are classified as Wetlands, and when subject to selective harvesting or biomass clearing remain reported as Wetlands.

Conversely, management activities may result in a change in reporting category, for example, when:

Seagrass meadows are initially classified as Wetlands, but are considered a Settlement following introduction of aquaculture activity.

Tidal marshes are classified as Wetlands and are drained for agriculture and subsequently classified as a Cropland or Grassland.

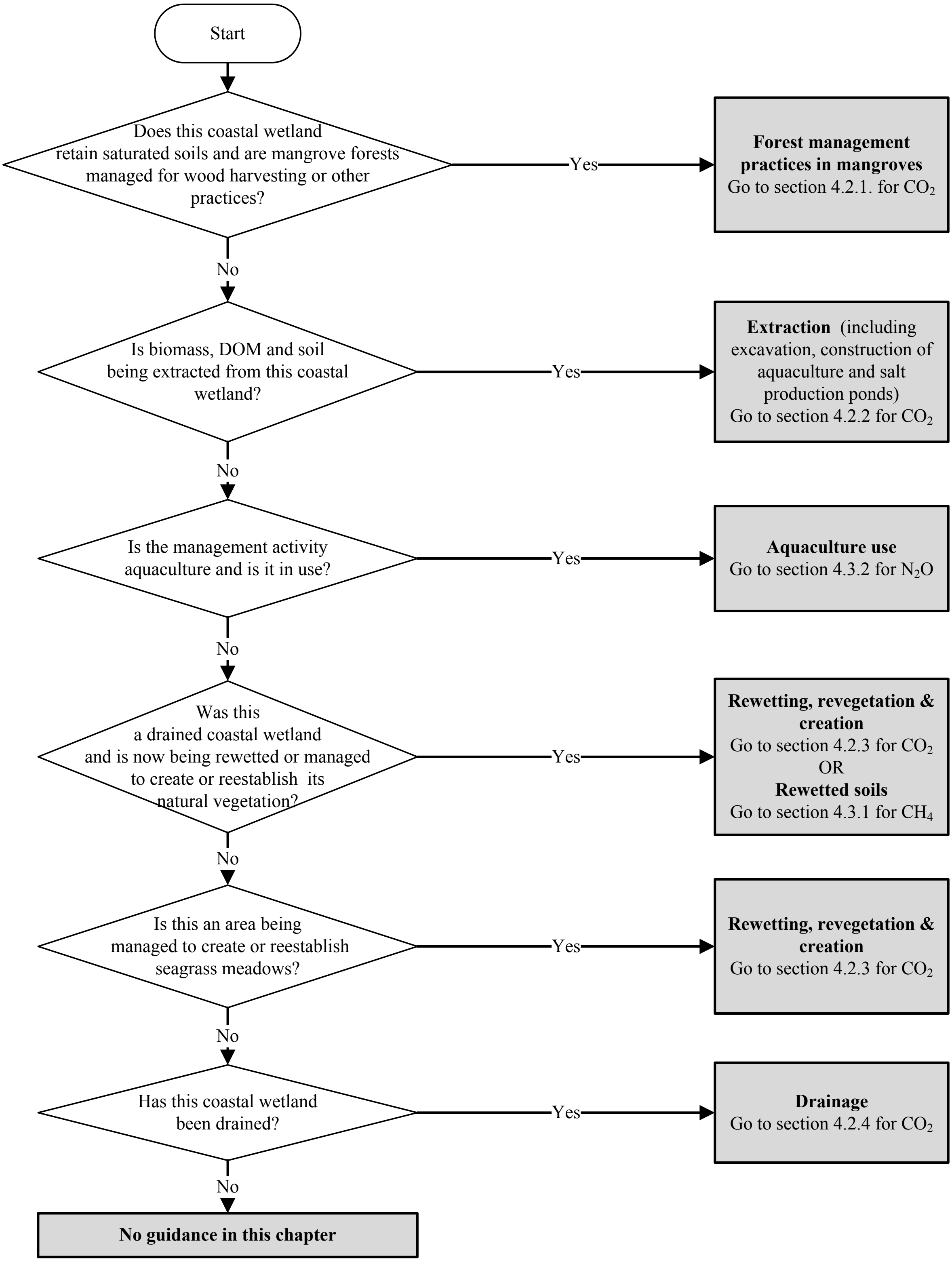
Mangroves are classified as Forest Land and undergo clearing, or drainage and converted to another land-use category.

MANAGEMENT ACTIVITIES IN COASTAL WETLANDS

Coastal wetlands that have been modified by anthropogenic activities are often reduced in area. Globally about 35% of the area of mangroves has disappeared since 1980, with a current global areal rate of loss of between 0.7 and 3% yr^{-1} (Pendelton *et al.*, 2012). The management activities that have led to the majority of mangrove loss include forestry activities (26%) and aquaculture, comprising the construction (and extraction of soil) for shrimp ponds (38%) and fish farms (14%) (Vaiela *et al.*, 2009). Other management activities may lead to the removal of mangrove biomass without necessarily resulting in mangrove clearance i.e. harvesting for fuelwood, charcoal and construction. The current global areal rate of loss of tidal marsh is estimated to be between 1 and 2% yr^{-1} (Pendelton *et al.*, 2012). Draining for agriculture, diking to isolate marsh from tides, filling (after extraction) with sediment, and the extraction of soil during the construction of ponds for salt production are common management activities affecting tidal marshes. Seagrass meadows are experiencing a global areal rate of loss currently of between 0.4 and 2.5% yr^{-1} (Pendelton *et al.*, 2012). Globally, the main reasons for seagrass loss are management activities such as dredging, leading to the excavation of soil to raise the elevation of land in low lying areas and contribute to new land areas for settlement and aquaculture.

Revegetation efforts with mangroves, tidal marsh plants and seagrass, have been made worldwide to compensate or mitigate for coastal wetland loss resulting from management activities (e.g. Bosire *et al.*, 2008; Orth *et al.*, 2011). Recovery of vegetation that characterised the coastal zone generally requires reestablishment of the pre-existing environmental setting, such as rewetting (restored hydrology), to maintain saturated soils and facilitate plant growth. Management activities do not always affect all vegetation types (i.e. mangroves, tidal marsh plants and seagrasses) or occur in all countries and not all coastal wetlands will be managed**.** To identify areas affected refer to respective sections on Activity Data and throughout this supplement.

Figure 4.1 Decision tree to indicate relevant section for Tier 1 estimation of GHG emissions and removals due to specific management activities in coastal wetlands[2].



[2] For extraction activities, CO_2 emissions and removals are estimated for the initial change in carbon stocks that occur during the year the extraction activities take place. Once the activity/activities is/are completed, these lands are continually tracked but CO_2 emissions and removals are reported as zero at Tier 1. Forest management practices in mangroves, drainage and rewetting are reported based on the area of land where it occurs, lands are tracked and CO_2 emissions and removals subsequently are reported in the annual inventory.

The following sections provide some general information on the specified management activities in coastal wetlands that result in large anthropogenic emissions and removals.

Forest management practices in mangroves

Removal of wood occurs throughout the tropics where mangrove forests are harvested for fuelwood, charcoal, and construction (Ellison and Farnsworth, 1996; Walters *et al*., 2008). The wood removal can range from extensive forest clearing to more moderate, selective harvesting of individual trees, or to minimally invasive activities such as bark removal. Natural disturbances are another form of biomass carbon stock loss. There may also be conversion to forest land where mangrove replanting can take place on rewetted, or already saturated, soils.

Extraction

Extraction collectively refers to:

(A) Excavation of saturated soils leading to unsaturated (drained) soils and removal of biomass and dead organic matter. Activities that lead to the excavation of soil often lead to loss of coastal wetlands. The excavated or dredged soil is also commonly used to help develop coastal infrastructure where there is a need to raise the elevation of land in low lying areas and/or contribute to new land areas for settlement.

(B) Excavation during the "construction" phase of aquaculture and salt production ponds in mangroves and tidal marshes followed by the "use" of these facilities.

Aquaculture and salt production are common activities in the coastal zone and similarly require excavation of soil and removal of biomass and dead organic matter for construction. There is a range of aquaculture practices, but the most important are fish farming and production from shrimp ponds (World Bank, 2006). Salt production, from the evaporation of seawater, is also a widespread activity with sites along tropical and subtropical coasts worldwide, some of which have been producing salt for centuries (Oren, 2009; Thiery and Puente, 2002). In both activities, ponds are constructed in mangroves and tidal marshes by clearing vegetation, levelling the soil and subsequently excavating the surface soils to build berms where water is held. Depending on the type of aquaculture (intensive, extensive etc.) and the species stocked in the ponds (shrimp, fish) the soils can be excavated to make ponds of 0.5 m to 2.5 m depth (Cruz, 1997; Kungvankij *et al*., 1986; Wang, 1990; Robertson and Phillips, 1995). In a similar manner the depth of salt production ponds can vary between depths of about 0.5 to 2.5 m (e.g. Ortiz-Milan, 2006; Madkour and Gaballah, 2012).

Construction is only the first phase in aquaculture and salt production. The second phase, termed "use" is when fish ponds, cages or pens are stocked and fish production occurs. In seagrass meadows, aquaculture is maintained by housing fish in floating cages or pens that are anchored to the sediment (Alongi *et al*., 2009) and these settings are considered during the use phase. N_2O is emitted from aquaculture systems primarily as a by-product of the conversion of ammonia (contained in fish urea) to nitrate through nitrification and nitrate to N_2 gas through denitrification. The N_2O emissions are related to the fish production (Hu *et al*., 2012). When use of the aquaculture systems has been stopped, often due to disease or declining water clarity (Stevenson *et al*., 1999), the systems transition to a final phase i.e. "discontinued". All three phases (construction, use and discontinued) of aquaculture and salt production are considered together with the other extraction activities, because the activity data are linked. However, only construction is addressed at Tier 1 for CO_2, with higher tiers addressing use and discontinued phases. For non-CO_2, only the use phase is considered at Tier 1.

Rewetting, revegetation and creation

Rewetting is a pre-requisite for vegetation reestablishment and/or creation of conditions conducive to purposeful planting of vegetation that is characteristic of coastal wetlands. This activity is also used to describe the management activities designed to reestablish vegetation on undrained soils in seagrass meadows. Once the natural vegetation is established, soil carbon accumulation is initiated at rates commensurate to those found in natural settings (Craft *et al*., 2002, 2003; Osland *et al*., 2012).

Rewetting in mangroves and tidal marshes occurs where hydrologic modifications reverse drainage or remove impoundments or other obstructions to hydrologic flow (e.g. levee breach). Also included in this activity are mangroves and tidal marshes that have been created, typically by raising soil elevation or removing the upper layer of upland soil or dredge spoil, and grading the site until the appropriate tidal elevation is reached to facilitate reestablishment of the original vegetation. Revegetation can occur by natural recolonisation, direct seeding and purposeful planting. Alternatively, created wetlands with mangroves can be found where high riverine sediment loads lead to rapid sediment accumulation, so that previously sub-aqueous soils can be elevated above tidal influence. This naturally created land can be reseeded or purposefully vegetated.

The rewetting of tidal marshes and mangroves through reconnection of hydrology may lead to CH_4 emissions (Harris, 2010), particularly at low salinities, with an inverse relationship between CH_4 emissions and salinity (Purvaja and Ramesh, 2001; Poffenbarger *et al*., 2011).

In coastal wetlands where seagrass loss has occurred due to anthropogenic activities, soils remain saturated. Initiatives to allow revegeation can include natural or purposeful dispersal of seed or planting of seagrass modules (Orth *et al*., 2011). These same techniques can also be used to create (rather than re-establish) seagrass meadows (Jones *et al*., 2012).

Drainage

Mangroves and tidal marshes have been diked and drained to create pastures, croplands and settlements since before the 11th century (Gedan *et al*., 2009). The practice continues today on many coastlines. On some diked coasts, groundwater of reclaimed former wetlands is pumped out to maintain the water table at the required level below a dry soil surface, while on other coasts drainage is achieved through a system of ditches and tidal gates. Due to the substantial carbon reservoirs of coastal wetlands, drainage can lead to large CO_2 emissions.

4.2 CO_2 EMISSIONS AND REMOVALS

This section provides the methodology to estimate CO_2 emissions and removals from human activities in coastal wetlands comprising forest management practices in mangroves, extraction, drainage and rewetting. The methodological guidance provided here is consistent with methods for biomass and dead organic matter in Volume 4 of the *2006 IPCC Guidelines* and are in large part based on that methodological guidance: (1) for forest management practices in mangroves, methods for biomass and dead organic matter are in large part based on Chapter 4 of Volume 4; (2) for extraction activities, the methodological guidance is generally consistent with guidance for peat extraction Chapter 7 of Volume 4; and (3) for rewetting and drainage activities, updated methodological guidance found in other chapters of this supplement is consistent with the methodologies presented here. Activities covered by this chapter are described in Table 4.1. Separate guidance is provided on estimation of changes in carbon stock from the five carbon pools.

Depending on circumstances, practices and definitions, specific coastal wetland management activities may or may not involve a change in land-use category. The guidance in this chapter needs to be applied regardless of the reporting categories. In particular, no recommendation is provided in relation to transition periods between land-use categories; countries can apply the existing transition period of appropriate land-use categories.

Consistent with the *2006 IPCC Guidelines*, the Tier 1 default approach assumes that the change in biomass and dead organic matter carbon stocks are zero on all lands except on Forest Land or on Cropland, Grassland and Wetlands with perennial woody biomass. On Forest Land and on Cropland, Grassland, or Wetlands with woody biomass, the woody biomass and woody dead organic matter pools are potentially significant and need to be estimated in a manner consistent with the guidance provided in Chapters 2 (generic methods), 4 (Forest Land), 5 (Cropland), 6 (Grassland) and 7 (Wetlands) in Volume 4 of the *2006 IPCC Guidelines*. Guidance provided here refers to Equations 2.7, 2.8 and the subsequent equations in Chapter 2 of the *2006 IPCC Guidelines* which split the carbon stock changes in the biomass pool or ΔC_B into the various possible gains and losses.

If specific management activities in coastal wetlands (Table 4.1) are accompanied by a change in land use that involves Forest Land or Cropland, Grassland or Wetlands with perennial woody biomass, changes in carbon stocks in biomass, dead wood and litter pools are equal to the difference in carbon stocks in the old and current land-use categories (see Section 2.3.1.2, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*). These changes in carbon stock occur only in the year of the conversion (extraction activities), or are uniformly distributed over the length of the transition period (e.g. planting, harvesting). In soils the change in carbon stocks for extraction activities occurs in the year of conversion, while for drainage, emissions persist as long as the soil remains drained or as long as organic matter remains, following the methodological guidance in this chapter.

4.2.1 Forest management practices in mangroves

This section deals with CO_2 emissions and removals associated with forest management practices in mangroves. It is *good practice* to follow a country's national definition of forest, but also to apply the appropriate guidance when mangrove wetlands have trees, but that do not necessarily satisfy all thresholds of the national definition of forest. Depending on how the land is classified, forest management practices in mangroves may or may not lead to a change in land-use category (examples provided in Box 4.1). For estimation methodologies refer to the generic guidance provided in Chapter 2 of Volume 4 and more specific guidance in the relevant chapters of the *2006 IPCC Guidelines* for reporting CO_2 emissions and removals for above-ground biomass, below-ground biomass and dead organic matter (litter and dead wood).

4.2.1.1 BIOMASS

Biomass can be stored in mangroves that contain perennial woody vegetation. The default methodology for estimating carbon stock changes in woody biomass is provided in Section 2.2.1, Chapter 2, Volume 4 of the *2006 IPCC Guidelines*. The change in biomass is only estimated for perennial woody vegetation of mangroves. Changes in mangrove biomass may be estimated from either: 1) annual rates of biomass gain and loss (Equation 2.7, Chapter 2) or 2) changes in carbon stocks at two points in time (Equation 2.8, Chapter 2). The first approach (Gain-Loss method) can be used for Tier 1 estimation (with refinements at higher tiers) whereas the second approach can be used for Tier 2 or 3 estimations. It is *good practice* for countries to strive to improve inventory and reporting approaches by advancing to the highest possible tier given national circumstances. For coastal wetlands with non-woody vegetation (i.e. seagrass meadows and many tidal marshes), increase in biomass stocks in a single year is assumed equal to biomass losses from mortality in that same year leading to no net change.

CHOICE OF METHOD

Tier 1

If the land (1) satisfies a country's definition of forest or (2) is a mangrove wetland with trees, that nonetheless do not meet the national definition of forest, and is managed for forest activities where no land-use change has occurred, guidance is provided in "Section 2.3.1.1 Land Remaining in a Land-Use Category" and in the specific guidance in Volume 4, of the *IPCC 2006 Guidelines.* Guidance is applied using the default data provided in this chapter (Table 4.2 – 4.6) and specific guidance below. Examples may include Forest Land to Forest Land, Wetlands to Wetlands or Other Wetlands to Other Wetlands.

If the land (1) satisfies a country's definition of forest or (2) is a mangrove wetland with trees, and is managed for forest activities where land-use change has occurred or trees have been cleared, guidance is provided in "Section 2.3.1.2 Land Converted to a Another Land-Use Category" and in the specific guidance in the relevant chapters of Volume 4 of the *2006 IPCC Guidelines.* Guidance is applied using the default data provided in this chapter (Table 4.2 – 4.6) and specific guidance below.

When either the biomass stock or its change in a category (or sub-category) is significant or a *key category*, it is *good practice* to select a higher tier for estimation. The choice of Tier 2 or 3 methods depends on the types and accuracy of data and models available, level of spatial disaggregation of activity data and national circumstances.

If using activity data collected via Approach 1 (see Chapter 3 of Volume 4 in the *2006 IPCC Guidelines*), and it is not possible to use supplementary data to identify land converted from and to the respective land category, the inventory compiler needs to estimate carbon stocks in biomass following Section 2.3.1.1 and specific relevant guidance as indicated above.

Because a biomass conversion and expansion factor (BCEF) is not available for mangroves, when above-ground biomass is estimated from merchantable growing stock, for conversion of net annual increment, or for conversion of woody and fuelwood removal volume to above-ground biomass removal, BCEF is derived from wood density (Table 4.6) and a default value of BEF (Table 3A.1.10- Annex 3A.10 of the *Good Practice Guidance for Land Use, Land-use Change, and Forestry*). This formulation follows Equation 4.1 and is described in Box 4.2 of Chapter 4, Volume 4 of the *2006 IPCC Guidelines.*

EQUATION 4.1
ESTIMATION OF BCEF USING BEF AND WOOD DENSITIES

$$BCEF = BEF \bullet D$$

(Section 2.3.1.1, Chapter 2 of the *2006 IPCC Guidelines*)

Where:

BCEF = biomass conversion and expansion factor for conversion of growing stock, net annual increment or wood removals into above-ground biomass, above-ground biomass growth or biomass removals; tonnes d.m. m^{-3}

BEF = biomass expansion factor to expand the dry weight of the merchantable volume of growing stock, net annual increment or wood removals to account for non-merchantable components; dimensionless

D = wood density; tonnes d.m. m^{-3}

Tier 2

As in Tier 1, the Gain-Loss method can be applied using country-specific data. In addition, the Stock-Difference method can also be applied using country-specific emission factors. If using the Stock-Difference method, country-specific BEF or BCEF data or species specific wood density values (provided in Annex 4A.3) could be applied. For Tier 2, countries may also modify the assumption that immediately following conversion to another land-use category, or after mangrove trees are cleared, biomass is zero. Refer to the relevant sections in Volume 4 of the *2006 IPCC Guidelines* for further guidance on Tier 2 methodologies for forest management practices in mangroves.

Tier 3

Tier 3 approach for biomass carbon stock change estimation allows for a variety of methods including process-based models that simulate the dynamics of biomass carbon stock changes. Country-defined methodology can be based on estimates of above-ground biomass through use of allometric equations (Annex 4A.2) or include detailed inventories based on permanent sample plots. Tier 3 could also involve substantial national data on disaggregation by vegetation type, ecological zone and salinity. Tier 3 approaches can use growth curves stratified by species, ecological zones, site productivity and management intensity. If developing alternative methods, these need to be clearly documented. Refer to the relevant sections in Chapter 4, Volume 4 of the *2006 IPCC Guidelines* for further guidance on Tier 3 methodologies for forest management practices in mangroves. Spaceborne optical and radar data can be used for mapping changes in the extent of mangroves and transitions to and from other land covers. Such techniques currently cannot routinely provide estimates of a sufficient level of accuracy, although this may become more feasible in the future (refer to this section, “Choice of Activity Data”).

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

For countries using the Gain-Loss method as a Tier 1 approach, the estimation of the annual carbon gains in living biomass requires the following: carbon fraction of above-ground biomass, average above-ground biomass, mean annual above-ground biomass growth, ratio of below-ground biomass to above-ground biomass and average wood density. The default values for these parameters are provided in Tables 4.2-4.6, respectively. It is *good practice* to apply annual growth rates that lead neither to over- nor underestimates. Losses due to wood removals, fuelwood removals and disturbances are also needed (refer to Choice of Activity Data for Tier 1 and uncertainty analysis in this section).

Tier 2

National data could include country specific values of any parameter used in the Tier 1 method or values that permit biomass carbon stock changes using the Stock-Difference method. Refer also to the relevant sections of Volume 4 of the *2006 IPCC Guidelines* for further guidance.

Tier 3

Tier 3 methods may employ the use of data that are of higher order spatial disaggregation and that depend on variation in salinity or further disaggregation of regional differences within a country. Forest growth rates of specific age ranges could be applied. Refer also to the relevant sections of Volume 4 of the *2006 IPCC Guidelines* for further guidance.

TABLE 4.2
CARBON FRACTION OF ABOVE-GROUND BIOMASS (TONNES C (TONNES D.M.)$^{-1}$) IN MANGROVES [1]

Component	%C	95% CI[3]	Range
Leaves + wood[2]	45.1 (n = 47)	42.9, 47.1	42.2-50.2

[1]This Table provides supplementary values to those presented in Table 4.3, Chapter 4, Volume 4 of the *2006 IPCC Guidelines*.

[2]Sources: Spain and Holt, 1980; Gong and Ong, 1990; Twilley *et al*., 1992; Bouillon *et al*., 2007; Saenger, 2002; Alongi *et al*., 2003, 2004; Kristensen *et al*., 2008

[3]95% CI of the geometric mean

TABLE 4.3
ABOVE-GROUND BIOMASS IN MANGROVES (TONNES D.M. HA^{-1}) [1]

Domain	Region	Above-ground biomass	95% CI[5]	Range	n
Tropical	Tropical Wet	192[2]	187, 204	8.7-384	49
	Tropical Dry	92[3]	88, 97	3.2-201	13
Subtropical		75[4]	66, 84	3.9-129	10

[1]This Table provides supplementary values to those presented in Table 4.7-4.9, Chapter 4, Volume 4 of the *2006 IPCC Guidelines*.

[2]Sources: Golley *et al*., 1975; Christensen, 1978; Ong *et al*., 1982; Putz and Chan, 1986; Tamai *et al*., 1986; Komiyama *et al*., 1987; 1988, 2000, 2008; Lin *et al*., 1990; Mall *et al*., 1991; Amarasinghe and Balasubramaniam, 1992; Kusmana *et al*., 1992; Slim *et al*., 1996; Fromard *et al*., 1998; Norhayati and Latiff, 2001; Poungparn, 2003; Sherman *et al*., 2003; Juliana and Nizam, 2004; Kirui *et al*., 2006; Kairo *et al*., 2008; Fatoyinbo *et al*., 2008; Camacho *et al*., 2011; Kauffman *et al*., 2011; Thant and Kanzaki, 2011

[3]Sources: Golley *et al*, 1962; Briggs, 1977; Suzuki and Tagawa, 1983; Steinke *et al*., 1995; Alongi *et al*., 2003; Medeiros and Sampoia, 2008; Khan *et al*., 2009

[4]Sources: Lugo and Snedaker, 1974; Woodroffe, 1984; Lee, 1990; Mackey, 1993; Tam *et al*., 1995; Saintilan, 1997; Ross *et al*., 2001; Coronado-Molina *et al*., 2004; Simard *et al*., 2006; Fatoyinbo *et al*., 2008; Komiyama *et al*., 2008; Abohassan *et al*., 2012

[5]95% CI of the geometric mean

TABLE 4.4
ABOVE-GROUND BIOMASS GROWTH IN MANGROVES (TONNES D.M. HA^{-1} YR^{-1})[1]

Domain	Region	Above-ground biomass growth[2,3]	95% CI[4]	Range	n
Tropical	Tropical Wet	9.9	9.4, 10.4	0.1-27.4	23
	Tropical Dry	3.3	3.1, 3.5	0.1-7.5	6
Subtropical		18.1	17.1, 19.1	5.3-29.1	4

[1]This Table provides supplementary values to those presented in Table 4.10, Chapter 4, Volume 4 of the *2006 IPCC Guidelines*.

[2]Sources: Ajonina 2008; Kairo *et al*., 2008; Alongi, 2010

[3]Biomass growth rates are from forests of varying age and such default values should only pertain to forests until the carbon biomass stock (Table 4.3) is reached.

[4]95% CI of the geometric mean

TABLE 4.5
RATIO OF BELOW-GROUND BIOMASS TO ABOVE-GROUND BIOMASS (R) IN MANGROVES[1]

Domain	Region	R [tonne root d.m. (tonne shoot d.m.)$^{-1}$]	95% CI[5]	Range	n
Tropical	Tropical Wet	0.49[2]	0.47, 0.51	0.04-1.1	18
	Tropical Dry	0.29[3]	0.28, 0.30	0.09-0.79	9
Subtropical		0.96[4]	0.91, 1.0	0.22-0.27	18

[1]This Table provides supplementary values to those presented in Table 4.4, Chapter 4, Volume 4 of the *2006 IPCC Guidelines*.

[2]Sources: Golley *et al*., 1975; Tamai *et al*., 1986; Komiyama *et al*., 1987, 1988; Gong and Ong, 1990; Lin *et al*., 1990; Poungparn, 2003

[3]Sources: Golley *et al*, 1962; Alongi *et al*., 2003; Hoque *et al*., 2010

[4]Sources: Briggs, 1977; Lin, 1989; Tam *et al*., 1995; Saintilan, 1997

[5]95% CI of the geometric mean

TABLE 4.6
AVERAGE DENSITY (D; TONNES M^{-3}) OF MANGROVE WOOD[1]

	D	95% CI[2]	Range	n
Wood	0.71	0.64, 0.74	0.41-0.87	85

[1]Sources: Global Wood Density Database http://datadryad.org/resource/doi:10.5061/dryad.234/1?show=full; Saenger, 2002; Komiyama *et al.*, 2005; Donato *et al.*, 2012

[2]95% CI of the geometric mean

CHOICE OF ACTIVITY DATA

All tiers require information on areas of forest management practices in mangroves. Information on mangrove forest types as well as soil types can be obtained from national wetland and soil type maps (if available) or the International Soil Reference and Information Centre (www.isric.org). Mangrove distributions for most countries can be obtained from the RAMSAR web site (www.ramsar.org). When information is gathered from multiple sources, it is *good practice* to conduct crosschecks to ensure complete and consistent representation and avoid omissions and double-counting.

Tier 1

For Tier 1, these data can be obtained from one of the following sources[3]:

FAOSTAT http://faostat.fao.org/

Global Mangrove Database & Information System: http://www.glomis.com/

The UNESCO Mangrove Programme: http://www.unesco.org/csi/intro/mangrove.htm

Mangrove and the Ramsar Convention: http://www.ramsar.org/types_mangroves.htm

USGS Global Mangrove Project http://lca.usgs.gov/lca/globalmangrove/index.php

Mangrove.org: http://mangrove.org/

Mangrove Action Project: http://www.mangroveactionproject.org/

FAO Mangrove Management: http://www.fao.org/forestry/mangrove/en/

USGS National Wetlands Research Center: http://www.nwrc.usgs.gov/index.html

World Atlas of Mangrove: http://data.unep-wcmc.org/datasets/22

World Distribution of Coral Reefs and Mangroves: http://www.unep-wcmc.org

For Tier 1 estimation, FAO data sources can be used to estimate wood removal and fuelwood removal. Further sources of activity data can be found in the relevant sections of Volume 4 of the *2006 IPCC Guidelines*. Additional resources can be found in IPCC (2010).

Global mangrove cover has been mapped by the United States Geological Service (USGS) for three epochs "1975" (1973-1983), "1990" (1989 – 1993), and "2000" (1997 -2000) and is available for download at http://edcintl.cr.usgs.gov/ip/mangrove/download.php. Global distribution of Mangroves (V3.0, 1997) has been compiled by UNEP World Conservation Monitoring Centre (UNEP-WCMC) in collaboration with the International Society for Mangrove Ecosystems (ISME).

The Kyoto & Carbon Initiative of the Japan Aerospace Exploration Agency (JAXA) Global Mangrove Watch project has used Synthetic Aperture Radar mosaics to create maps of global mangrove extent for the years 1995 and 2007-2010 (JAXA 2010a) and maps of annual changes in mangrove areas between the years 1995-2007, 2007-2008, 2008-2009 and 2009-2010. (http://www.eorc.jaxa.jp/ALOS/en/kyoto/mangrovewatch.htm).

Resources providing recent trends in coastal wetland area can help countries understand circumstances of those trends and what management activities contribute to them (FAO, 2007; Green and Short, 2003; http://archive.org/stream/worldatlasofseag03gree#page/n5/mode/2up; JAXA, 2010b; Sifleet *et al.*, 2011; http://nicholasinstitute.duke.edu/publications?topics=34; Fatoyinbo and Simard, 2013).

Sources providing international data can be verified, validated and updated data with national sources.

[3]If these links do not work, either paste into your browser or do a web search for the resources or institution.

Tiers 2 and 3

At Tiers 2 and 3, country-specific activity data is applied, and at Tier 3, at the resolution required for Tier 3 methods. At higher tiers, these data may be obtained from local, state or regional government department websites as many countries and regional government authorities report this information. Countries also have their own remote sensing systems which can be used for land change mapping (Nasciemto *et al.*, 2013) Wood density values (Annex 4A.3) of specific species need to be applied at Tiers 2 and 3. Areas of extensive harvesting of mangroves may be assessed with aerial imagery. When the ALOS-2 satellite is operational, generation of annual radar mosaics and mangrove extent and change maps is planned (http://www.eorc.jaxa.jp/ALOS/en/kyoto/mangrovewatch.htm).

UNCERTAINTY ASSESSMENT

The major sources of uncertainty for all wetland types, especially mangroves, are dominant species-specific differences in carbon content and differences due to forest age, species composition, intertidal location, soil fertility and community structure. The confidence intervals presented in Tables 4.2 - 4.6, range from about 24% to 200%. To reduce uncertainty, countries are encouraged to develop country- or region-specific BEFs and BCEF values. In case country- or region-specific values are unavailable, it is *good practice* to check the sources of default parameters and their correspondence with species present, as well as with the conditions in country.

The causes of variation of annual increment of mangrove growth include climate, site growth conditions, and soil fertility. Artificially regenerated and managed stands are less variable than natural forests. One of the ways to improve accuracy of estimates of these wetlands includes the application of country-specific or regional estimates of growth stratified by the dominant species present. If the default values of growth increments are used, the uncertainty of the estimates need to be clearly indicated and documented.

For mangroves, data on commercial fellings are relatively accurate, although they may be incomplete or biased due to illegal fellings and under-reported due to tax regulations. Traditional wood that is gathered and used directly, without being sold, is not likely to be included in any statistics. Countries must carefully consider these issues. The amount of wood removed from forests after storms and pest outbreaks varies both in time and volume. No default data can be provided on these types of losses. The uncertainties associated with these losses can be estimated from the amount of damaged wood directly withdrawn from the forest or using data on damaged wood subsequently used for commercial and other purposes. If fuelwood gathering is treated separately from fellings, the relevant uncertainties might be high, due to the level of uncertainty associated with traditional gathering.

4.2.1.2 DEAD ORGANIC MATTER

The guidance for changes in the carbon pools in dead organic matter (DOM; dead wood and litter) in mangroves provided in the *2006 IPCC Guideline* remains unchanged. Dead roots ≤2 cm diameter are included in the soil pool and not considered within the dead organic matter pool. This fraction of dead roots turns over rapidly (Alongi, 2009) with the assumption of approximating steady state. Dead organic matter C stocks can vary depending on tidal inundation and frequency, as well as soil oxidation and vegetation cover. Fine litter can be exported with tidal activity (Alongi, 2009) while a larger fraction of senesced woody biomass is buried or decomposed *in-situ*. In wetlands, decomposition of DOM, especially wood, is slow (Robertson and Daniel, 1989) and accumulates as soil organic matter. Careful consideration of pools is needed in estimating inputs, outputs or changes of dead organic matter carbon stocks to avoid double-counting. Consistent with the *2006 IPCC Guidelines*, it is *good practice* to consider dead organic matter carbon stock changes when management activities in coastal wetlands result in changes in mangrove cover due to human-induced impacts.

CHOICE OF METHOD

Tier 1

If the land (1) satisfies a country's definition of forest or (2) is a mangrove wetland with trees, that nonetheless does not meet the national definition of forest, and is managed for forest activities, where no land-use change has occurred, guidance is provided in "Section 2.3.1.1 Land Remaining in a Land-Use Category" and in the specific guidance in Volume 4, of the *IPCC 2006 Guidelines* and applied using the default data provided in this chapter (Table 4.7) and specific guidance below. Examples may include Forest land to Forest land, Wetlands to Wetlands or Other Wetlands to Other Wetlands.

If the land (1) satisfies a country's definition of forest or (2) is a mangrove wetland with trees, and is managed for forest activities where land-use change has occurred or trees have been cleared, guidance is provided in "Section 2.3.1.2 Land Converted to a Another Land-Use Category" and in the specific guidance in the relevant chapters of Volume 4 of the *IPCC 2006 Guidelines* and applied using the default data provided in this chapter (Table 4.7) and specific guidance below.

Tier 2

Estimation methodologies for Tier 2 can follow Tier 1 methods, but apply country-specific data. The Stock-Difference method (Chapter 4, Volume 4 of the *2006 IPCC Guidelines*) could also be applied if countries have sample plot data from forest inventories for two points in time. Literature data or carbon databases may provide more feasible and cost-effective data to apply this method.

Tier 3

Loss estimates of dead wood and litter due to tidal movement (export) can also be considered (Appendix 4a.1). Tier 3 methods may further employ stratification by ecological zone or disturbance regime to reduce uncertainties. It is *good practice* to sum changes in both dead wood and litter to report changes in total dead organic matter. Additional Tier 3 guidance is provided in Chapter 4, Volume 4 of the *2006 IPCC Guidelines*.

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

Default values are provided in Table 4.7 of this supplement for use in Tier 1 assessment of emissions and removals.

Tier 2

Tier 2 methods using country-specific data can be used if such country-specific data can be acquired at reasonable cost.

Tier 3

Tier 3 emission factors include model output and validation and disaggregated data sources. Field measurements can be developed and used to inform and validate model output at Tier 3. For mangroves, Tier 3 methodologies can employ empirical relationships to provide estimates of canopy litter fall and census of downed wood lying on the forest floor.

TABLE 4.7
TIER 1 DEFAULT VALUES FOR LITTER AND DEAD WOOD CARBON STOCKS IN MANGROVES

Domain	Ecosystem type	Litter C stocks of mature stands (tonnes C ha^{-1}) with 95% CI[1]	Dead wood C stocks of mature stands (tonnes C ha^{-1}) with 95% CI[1]
Tropical/Subtropical	mangroves	0.7 (0-1.3)	10.7 (6.5-14.8)

Litter: Utrera-Lopez and Moreno-Casasola, 2008; Liao *et al.,* 1990; Chen *et al.,* 2008; Richards *et al.,* 2011; Ramose-Silva *et al.,* 2007; Twilley *et al.,* 1986

Dead Wood: Kauffman *et al.,* 2011; Donato *et al.,* 2012; Allen *et al.,* 2000; Steinke *et al.,* 1995; Robertson *et al.,* 1989; Tam *et al.,* 1995; Krauss *et al.,* 2005

[1]95% CI of the geometric mean

CHOICE OF ACTIVITY DATA

Tier 1

Carbon stock changes in dead organic matter are generally not reported at Tier 1 when management activities in coastal wetlands do not result in changes in mangrove cover due to human-induced impacts (following guidance in Section 4.2.2.3 of Chapter 4, Volume 4 of the *2006 IPCC Guidelines*), and thus no activity data are required. If a land-use change has occurred resulting from an increase in woody biomass stock, it is *good practice* to report the change in dead organic matter carbon stock. For a Tier 1 method, the annual rate of conversion to Forest Land or other land-use categories with woody mangrove biomass is required, following Section 4.3.2.3 of Chapter 4, Volume 4 of the *2006 IPCC Guidelines*. Activity data should be consistent with those used for estimating changes in carbon stock.

Tier 2 and Tier 3

Inventories using higher tiers will require more comprehensive information on the establishment of new forests, using climate, for example, as a disaggregating factor and at higher spatial and temporal resolution. Additional resources can be found in IPCC (2010).

UNCERTAINTY ASSESSMENT

The uncertainty assessment given in section 4.2.2.5 in Chapter 4, Volume 4 of the *2006 IPCC Guidelines* identifies sources of uncertainty in estimates of carbon stock changes in the dead organic matter pool of mangroves. Other sources of uncertainty include output of dead organic matter due to decomposition or tidal export.

4.2.1.3 SOIL CARBON

The Tier 1 default assumption is that soil CO_2 emissions and removals are zero (EF=0) for forest management practices in mangroves. This assumption can be modified at higher tiers. At higher tiers, it is recommended to consider CO_2 emissions from soils due to forest clearing in carbon stock estimations (Alongi *et al*., 1998). It should also be considered that at Tier 1, rewetting (section 4.2.3) and drainage activities (section 4.2.4) can occur as a result of forest management practices. In this case, follow the guidance for estimating CO_2 emissions and removals from soil carbon stock changes (Sections 4.2.3.3 and 4.2.4.3, respectively).

4.2.2 Extraction

Extraction refers collectively to the following activities: (A) excavation (associated with dredging used to provide soil for raising the elevation of land, or excavation to enable port, harbour and marina construction and filling), (B) construction of aquaculture ponds and (C) construction of salt production ponds (where soil is excavated to build berms where water is held in ponds). Each of these extraction activities is associated with the removal of biomass, dead organic matter and soil, which results in significant emissions when their removal is from saturated (water-logged) to unsaturated (aerobic) conditions (World Bank, 2006). The Tier 1 methodology assumes that the biomass, dead organic matter and soil are all removed and disposed of under aerobic conditions where all carbon in these pools is emitted as CO_2 during the year of the extraction with no subsequent changes. Tier 1 guidance is given here for reporting the intial changes in carbon (Table 4.1). Regardless of whether the extraction activities result in a change in land-use category, CO_2 emissions and removals associated with extraction are the same, following Equation 4.2 below. This approach follows the methodology applied for peat extraction in Chapter 7, Volume 4 of the *2006 IPCC Guidelines*.

EQUATION 4.2
TIER 1 ESTIMATION OF INITIAL CHANGE IN CARBON STOCKS WITH EXTRACTION (ALL C POOLS)

$$\Delta C_{EXT} = \Delta C_{excav} + \Delta C_{aq\text{-}constr} + \Delta C_{sp\text{-}constr}$$

Where:

ΔC_{EXT} = Changes in carbon stocks from all extraction activities; tonnes C

ΔC_{excav} = Initial change in biomass, dead organic matter and soil carbon stocks from extraction due to excavation; tonnes C

$\Delta C_{aq\text{-}constr}$ = Initial change in biomass, dead organic matter and soil carbon stocks from extraction during construction of aquaculture ponds; tonnes C

$\Delta C_{sp\text{-}constr}$ = Initial change in biomass, dead organic matter and soil carbon stocks from extraction during construction of salt production ponds; tonnes C

Equation 4.2 is applied to the total area of coastal wetland where extraction activities take place. The terms ΔC_{excav}, $\Delta C_{aq\text{-}constr}$, and $\Delta C_{sp\text{-}constr}$ are estimated as $\Delta C_{CONVERSION}$ (Equations 4.4 - 4.6) for intial change in carbon stocks of each of the C pools for each of the respective activities comprising extraction. Equation 4.3 is applied for each of the extraction activities (and A-C as described above) to estimate the intial change in stocks of each of the C pools.

EQUATION 4.3
INITIAL CHANGE IN CARBON STOCKS WITH EXCAVATION (ALL C POOLS)

$$\Delta C_{excav} = \Delta C_{excav\text{-}AB} + \Delta C_{excav\text{-}BB} + \Delta C_{excav\text{-}DOM} + \Delta C_{excav\text{-}SO}$$

Where:

ΔC_{excav} = Initial change in biomass, dead organic matter and soil carbon stocks with excavation; tonnes C

$\Delta C_{excav\text{-}AB}$ = Initial change in above-ground biomass carbon stock changes with excavation; tonnes C

$\Delta C_{excav\text{-}BB}$ = Initial change in below-ground biomass carbon stock changes with excavation; tonnes C

$\Delta C_{excav\text{-}DOM}$ = Initial change in dead organic matter carbon stock changes with excavation; tonnes C

$\Delta C_{excav\text{-}SO}$ = Initial change in soil carbon stock changes with excavation as annual CO_2 emissions and removals; tonnes C

At Tier 1,

$\Delta C_{excav\text{-}AB} + \Delta C_{excav\text{-}BB} = \Delta C_{B\text{-}CONVERSION}$ (Equation 4.4, Section 4.2.2.1)

$\Delta C_{excav\text{-}DOM} = \Delta C_{DOM\text{-}CONVERSION}$ (Equation 4.5, Section 4.2.2.2)

$\Delta C_{excav\text{-}SO} = \Delta C_{SO\text{-}CONVERSION}$ (Equation 4.6, Section 4.2.2.3)

Equation 4.3 provides the formulation to estimate the initial change in carbon stock in each C pool for the specific extraction activity, excavation. To estimate the initial changes in intial carbon stock change for these pools for construction of aquaculture and salt production ponds, replace ΔC_{excav} with $\Delta C_{aq\text{-}constr}$ and $\Delta C_{sp\text{-}constr}$ in Equation 4.3, respectively.

The Tier 1 methodology assumes that the biomass, dead organic matter and soil are all removed and disposed of under aerobic conditions where all carbon in these pools is emitted as CO_2 during the year of extraction (consistent with the assumption applied for peat extraction in Section 7.2.1.1, Chapter 7, Volume 4 of the *2006 IPCC Guidelines*) and that no subsequent changes occur.

Table 4.8 summarises the Tier level guidance provided for extraction activities, which deals with excavation in general and excavation during the construction phase of aquaculture and salt production, in particular. Estimates are not made at Tier 1 for CO_2 emissions and removals while (1) fish ponds are stocked and salt production is occuring (use phase of aquaculture and salt production) or (2) when the activity has ceased (discontinued phase), although they are considered together with other extraction activities because the activity data are linked.

TABLE 4.8
SUMMARY OF TIER 1 ESTIMATION OF INITIAL CHANGES IN CARBON POOLS FOR EXTRACTION ACTIVITIES

			C pools			
			Mangrove biomass, dead wood and litter[1]	Soils		
				Mangrove and Tidal Marsh		Seagrass Meadow
				Organic	Mineral	Mineral[2]
Extraction activities	Excavation		Tier 1	Tier 1	Tier 1	Tier 1
	Aquaculture and Salt Production	Construction	Tier 1	Tier 1	Tier 1	NA[3]
		Use	No guidance[4]			
		Discontinued	No guidance[4]			

[1]Removal of biomass resulting from extraction activities is estimated at Tier 1 level in mangroves only.
[2]Tier 1 assumption is that all seagrass soils are mineral.
[3]Extraction activity of aquaculture pond construction, is not applicable for seagrass meadows.
[4]No suitable Tier 1 methodologies are available for C pools during these phases/activities.

4.2.2.1 BIOMASS

This section addresses estimation of changes in living (above and below-ground) biomass pools associated with extraction activities comprising excavation, and construction of aquaculture and salt production ponds in coastal wetlands. For extraction in coastal wetlands with tidal marshes and seagrass meadows, changes in biomass carbon stocks are reported at only Tier 2 or higher estimations. It is *good practice* to report the conversion of above-ground and below-ground biomass that occurs with extraction of mangroves.

CHOICE OF METHOD

Following Box 4.1 extraction may or may not result in a change in land-use category, however the same methodologies apply for mangrove wetlands with forest regardless of how the land is classified.

Tier 1

Changes in carbon stock of living biomass during extraction are associated with clearing and removal of vegetation. The area applied is that of a certain year in which the conversion occurs. Regardless of the land-use category, the loss in biomass associated with extraction activities is estimated as $\Delta C_{conversion}$ following the methodology for peat extraction (Chapter 7, Volume 4 of the *2006 IPCC Guidelines*), modified here as Equation 4.4.

EQUATION 4.4
TIER 1 ESTIMATION OF INITIAL CHANGE IN BIOMASS CARBON STOCKS DUE TO EXTRACTION ACTIVITIES

$$\Delta C_{B\text{-}CONVERSION} = \sum_{v,c} \{B_{AFTER} \bullet (1+R) - B_{BEFORE} * (1+R)\} \bullet CF \bullet A_{CONVERTED\,v,c}$$

Where:

$\Delta C_{B\text{-}CONVERSION}$ = Changes in biomass carbon stock from conversion due to extraction activities; tonnes C

B_{AFTER} = Carbon stock in above-ground biomass per unit of area immediately after the conversion by vegetation type (v) and climate (c); tonnes d.m. ha^{-1}; default value = 0

B_{BEFORE} = Carbon stock in above-ground biomass per unit of area immediately before the conversion; tonnes d.m. ha^{-1}

R = ratio of below-ground biomass to above-ground biomass by vegetation type (v) and climate (c); tonnes d.m. below-ground biomass (tonnes d.m. above ground biomass)$^{-1}$

CF = carbon fraction of dry matter; tonnes C (tonnes d.m.)$^{-1}$

$A_{CONVERTED}$ = Area of conversion by vegetation type (v) and climate (c); ha

The Tier 1 methodology assumes that the biomass is removed and disposed of under aerobic conditions where all carbon is emitted as CO_2 during the year of the extraction and that no subsequent changes occur. At Tier 1, initial change in carbon stocks of biomass $\{B_{AFTER} \bullet (1+R) - B_{BEFORE} \bullet (1+R)\}$ is assumed to be zero for coastal wetlands without perennial biomass or trees. For mangrove wetlands with perennial biomass or trees, the stock after the conversion (B_{AFTER}) at Tier 1 is taken to be zero.

Tier 2

At Tier 2, changes of carbon stock in living above-ground biomass of tidal marsh and seagrass meadow vegetation can be estimated and reported for the specified activities employing the equation for $\Delta C_{B\text{-}CONVERSION}$, using country-specific emission factors and default values for R given in Tables 4.9 and 4.10, in conjunction with country-specific data on above-ground biomass. At Tier 2, the Gain-Loss or Stock-Difference methods can be applied to estimate biomass carbon stock changes of mangrove in lands where extraction activities (aquaculture and salt production) are discontinued (i.e. regrowth). Tier 2 approaches could also include evaluation of the assumption of instantaneous oxidation of the converted biomass pool.

Tier 3

In Tier 3, estimation could include methods to incorporate data on the fraction of biomass carbon stock that is retained under saturated conditions to improve estimation of proportion of carbon that is oxidized.

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

Default data for Tier 1 method is provided for mangroves in Tables 4.2-4.6, Section 4.2.1, including above-ground biomass carbon stock, carbon fraction and below-ground to above-ground ratio, for the different climate domains and regions, where applicable.

Tier 2

Under Tier 2, countries apply country-specific data to estimate changes in carbon stock in above-ground biomass. The conversion of above-ground and below-ground biomass that occurs with extraction activities in tidal marsh and seagrass meadows may be estimated using Tables 4.9 and 4.10 for tidal marshes and seagrass meadows respectively. These data are to be used in conjunction with the carbon fraction of dry matter alongside country-specific data on above-ground biomass carbon stock.

Tier 3

Field measurements can be developed and used to inform and validate model output at Tier 3. It is expected that data improvements for excavation activities such as ground-truth estimates of overall area impacted, the depth at which removal of biomass has occurred, or the fraction of biomass removal, could be used to develop and verify models.

TABLE 4.9 **RATIO OF BELOW-GROUND BIOMASS TO ABOVE-GROUND BIOMASS (R) FOR TIDAL MARSHES**				
Domain	**R** **[tonne root d.m. (tonne shoot d.m.)$^{-1}$]**	**95% CI[5]**	**Range**	**n**
Mediterranean	3.63[1]	3.56, 3.70	1.09-7.15	5
Subtropical	3.65[2]	3.56, 3.74	2.23-9.41	5
Temperate freshwater tidal	1.15[3]	1.12, 1.18	0.36-3.85	7
Temperate	2.11[4]	2.07, 2.15	0.33-10.15	17

[1]Sources: Scarton *et al*., 2002; Neves *et al*., 2007; Boyer *et al*., 2000

[2]Sources: Lichacz *et al*., 1984; da Cunha Lana *et al*., 1991

[3]Sources: Birch and Cooley, 1982; Whigham *et al*., 1978

[4]Sources: Kistritz *et al.,* 1983; Hussey and Long, 1982; Smith *et al*., 1979; Dunn, 1981; Connor and Chmura, 2000; Gross *et al*., 1991; Whigham *et al*., 1978; Elsey-Quirk *et al*., 2011; Adams *et al*., 2012

[5]95% CI of the geometric mean

TABLE 4.10 **RATIO OF BELOW-GROUND BIOMASS TO ABOVE-GROUND BIOMASS (R) FOR SEAGRASS MEADOWS**				
Domain	**R** **[tonne root d.m. (tonne shoot d.m.)$^{-1}$]**	**95% CI[4]**	**Range**	**n**
Tropical	1.7[1]	1.5, 1.9	0.05-25.62	396
Subtropical	2.4[2]	2.3, 2.6	0.07-16.8	391
Temperate	1.3[3]	1.1, 1.5	0.14-13.8	91

[1]Sources: Aioi and Pollard, 1993; Brouns, 1985; Brouns, 1987; Coles *et al*., 1993; Daby, 2003; Devereux *et al*., 2011; Fourqurean *et al*., 2012; Halun *et al*., 2002; Holmer *et al*., 2001; Ismail, 1993; Lee, 1997; Lindeboom and Sandee, 1989; McKenzie, 1994; Mellors *et al*., 2002; Moriarty *et al*., 1990; Nienhuis *et al*., 1989; Ogden and Ogden, 1982; Paynter *et al.,* 2001; Poovachiranon and Chansang, 1994; Povidisa *et al*., 2009; Rasheed, 1999; Udy *et al*., 1999; van Lent *et al*., 1991; van Tussenbroek, 1998; Vermaat *et al*., 1993; Vermaat *et al*., 1995; Williams, 1987

[2]Sources: Aioi, 1980; Aioi *et al*., 1981; Asmus *et al*., 2000; Bandeira, 2002; Boon, 1986; Brun *et al.,* 2009; Collier *et al*., 2009; de Boer, 2000; Devereux *et al*., 2011; Dixon and Leverone, 1995; Dos Santos *et al*., 2012; Dunton, 1996; Fourqurean *et al*., 2012; Hackney, 2003; Herbert and Fourqurean, 2008; Herbert and Fourqurean, 2009; Holmer and Kendrick, 2012; Jensen and Bell, 2001; Kim *et al*., 2012; Kirkman and Reid, 1979; Kowalski *et al*., 2009; Larkum *et al*., 1984; Lee *et al*., 2005; Lee *et al*., 2005b; Lipkin, 1979; Longstaff *et al*.,1999; Masini *et al*., 2001; McGlathery *et al*., 2012; McMahan, 1968; Meling-Lopez and Ibarra-Obando, 1999; Mukai *et al*., 1979; Paling and McComb, 2000; Park *et al*., 2011; Powell, 1989; Preen, 1995; Schwarz *et al*., 2006; Stevensen, 1988; Townsend and Fonseca, 1998; Udy and Dennison, 1997; van Houte-Howes *et al*., 2004; van Lent *et al*., 1991; van Tussenbroek, 1998; Walker, 1985; West and Larkum, 1979; Yarbro and Carlson, 2008

[3]Sources: Agostini *et al*., 2003; Cebrian *et al*., 2000; Fourqurean *et al*., 2012; Hebert *et al*., 2007; Holmer and Kendrick, 2012; Larned, 2003; Lebreton *et al*., 2009; Lillebo *et al*., 2006; Marba and Duarte, 2001; McRoy, 1974; Olesen and Sand-Jensen, 1994; Rismondo *et al*., 1997; Sand-Jensen and Borum, 1983; Terrados *et al*., 2006

[4]95% CI of the geometric mean

CHOICE OF ACTIVITY DATA

Extraction: Submissions of licenses for prospecting and exploitation and associated environmental impact assessments (EIAs) can be used to obtain areas under extraction activities. Relevant regulation for extraction can be found at international and national levels. International regulation is covered by the UN Convention on the Law of the Sea (UNCLOS) 1982 (www.un/org/Depts/los/index.htm). Contracting Parties are under the obligation to publish/communicate reports on monitoring and assessment of potential harmful effects of extraction. The OSPAR Convention 1992 (www.ospar.org) provides guidance for programmes and measures for the control of the human activities in the North-East Atlantic region. The "Agreement on Sand and Gravel Extraction" provides that authorisation for extraction of marine soils from any ecologically sensitive site should be granted after consideration of an EIA. The Helsinki Convention 1992 (www.helcom.fi) covers the Baltic Sea Area and requires EIAs to be carried out as part of the extraction process and that "monitoring data" and "results of EIA's………be made available for scientific evaluation". The Barcelona Convention 1995 (www.unepmap.org), covers the regulatory framework for the Mediterranean. The ICES Convention 1964 (www.ices.dk) provides data handling services to OSPAT and Helsinki Commissions. An overview of the regulation of marine aggregate operations in some European Union Member States is reported in Radzevicius et al. (2010) and includes relevant EC Directives and national legislation/regulation. Other such sources of activity data include, for example, statistics on sand and gravel extraction for the OSPAR martime area (e.g. www.ospar.org/documents/dbase/publications/p0043) as well as information on sand and gravel activities and related statistics for North Sea Continental Shelfs and UK waters (http://www.sandandgravel.com/).

If time series data back to 1990 are unavailable, it is suggested that surrogate data be used, derived from statistical reports/databases containing information on temporal changes in proxy factors such as human population density, port or marina development, port revenue, shipping tonnage, and commodity exports. Such data can be obtained from the internet e.g. for the Asia-Pacific region from the UN ESCAP Commission (http://www. unescap.org/stat/) and for the Baltic from http://epp.eurostat.ec.europa.eu/portal/page/portal/statistics/themes. Data on shipping indices can be obtained from http://www.worldshipping.org/about-the-industry/global trade/trade-statistics. Such data for most countries can also be obtained from http://datacatalog.worldbank.org.

Aquaculture and salt production: Annual data (1950 – present) providing statistics on aquaculture production is collated by the FAO Fisheries and Aquaculture Department. Additional data on type aquaculture (e.g. freshwater or brackish) and area under aquaculture production is summarised in country profiles enabling stratification of aquaculture into those occurring in coastal wetlands (http://www.fao.org/fishery/countryprofiles/search/en). As local regulations typically apply for developing new aquaculture activites (i.e licensing, permitting), regulations also typically apply to report such activities to the Ministry of Fisheries and Marine Affairs (or country equivalent). For example an aquaculture farm needs to get a license (or permission) to operate. Depending on the country, it is given by the regional (e.g. in Spain it is the autonomic, e.g. Balearic- government, who approves it) or local (e.g. at Bolinao, The Philipines) and maybe in others the national government. For example, in Indonesia local government must be consulted on land-use change including aquaculture pond construction and are obliged to report activities to the Ministry of Fisheries and Marine Affairs.

Similar project information for salt production activities can be obtained from the Salt Institute at www.saltinstitute.org.

Literature sources can also provide national area change statistics from aerial photographs of ponds or structures used for aquaculture and salt production.

A map of available tidal marsh distribution (with area data) is in production by the World Conservation and Monitoring Center (WCMC; http://data.unep-wcmc.org/) currently holding layers for Europe, the United States, Australia and China. It is the intent to expand mapping of tidal marsh to global coverage.

A map of global distribution of seagrasses (V2.0, 2005) is also available at the WCMC (http://data.unep-wcmc.org/) and prepared in collaboration with Dr. Frederick T. Short. Other regional and national maps are also available (e.g. http://www.ospar.org/documents/dbase/publications/p00426_zostera_beds). A tabulated list of web sites for existing seagrass monitoring programmes is given in Borum *et al.*, (2000; http://www.seagrasses.org/handbook/european_seagrasses_high.pdf).

These data sources, and those provided in Section 4.2.1.1, can be used in conjunction with activity data described above to improve estimations of areas of mangroves, tidal marsh and seagrass meadow undergoing extraction activities.

UNCERTAINTY ASSESSMENT

For uncertainty assessment for mangroves, see Section 4.2.1 (this chapter). The uncertainties involved in extraction in mangroves also follow those outlined in Section 4.3.1.5 of Chapter 4, Volume 4 of the *2006 IPCC Guidelines*. Variability in tidal marsh biomass will be due to differences in dominant species and competition between species, as well as salinity of flood waters, frequency of tidal flooding and climate. For example, the high biomass in mediterranean climates is due to the frequent dominance of perennial shrubs. For all vegetation there can be considerable interannual variability in production of biomass and seasonal variability in standing biomass that contributes to uncertainty in ratios of below-ground to above-ground biomass. Most empirical data are available from temperate regions and North America and there are limited data available for tidal freshwater and boreal and subtropical tidal marshes. The average ratio of below-ground to above-ground biomass for seagrass is variable depending on the dominant species, and fertility of the soil. The data are mainly derived from observations along the coasts of North America, Western Europe and Australia. Data were scarce from South America and Africa.

4.2.2.2 DEAD ORGANIC MATTER

Previously saturated dead organic matter (DOM), which is exposed to aerobic conditions, can contribute to large sources of CO_2 emissions from extraction activities. Consistent with the *2006 IPCC Guidelines* for Forest Land, in coastal wetlands, it is *good practice* to consider dead organic matter carbon stock changes when extraction activities result in changes in mangrove cover due to these human-induced impacts.

CHOICE OF METHOD

Tier 1

During extraction activities, existing dead organic matter pools may be reduced to zero as vegetation is cleared and removed while at the same time no new carbon enters the dead organic matter pool. At Tier 1, changes in carbon stock in dead organic matter in tidal marshes and seagrass meadows are assumed to be zero. It is noted, however, that extraction activities that result in vegetation or soil disturbance in tidal marsh with perennial woody biomass may have significant impacts on CO_2 emissions and removals. It is *good practice* for country-specific methods to be developed to cover these cases, if feasible. Regardless of the land-use category, the loss in dead organic matter associated with extraction activities is estimated as $\Delta C_{conversion}$ following the methodology applied for peat extraction (Chapter 7, Volume 4 of the *2006 IPCC Guidelines*), modified here as Equation 4.5:

EQUATION 4.5
TIER 1 ESTIMATION OF INITIAL CHANGE IN DEAD ORGANIC MATTER CARBON STOCKS DUE TO EXTRACTION ACTIVITIES

$$\Delta C_{DOM\text{-}CONVERSION} = \sum_v (DOM_{AFTER} - DOM_{BEFORE})_v \bullet A_{CONVERTEDv}$$

Where:

$\Delta C_{DOM\text{-}CONVERSION}$ = Initial changes in dead organic matter carbon stock from conversion due to extraction activities by vegetation type (v); tonnes C

DOM_{AFTER} = Carbon stock in dead organic matter per unit of area immediately after the conversion by vegetation type (v); tonnes d.m. ha^{-1}; default value = 0

DOM_{BEFORE} = Carbon stock in dead organic matter per unit of area immediately before the conversion by vegetation type (v); tonnes d.m. ha^{-1}

$A_{CONVERTED}$ = Area of conversion by vegetation type (v); ha

The Tier 1 methodology assumes that the dead organic matter is removed and disposed of under aerobic conditions where all carbon is emitted as CO_2 during the year of the extraction and that no subsequent changes occur. The choice of method follows that in Section 4.2.2.

Tiers 2 and 3

The choice of method follows that in Section 4.2.2. For these management activities that impact dead organic matter pools in tidal marshes with perennial or woody biomass, Tier 2 and higher estimation methods are recommended.

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

Default values of dead organic matter carbon stock (for dead wood and litter) for mangroves are provided in Table 4.7 of this supplement for use in Tier 1 estimations. In tidal marsh and seagrass meadows the Tier 1 assumption is that carbon stocks in the dead organic matter pools resulting from extraction activities are zero.

Tier 2

At Tier 2, the assumption that all dead organic matter lost in the year of conversion is oxidized can be reassessed. Tier 2 assumption of zero for dead organic matter pools in tidal marsh can also be assessed. It is *good practice* for countries, in such cases, to use national estimates for dead organic matter carbon stocks for mangroves and tidal marshes with perennial biomass, if such country-specific data can be acquired at reasonable cost.

Tier 3

Tier 3 emission factors include model output and validation and disaggregated data sources.

CHOICE OF ACTIVITY DATA

Choice of activity data follows from guidance provided in Section 4.2.2.1. The area in which the extraction activities occur will be the same area applied for each carbon pool, especially forest biomass.

UNCERTAINTY ASSESSMENT

The discussion on uncertainty outlined in Section 4.3.2.5 of Chapter 4, Volume 4 of the *2006 IPCC Guidelines* is also relevant for extraction of mangroves.

4.2.2.3 SOIL CARBON

Extraction activities that occur within coastal wetlands can influence organic and mineral stocks of carbon in soils and both soil types are covered at Tier 1 (Table 4.11). During extraction activities, the stock of soil carbon that is removed depends on the soil type (i.e. carbon stock is higher in organic soils). For Tier 1 estimation, in the absence of soil map data or other resources to differentiate soil type, the following assumptions can be applied.

i. Assume that soils in which seagrass grow are mineral.

ii. Assume all soils, regardless of dominant vegetation in or at the mouth of estuaries or adjacent to any river characterised by a large and/or mountainous catchment and high flow, are mineral. For all other mangroves and tidal marshes the soils are organic. See Durr *et al.* (2011) for additional national level guidance.

iii. If soils cannot be dissagregated into organic and mineral, use the aggregated default data given in Table 4.11.

CHOICE OF METHOD - ORGANIC AND MINERAL SOILS

Tier 1

Regardless of the land-use category, the loss in soil carbon associated with extraction activities is estimated as $\Delta C_{conversion}$ following the methodology applied for peat extraction (Chapter 7, Volume 4 of the *2006 IPCC Guidelines*), modified here as Equation 4.6.

EQUATION 4.6
TIER 1 ESTIMATION OF INITIAL CHANGE IN SOIL CARBON STOCKS DUE TO EXTRACTION ACTIVITIES

$$\Delta C_{SO\text{-}CONVERSION} = \sum_{v,s} (SO_{AFTER} - SO_{BEFORE})_{v,s} \bullet A_{CONVERTED\,v,s}$$

Where,

$\Delta C_{SO\text{-}CONVERSION}$ = Initial changes in soil carbon stock from conversion due to extraction activities by vegetation type (v) and soil type (s); tonnes C

SO_{AFTER} = Soil carbon stock per unit of area, immediately after the conversion, by vegetation type (v) and soil type (s); tonnes C ha^{-1}; default value = 0

SO_{BEFORE} = Soil carbon stock per unit of area, immediately before the conversion, by vegetation type (v) and soil type (s); tonnes C ha^{-1}

$A_{CONVERTED}$ = Area of conversion by vegetation type (v) and soil type (s); ha

At Tier 1, soil extraction depth to 1 m approximates the mid-range of the extraction depth for construction of aquaculture and salt production ponds (see extraction activities in section 4.1). Countries may modify the assumption of 1 m extraction depth at higher tiers.

The Tier 1 methodology assumes that the soil is removed and disposed of under aerobic conditions where the carbon stock is emitted as CO_2 (oxidised) during the year of the extraction. The carbon stock is taken as all soil carbon except any refractory (unoxidisable) carbon. In mangrove soils, 4% of the carbon stock is refractory (Annex 4A.4) and this is taken to be representative of the refractory carbon in tidal marshes and seagrass meadows as well. Therefore, after the initial conversion of the soil pool in the year in which the activity occurs, CO_2 emissions are reported as zero. It is *good practice* to track these lands to consider management activities that may occur on those lands in the future and for higher tier estimations. The choice of method follows that in Section 4.2.2. For Tier 1, CO_2 emissions are reported as the conversion in soil carbon where this activity occurs; the type of vegetation and the available activity data to distinguish between organic and mineral soils determines which data are applied from Table 4.11.

Tier 2

At Tier 2, methodology can be applied to disaggregate by vegetation type and soil type. For the specific extraction activity, countries may use national data to determine their particular extraction processes and the volume of soil removed, if sufficient data are available. Because tidal marshes can occur in a range of climates, disaggregating by climate may also be applied to improve estimates if those country-specific data are available. Tier 2 may also refine the estimate for the soil carbon stock that is excavated to construct the aquaculture or salt production ponds by including country-specific information on the depth excavated during the construction phase.

Tier 3

Tier 3 methods can employ models to estimate CO_2 emissions based on the effect of temperature and salinity on soil oxidation both seasonally and with climate and vegetation type. At Tier 3, it is *good practice* for countries to validate models with field measurements. Tier 3 methods may also include site-specific measurements of, for example, carbon content, bulk density, clay content, salinity, redox potential, etc., to determine the underlying processes of emissions.

CHOICE OF EMISSION FACTORS - ORGANIC AND MINERAL SOILS

Tier 1

Default Tier 1 soil carbon stocks (to 1 m depth) for mangrove, tidal marsh and seagrass meadows for the calculation of CO_2 emissions are given in Table 4.11. These values are to be used in conjunction with Equation 4.6 to estimate emissions. If soil type is not known, a generic default value for aggregated organic and mineral soils can be applied (Table 4.11).

Tier 2

Tier 2 includes the use of country-specific emission factors that can be applied to disaggregate by soil type and vegetation type to improve on Tier 1 estimates. Country-specific data may include excavation depth to improve on the default estimation of soil extracted.

Tier 3

A Tier 3 approach could use models that take into account the time-dependent nature of the CO_2 fluxes over a range of timescales. For example, during the construction phase, a pulse of CO_2 efflux from soil directly after mangrove clearing and prior to excavation, followed by a logarithmic decline in CO_2 fluxes over time, has been shown to occur (Lovelock *et al*., 2011). For fish and shrimp ponds, the actual area excavated and the depth to which soil is excavated, could be taken into account as this varies with aquaculture and salt production practices.

CHOICE OF ACTIVITY DATA

Choice of activity data follows from guidance above provided in Section 4.2.2.1 as the area in which the extraction activities occur will be the same area applied for each C pool.

UNCERTAINTY ASSESSMENT

Variability in soil carbon stocks will derive from a number of sources. The soil stock represents global averages and may therefore under or over-estimate emissions and removals when applied to specific countries. Deriving country-specific carbon stocks can reduce uncertainties using Tier 2 methodology. There may also be significant within country differences due to: (1) the dominant species present in mangroves, tidal marshes or seagrass meadows, (2) climatic conditions and (3) general environmental setting in which the vegetation is found, all of which may influence the carbon stock. When deriving global emission factors, uncertainties can also be introduced by areas where there is greater prevalence of data from specific regions of the globe. The change in carbon stock on extraction is dependent on the value assigned to the percent refractory organic carbon. The value applied is taken from soil in mangroves and may not be fully representative of the value for tidal marshes and seagrass meadows.

TABLE 4.11 SOIL CARBON STOCKS FOR MANGROVES, TIDAL MARSHES AND SEAGRASS MEADOWS FOR EXTRACTION ACTIVITIES				
ORGANIC SOILS (TONNES C HA^{-1})				
Vegetation type	**SO_{BEFORE}**	**95% CI[1]**	**range**	**n**
Mangrove	471[2]	436, 510	216-935	43
Tidal marsh	340[3]	315, 366	221-579	35
Seagrass meadow	NA[4]			
MINERAL SOILS (TONNES C HA^{-1})				
Vegetation type	**SO_{BEFORE}**	**95% CI[1]**	**range**	**n**
Mangrove	286[5]	247, 330	55-1376	77
Tidal marsh	226[6]	202, 252	15.6-623	82
Seagrass meadow[7]	108[8]	84, 139	9.1-829	89
AGGREGATED ORGANIC AND MINERAL SOILS (TONNES C HA^{-1})				
Vegetation type	**SO_{BEFORE}**	**95% CI[1]**	**range**	**n**
Mangrove	386	351, 424	55-1376	119
Tidal marsh	255	254, 297	15.6-623	117

[1]95% CI of the geometric mean

[2]Sources: Adame *et al*., 2012; Breithaupt *et al*., 2012; Chmura *et al*., 2003; Donato *et al*., 2011; Kauffman *et al*., 2011; Osborne *et al*., 2011; Vegas-Vilarrúbia *et al*., 2010

[3]Sources: Anisfeld *et al*., 1999; Callaway *et al*., 1996; Callaway *et al*., 2012; Chmura and Hung, 2004; Craft *et al*., 1988; Craft, 2007; Hussein *et al*., 2004; Kearney and Stevenson, 1991; Orson *et al*., 1998; Markewich *et al*., 1998; McCaffrey and Thomson, 1980

[4]Seagrass meadows are assumed to be on mineral soils.

[5]Sources: Donato *et al*., 2011; Chmura *et al*., 2003; Breithaupt *et al*., 2012; Fujimoto *et al*., 1999; Adame *et al*., 2012; Perry and Mendelssohn, 2009; Ren *et al*., 2010; Kauffman *et al*., 2011; Ray *et al*., 2011; Zhang *et al*., 2012; Khan *et al*., 2007; Matsui, 1998

[6]Sources: Cahoon *et al*., 1996; Callaway *et al*., 2012; Chmura and Hung, 2004; Connor *et al*., 2001; Craft *et al*., 1988; Craft, 2007; Hatton, 1981; Kearney and Stevenson, 1991; Livesley and Andrusiak, 2012; Loomis and Craft, 2010; Morris and Jensen, 2003; Oenema and DeLaune, 1988; Patrick and DeLaune, 1990; Roman *et al*., 1997; Yu and Chmura, 2009

[7]For extraction only

[8]Source: Fourqurean *et al*., 2012

4.2.3 Rewetting, revegetation[4] and creation of mangroves, tidal marshes and seagrass meadows

This section addresses the carbon stock changes and CO_2 emissions and removals for the rewetting, revegetation and creation activities relating to mangroves, tidal marshes and seagrass meadows.

The rewetting and revegetation activity refers collectively to the following (1) rewetting, which saturates the soil of drained sites previously colonised by mangrove and tidal marshes and is a prerequisite for, and thus facilitates, reestablishment of the original vegetation by natural recolonisation, direct seeding and/or purposeful planting, (2) raising or lowering the soil elevation to facilitate reestablishment of the original vegetation by natural recolonisation, direct seeding and/or purposeful planting, (3) creation of coastal wetlands where it may be difficult to identify where they previously occurred and are in proximity to the coastal margin, and (4) reestablishment of seagrass on undrained soils by natural recolonisation, direct seeding and/or purposeful planting.

4.2.3.1 BIOMASS

The initiation of soil carbon accumulation is only possible with the presence of vegetation, which is introduced by purposeful seeding/planting or natural recolonisation For mangroves, methodological guidance for estimating

[4] The term revegetation is used to refer to practices within the framework of UNFCCC reporting.

carbon stock changes in the biomass pool, including choice of method and choice of emission and removal factors, follows Section 4.2.1.1 of this Chapter. For tidal marshes and seagrass meadows, changes in biomass carbon stocks, are reported only for Tier 2 or higher estimations. Guidance for estimating biomass carbon stock changes for tidal marshes and seagrass meadows follow those presented in Volume 4, Section 6.2.1.1 of the *2006 IPCC Guidelines* (Grassland Remaining Grassland) for Gain-Loss and Stock-Difference methods. These are used with country-specific data on above-ground biomass stocks and ratios of below-ground to above-ground biomass provided in Tables 4.9 and 4.10. Refer to Volume 4, Section 6.2.1.4 of the *2006 IPCC Guidelines* for calculation steps useful in applying these methods.

4.2.3.2 DEAD ORGANIC MATTER

For mangroves, methodological guidance for estimating carbon stock changes in the dead organic matter pool, including choice of method and choice of emission and removal factors, follows Section 4.2.1.2 of this Chapter. For tidal marshes and seagrass meadows, changes in biomass carbon stocks, are reported only for Tier 2 or higher estimations. Guidance for estimating dead organic matter carbon stock changes for tidal marshes and seagrass meadows follows that presented in Volume 4, Section 6.2.2.1 of the *2006 IPCC Guidelines* (Grassland Remaining Grassland) for Gain-Loss and Stock-Difference methods. These are used with country-specific data. Refer to Volume 4, Section 6.2.2.4 of the *2006 IPCC Guidelines* for calculation steps useful in applying these methods.

4.2.3.3 SOIL CARBON

The guidance provided in this section on soils differs from that in Chapter 3 (this supplement) because, on coastal wetland soils, revegetation leads to the accumulation of soil organic carbon when vegetation is reestablished and a CO_2 sink is then developed. The CO_2 emission factor is approximated as zero when resaturated soils are devoid of vegetation. This is consistent with the default EFs for rewetted soils for temperate and tropical regions (but not the boreal region) presented in Chapter 3 of this supplement. Based on information for natural fluxes from rewetted organic soils, it is consistent with data illustrating that rewetting effectively stops soil organic matter oxidation but does not necessarily reestablish the soil carbon sink function.

Guidance for inventories of rewetting and revegetation activities of coastal wetlands follows the assumptions at Tier 1 level of estimation that:

i. upon rewetting and revegetation of previously drained soil, creation of a mangrove or tidal marsh or on restablishment of a seagrass meadow, soil carbon accumulation is initiated when natural vegetation becomes established and

ii. the rate of soil carbon accumulation is instantaneously equivalent to that in natural settings.

Craft *et al*. (2003) found that (a) soil carbon accumulation, developed almost instantaneously with the establishment of vegetation along a chronosequence of 1- to 28-yr old constructed marshes and (b) a similar soil carbon accumulation rate over 10 years in a natural and created marsh (Craft *et al*., 2002) and over 20 years in a created mangrove (Osland *et al*., 2012). Given this equivalence, estimates of soil carbon accumulation rates in mangroves, tidal marshes and seagrass meadows (Chmura *et al*., 2003; Breithaupt *et al*., 2012; Duarte *et al*., 2013) make it possible to quantify carbon gains at sites characterised by rewetting and revegetation activities. A transition time for soil carbon stocks to become equivalent to those in natural/undrained settings with vegetation (Table 4.11) will exceed the default land-use transition time of the typically used land-use category conversions (i.e. 20 years). Instead it is suggested to apply the EF for soil carbon accumulation as long as the soil remains rewetted and vegetated, until such time as stocks are equivalent to soil carbon stocks in natural/undrained settings with vegetation (Table 4.11) or there is a change in management practice.

CHOICE OF METHOD

Changes in soil carbon resulting from rewetting, revegetation and creation activities for mangroves, tidal marshes and seagrass meadows are estimated because they represent potentially large carbon removals from the atmosphere.

Tier 1

At Tier 1, the default method, EF_{RE} values are to be used in conjunction with Equation 4.7 to estimate CO_2 emissions.

EQUATION 4.7
CO_2 EMISSIONS FROM REWETTING, REVEGETATION AND CREATION OF COASTAL WETLANDS

$$CO_{2SO\text{-}RE} = \sum_{v,s,c}(A_{RE} \bullet EF_{RE})_{v,s,c}$$

Where:

$CO_{2SO\text{-}RE}$ = CO_2 emissions associated with rewetting, revegetation and creation activities by vegetation type (v), soil type (s) and climate (c); tonnes C yr^{-1}

A_{RE} = Area of soil that has been influenced by rewetting, revegetation and creation activities by vegetation type (v), soil type (s) and climate (c); ha

EF_{RE} = CO_2 emissions from aggregated mineral and organic soils that have been influenced by rewetting and revegetation activities by vegetation type (v), soil type (s) and climate (c); tonnes C ha^{-1} yr^{-1}

EF_{RE} = 0 for rewetted and naturally saturated soils where no vegetation has been re-estabished or where re-establishment is expected to occur by recolonization.

At Tier 1, EF_{RE} is applied (Table 4.12) when vegetation has been established through replanting or reseeding. If, however, re-establishment of vegetation is expected to occur by recolonization, EF_{RE} = 0 is applied at Tier 1. It is *good practice* to document the basis on which the EF_{RE} is applied. When vegetation has been established the EF_{RE} is disaggregated with respect to vegetation type. Organic and mineral soils are not differentiated at Tier 1 within any particular vegetation type, as the organic carbon inputs mainly derive from the production of above-ground and below-ground biomass under similar conditions of soil saturation. Land area estimates should be based on land classification within the new land-use category (if applicable) to apply Tier 1 EF_{RE}.

Tier 2

Under the Tier 2 method, country-specific carbon accumulation rates could be dissagregated with respect to area of organic and mineral soils. Where such country-specific data can be acquired and used to improve estimations, disaggregation by climate zone could also be applied.

Tier 3

Under the Tier 3 method, the land use prior to rewetting, its climate and vegetation type could be taken into account. A comprehensive understanding and representation of the dynamics of CO_2 gas emission factors, based on field measurements of, for example, carbon content, bulk density, clay content, salinity, redox potential, etc., could be employed at Tier 3. A Tier 3 approach could also use empirical measurements and models that take into account the time-dependent nature of the CO_2 fluxes over a range of timescales (Morris *et al*., 2012), location relative to the low to high intertidal zone (Alongi, 2010) or other dynamics (Craft, 2007).

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

The choice of EFs at Tier 1 is applied based on the coastal wetland vegetation type being established through the rewetting, revegetation or creation activity. It is assumed that within each vegetation type, CO_2 emissions are the same regardless of how the suitable conditions for revegetation are facilitated. If vegetation is reestablished through direct reseeding or purposeful planting, apply EF_{RE} in Table 4.12. If the rewetting, revegetation or creation activity is associated with recolonization (no direct replanting or reseeding), apply EF_{RE} = 0. It is *good practice* to evaluate and document these activities (See Choice of Activity Data below) and modify what EF is applied, as appropriate. If the rewetting and revegetation activity results in patches of biomass (if coverage data are available), EF_{RE} >0 should only be applied when the mangrove, tidal marsh plant or seagrass canopy covers at least 10% of the overall area. This consideration follows the definition of forest (Table 4.2, Chapter 4, Volume 4, *2006 IPCC Guidelines).*

Tier 2

In a Tier 2 approach, country-specific emission factors for rewetting, revegetation or creation activities could be applied. The assumption of EF_{RE}=0 in areas where vegetation had not been established could also be reassessed. Country-specific emission factors could be applied based on disaggregation of organic and mineral soils and climate.

Tier 3

In a Tier 3 approach, field measurement of soil organic carbon content and CO_2 emissions from areas where rewetting and revegetation activities occur could be used to develop an empirical relationship (for example, a simple regression equation) that can be used across other sites where rewetting and revegetation activities occur within a particular area or country. Country-specific values can be developed to model possible time-dependent changes in CO_2 emissions. Soil carbon accumulation rates will likely change, as vegetation grows and biomass matures. Increased inundation and soil saturation, as a result of intertidal location in tidal marshes and mangroves, will accelerate development of soil characteristics of revegetated soils. Thus, rates of CO_2 emissions in these tidal wetlands will vary in relation to a combination of these factors and consideration of them would result in more accurate estimation of CO_2 emissions.

TABLE 4.12
ANNUAL EMISSION FACTORS ASSOCIATED WITH REWETTING (EF_{RE}) ON AGGREGATED ORGANIC AND MINERAL SOILS (TONNES C HA^{-1} YR^{-1}) AT INITIATION OF VEGETATION REESTABLISHMENT

Ecosystem	EF_{REWET}[1]	95% CI[5]	range	n
Mangrove	-1.62[2]	1.3, 2.0	0.10-10.2	69
Tidal marsh	-0.91[3]	0.7, 1.1	0.05-4.65	66
Seagrass meadow	-0.43[4]	0.2, 0.7	0.09-1.12	6

[1]Negative values indicate removal (i.e. accumulation) of C

[2]Sources: Breithaupt *et al*., 2012; Chmura *et al*., 2003; Fujimoto *et al*., 1999; Ren *et al*., 2010

[3]Sources: Anisfeld *et al.,* 1999; Cahoon *et al*., 1996; Callaway *et al.,* 1996; Callaway *et al.,* 1997; Callaway *et al.,* 1998; Callaway *et al.,* 1999; Callaway *et al*., 2012; Chmura and Hung, 2003; Hatton, 1981; Craft, 2007; Kearney and Stevenson, 1991; Markewich *et al*., 1998; Oenema and DeLaune, 1988; Orson *et al.,* 1998; Patrick and DeLaune,1990; Roman *et al.,* 1997

[4]Sources: Mateo and Romero, 1997; Serrano *et al*., 2012

[5]95% CI of the geometric mean

CHOICE OF ACTIVITY DATA

Historical photos and coastal wetland maps, if available at the appropriate spatial resolution, may be used to estimate the pre-restored wetland area. Information on regional wetland restoration and creation projects worldwide can be obtained from the Global Gateway to Geographic Information Systems of the FAO (www.fao.org) as well as from the websites, www.wetlands.org and www.globalrestorationnetwork.org. Within a given country, government agencies responsible for issuance of permits for restoration/creation/alteration of wetland are to be consulted for information of area data on the wetlands being considered. In addition, many countries may have a process for reporting rewetting and revegetation activities as permission is often required. For example, in Australia, the Environmental Protection Agency in Western Australia approves revegetation projects as part of their Ministerial Conditions. The Australian Government Department of Sustainability, Environment, Water, Population and Communities also directs the Federal Minister to approve or reject revegetation programs. The establishment of vegetation and/or change in areal extent can be reviewed on a five year period and assessed for accurate implementation of the appropriate soil EF. If data are lacking, expert judgement about success rates of projects implemented under similar conditions could be used for initial assessments (examples are size of project, vegetation type, tidal range, proximity to coast, climate). In general, for rewetting activities that include purposeful planting or direct reseeding, an EF_{RE} (using Table 4.12) is appropriate for Tier 1 estimation. Information on which the choice in EF is based should be documented.

UNCERTAINTY ASSESSMENT

Uncertainties in estimating CO_2 emissions and removals from rewetting, revegetation and creation of mangroves, tidal marshes and seagrass meadows largely lie in the underlying assumptions and area to which the EFs are applied. The values for EF_{REWET} in Table 4.12 represent global averages and have large uncertainties due to variability in soil carbon accumulation rate with 1) depth of the intertidal zone, 2) the dominant species type, its morphology and rate of growth, and 3) climate. The underlying assumption of EF_{RE}=0 for rewetted/saturated soils where vegetation has not been re-established may introduce uncertainty into estimates. Also, the assumption of complete areas with or without vegetation cover could introduce under- or overestimates.

4.2.4 Drainage in mangroves and tidal marshes

This section addresses the changes in carbon stock and CO_2 emissions and removals for drainage in mangroves and tidal marshes. Drainage may be accompanied by land clearing, also resulting in changes in biomass and dead organic matter pools. If burning accompanies drainage, it is *good practice* to report emissions from changes in those C pools. For methods to estimate changes in carbon stock in biomass, and for default data, refer to Section 4.2.1 of this report for guidance on mangroves and Section 4.2.2 for guidance on tidal marshes. It is important to retain information about drained coastal wetlands so that guidance in this supplement can be applied if a reversal of drainage conditions occurs.

Drainage causes soils to dry and ordinarily increases rates of organic matter decomposition, resulting in loss of soil carbon via CO_2 release (Armentano and Menges, 1986). This response varies with climate (Pozo and Colino, 1992) and locally with soil salinity and texture, and the quantity of labile organic matter available (Setia *et al.*, 2011). Activities associated with extensive lowering of the water table are often linked to the construction of drainage channels leading to CO_2 fluxes due to oxidation of DOC and POC in the water carried by drainage channels. However, there is currently not enough information to provide emission factors for DOC and POC export (see Appendix 4a.1, "Future methodological development for estimating carbon export").

4.2.4.1 BIOMASS

Methodological guidance for estimating carbon stock changes in the biomass pool, including choice of method and choice of emission and removal factors, follows Section 4.2.3.1 of this chapter. For tidal marshes, increase in biomass stocks in a single year is assumed equal to biomass losses from mortality in that same year at Tier 1.

4.2.4.2 DEAD ORGANIC MATTER

Methodological guidance for estimating carbon stock changes in the dead organic matter pool, including choice of method and choice of emission and removal factors, follows Section 4.2.3.2 of this chapter. For tidal marshes, CO_2 emissions and removals from change in biomass and dead organic matter pools are reported as zero at Tier 1.

4.2.4.3 SOIL CARBON

Annual carbon losses from drained mineral and organic soils are applied similarly for mangroves and tidal marshes (but not applicable to seagrass meadows) at Tier 1 level of estimation (Table 4.13). Data on CO_2 emissions from drainage in mangroves is limited, however, the CO_2 emission rate from drainage in tidal marshes was considered to provide an appropriate Tier 1 default emission factor. This value is also consistent with drained forest default EF presented in Chapter 2 of this supplement.

CHOICE OF METHOD

Tier 1

Guidance for inventories on drainage in coastal wetlands follows the assumptions at Tier 1 level of estimation that:

i. emissions persist as long as the soil remains drained or as long as it takes for soil carbon stocks equivalent to those in natural/undrained settings with vegetation (Table 4.11) to be oxidised and

ii. the drainage condition is characterized by full drainage (i.e. the water table has been changed to 1 m below the soil surface for organic and mineral soils), consistent with the Tier 1 approach in Chapter 2 of this supplement.

Emissions from drained coastal wetland soils are estimated at Tier 1 for mangrove forests and tidal marshes using Equation 4.8.

EQUATION 4.8
CO_2 EMISSIONS ON DRAINED ORGANIC AND MINERAL SOILS

$$CO_{2\text{-}SO\text{-}DR} = (A_{DR} \bullet EF_{DR})$$

Where:

$CO_{2\text{-}SO\text{-}DR}$ = CO_2 emissions from aggregated organic and mineral soil carbon associated with drainage; tonnes C yr^{-1}

A_{DR} = land area under drainage; ha

$EF_{DR,}$ = CO_2 emissions from organic or mineral soil carbon associated with drainage; tonnes C ha^{-1} yr^{-1}

As described above, the Tier 1 emission factor is applied until the soil carbon stock (Table 4.11) is depleted and determines the time frame for emissions due to drainage regardless of whether a land-use change occurs. Once depleted, guidance from the *2006 IPCC Guidelines* applies.

Tier 2

The Tier 2 estimation method is the same as the Tier 1 method, but national data can be used to additionally disaggregate by vegetation, soil type and regional climatic factors, if such data are available at reasonable cost.

Tier 3

Tier 3 methods could take account of differences in the management of the drained wetland. Empirical measurements of gas flux based on site-specific measurements of, for example, carbon content, bulk density, clay content, salinity, redox potential, etc., to determine the underlying processes of emissions could be included. Site differences in frequency of drainage activity could also be considered at Tier 3 methods. Other factors that could be used to apply disaggregated data include salinity and tidal export of DOC and POC (Appendix 4a.1).

CHOICE OF EMISSION/REMOVAL FACTORS

Tier 1

At Tier 1, a generic default emission factor is applied for drainage, regardless of vegetation or soil type (Table 4.13). That is, the same EF is applied regardless of the management activity involving soil drainage.

TABLE 4.13
ANNUAL EMISSION FACTORS ASSOCIATED WITH DRAINAGE (EF_{DR}) ON AGGREGATED ORGANIC AND MINERAL SOILS ($TONNES\ C\ HA^{-1}\ YR^{-1}$)

Ecosystem	EF_{DR}	95% CI[2]	Range	N
Tidal marshes and mangroves	7.9[1]	5.2, 11.8	1.2-43.9	22

[1]Sources: Camporese *et al.*, 2008; Deverel and Leighton, 2010; Hatala *et al.*, 2012; Howe *et al.*, 2009; Rojstaczer and Deverel,1993
[2]95% CI of the geometric mean

Tier 2

Tier 2 emission factors apply country-specific data disaggregated by soil type, vegetation type, and climate, where feasible. Data to address any change in emissions since initiation of drainage could additionally be implemented.

Tier 3

In a Tier 3 approach, field measurements of soil organic carbon content and CO_2 emissions from the drained site would be useful to develop an empirical relationship (for example, a simple regression equation of soil carbon content versus rate of carbon removal) that can be used across other drained sites within a particular area or country. Country-specific values can thus be developed to model possible time-dependent changes in CO_2 emissions such as changes in relation to timing and rate of soil drainage, depth of drainage and additional national information about mean annual water table and land-use type or intensity. A comprehensive understanding and representation of the dynamics of CO_2 emission factors, based on field measurements of, for example, carbon content, bulk density, clay content, salinity, redox potential, etc., could be employed at Tier 3.

CHOICE OF ACTIVITY DATA

Tier 1

The Tier 1 approach requires area data of drained land for each land-use category that have been identified in coastal wetlands. Classification systems for activity data that form the basis for a Tier 1 inventory are provided in the respective chapters of the *2006 IPCC Guidelines*. For coastal wetlands, the predominant land-use category conversion is to Cropland and Grassland.

Tier 2 and 3

Activity data for higher tier estimates are generally derived following the methods presented in Chapter 3 of the *2006 IPCC Guidelines.* To disaggregate by soil type and vegetation type, several institutions, including ISRIC and FAO have country-specific and global maps that include organic soils (http://www.fao.org/geonetwork/srv/en/main.home or http://www.isric.org/). A global consortium has been formed to make a new digital soil map of the world at fine resolution (http://www.globalsoilmap.net/).

Drainage is assumed to result in persistent emissions from soils as long as the management system remains in place. Activity data may be spatially explicit and could be disaggregated by type of management, if appropriate emissions factors are available.

The combination of land-use databases and soil maps or spatially-explicit data allow delineation of combinations of land-use categories, climate domains, and management systems and their changes over time on organic soils.

Information sources about drainage with adequate disaggregation may include that listed below.

- National land-use statistics. Land-use maps and soil maps, maps of water and nature conservation zones with restrictions for water management, wetlands.
- National water management statistics. In most countries, the agricultural land base including croplands is usually surveyed regularly, providing data on distribution of different land-uses and other aspects of management, often at sub-national, regional level. These statistics may originate, in part, from remote sensing methods, from which additional information about wetness or periods with seasonal flooding could be extracted.
- Inventory data from a statistically based, plot-sampling system of water table wells, ditches and surface waters on organic soils. Water table is monitored at specific permanent sample plots either continuously or on plots that are revisited on a regular basis. It has to be documented that the water data represent the water table in the organic soil and for what land-use and drainage stratum and that the data cover a representative period, which represents a multi-year mean annual water table.
- Water management plans and documentation from water management installations.
- Drainage maps.

UNCERTAINTY ASSESSMENT

Three broad sources of uncertainty exist in estimating emissions and removals from drainage: 1) uncertainties in land-use and environmental data; 2) uncertainties in the emission/removal factors for Tier 1 or 2 approaches; and 3) model structure/parameter error for Tier 3 model-based approaches, or measurement error/sampling variability associated with Tier 3 measurement-based inventories. In general, precision of an inventory is increased and confidence ranges are smaller with more sampling to estimate values for these categories, while accuracy is more likely to be increased through implementation of higher Tier methods that incorporate country-specific information.

For Tier 1, the default uncertainty level of emissions/removal factors is the 95% confidence interval in Table 4.13. Countries developing specific emission factors for their inventories at higher tiers should assess the uncertainty of these factors.

If using aggregate land-use area statistics for activity data (e.g. FAO data), the inventory agency may have to apply a default level of uncertainty for the land area estimates, for example. It is *good practice* for the inventory compiler to derive uncertainties from country-specific activity data instead of using a default level of uncertainty. Uncertainties in activity data may be reduced through a better national system, such as developing or extending a ground-based survey with additional sample locations and/or incorporating remote sensing to provide additional coverage. Uncertainties in activity data and emission/removal factors need to be combined using an appropriate method, such as simple error propagation equations. Details are given in Chapter 3, Volume 1 of the *2006 IPCC Guidelines* and in Chapter 5 of the *GPG-LULUCF.*

4.3 NON-CO_2 EMISSIONS

This section provides methods for estimating the emissions of CH_4 emissions from rewetted mangroves and tidal marshes and N_2O from aquaculture use.

4.3.1 CH_4 emissions from rewetted soils and created mangroves and tidal marshes

Rewetting of drained soils, through reconnection of hydrology, shifts microbial decomposition from aerobic to anaerobic conditions, increasing the potential for CH_4 emissions (Harris *et al*., 2010). In environments where low salinity also occurs (especially <5 ppt), microbial decomposition of organic matter may result in production of CH_4. However, in soils saturated with seawater, microbial reduction of sulfate to sulfide will generally occur before methanogens produce CH_4 regardless of the organic matter content. A strong inverse relationship between CH_4 emissions and salinity of mangrove soils exists (Purvaja and Ramesh, 2001). A review by Poffenbarger *et al.* (2011) showed that CH_4 emissions decrease as salinity in tidal marshes increases.

Guidance for estimating CH_4 emissions associated with rewetting land previously characterised by mangrove and tidal marsh vegetation differs from that for estimation of CO_2 emissions in that, at Tier 1 level of estimation, the EF remains the same for CH_4, regardless of extant vegetation.

4.3.1.1 CHOICE OF METHOD

TIER 1

In the case of rewetting of lands that had been previously in an agricultural (or any other drained) land-use category, the Tier 1 method estimates CH_4 emissions without considering the land-use prior to rewetting.

EQUATION 4.9
CH_4 EMISSIONS FROM REWETTED SOILS AND CREATED TIDAL MARSHES AND MANGROVES

$$CH_{4\text{-}SO\text{-}REWET} = \Sigma_v (A_{REWET} \bullet EF_{REWET})_v$$

Where:

$CH_{4\text{-}SO\text{-}REWET}$ = CH_4 emissions associated with rewetted and created coastal wetlands by vegetation type (v); kg CH_4 yr^{-1}

A_{REWET} = Area of soil that has been rewetted (including tidal marsh or mangrove wetland creation), by vegetation type (v); ha

EF_{REWET} = CH_4 emissions from mineral and organic soils that have been rewetted by vegetation type (v); kg CH_4 ha^{-1} yr^{-1}

TIER 2

At Tier 2, country-specific data can be applied. Improved estimates can be produced if country-specific data could include more disaggregation by salinity and vegetation type.

TIER 3

At Tier 3, country-specific values can be used and developed to model possible time-dependent changes in CH_4 emissions. Tier 3 methods may also consider vegetation composition and density, as plants can act as a conduit for gas exchange between the soil and atmosphere (e.g. Burdick, 1989; Purvaja and Ramesh, 2001; Kristensen *et al*., 2008).

4.3.1.2 CHOICE OF EMISSION FACTORS

TIER 1

Tier 1 CH_4 emission factors are found in Table 4.14 and should be used in conjunction with Equation 4.9 to estimate emissions taking into account vegetation type (and associated salinity level). The choice of emission factor at Tier 1 is differentiated between rewetting by freshwater and brackish water (<18ppt) and saline water (>18ppt, Annex 4A.1). Rates of CH_4 emissions approximate 0 in saline water marshes and mangroves but are greater than zero in freshwater tidal and brackish marshes and mangroves (Table 4.14). For rewetting that results in salinities >18 ppt), the Tier 1 assumption is to apply an annual CH_4 emission rate = 0. Within each vegetation type, CH_4 emissions are the same regardless of the management activity involving rewetting at Tier 1.

TIER 2

In a Tier 2 approach, country-specific CH_4 emissions are encouraged to be used and will provide better estimates based on the salinity of water used to rewet the mangrove or tidal marsh, particularly to determine CH_4 emissions from tidal brackish marshes.

TIER 3

In a Tier 3 approach, field measurements of soil salinity and CH_4 emissions from the rewetted site could be used to develop an empirical relationship (for example, a simple regression equation of salinity versus rate of methane emission) and applied across other rewetted sites within a particular area or country. Country-specific values can thus be developed to model possible time-dependent changes in CH_4 emissions such as changes in relation to frequency of tidal inundation, frequency of the rewetting activity and elevation from the water's edge. Such considerations would result in more accurate estimation of CH_4 emissions.

TABLE 4.14
EMISSION FACTORS FOR CH_4 (EF_{REWET}) FOR TIER 1 ESTIMATION OF REWETTED LAND PREVIOUSLY VEGETATED BY TIDAL MARSHES AND MANGROVES

Vegetation Type	Salinity (ppt)	EF_{REWET} (kg CH_4 ha^{-1} y^{-1})	95% CI[4]	Range
Tidal freshwater and brackish marsh and mangrove[1]	<18	193.7[2]	99.8, 358	10.95-5392
Tidal saline water marsh and mangrove[1]	>18	0[3]		0-40

[1]See Annex 4A.1 for salinity-based definitions

[2]Sources: Keller *et al*., 2013; Ma *et al*., 2012; Poffenbarger *et al*., 2011; Sotomayor *et al*., 1994; Tong *et al*., 2010

[3]Marshes and mangroves with salinities >1 ppt approximate an order of magnitude lower rates than from tidal freshwater and brackish marsh (as defined here, salinity <18ppt), so a Tier 1 assumption is to apply 0.

[4]95% CI of the geometric mean

4.3.1.3 CHOICE OF ACTIVITY DATA

To estimate emissions using CH_4 emission factors refer, in part, to the guidance for rewetting in Section 4.2.3 above. The EF should be applied to the specific type of vegetation that will be reestablished, which is associated with salinity. When salinity data are not available the type and location of rewetting may be used as a proxy for salinity. For example, breaching of sea walls and rewetting in an estuarine setting will result in rewetting with saline waters. If rewetting occurs with freshwater, a salinity of <18ppt is likely. When applying guidance for tidal freshwater marsh, it is *good practice* to determine the inland boundary for rewetting of tidal freshwater wetlands as based on national circumstances, and to consistently apply these conditions to identifying these rewetted lands. If more information is available on salinity concentrations associated with the area being rewetted, better estimates of CH_4 emissions can be determined. Information used for these assessments should be documented.

4.3.1.4 UNCERTAINTY ASSESSMENT

There have been few empirical measurements of emissions disaggregated by factors such as temperature, tidal frequency or duration of inundation, which introduce uncertainty in global default emission factors. However, higher tier approaches can take these factors into account to improve estimations. Few reports are available to give specifics of the types of rewetting activities that may vary geographically. Because activity data may be limited in terms of delineating salinity boundaries to apply more constrained CH_4 emission factors, aggregation of data to produce Tier 1 emission factors was based upon expert knowledge. There is also uncertainty in the time, depth of soil affected, and the contribution of vegetation to rate of CH_4 loss.

4.3.2 N_2O emissions during aquaculture use in mangroves, tidal marshes and seagrass meadows

The most significant activity contributing to N_2O emissions from managed coastal wetlands is aquaculture. One-third of global anthropogenic N_2O emissions are from aquatic ecosystems, and nearly 6% of anthropogenic N_2O–N emission is anticipated to result from aquaculture by 2030 at its current annual rate of growth (Hu *et al*., 2012). Shrimp and fish cultivation increases nutrient loads in culture ponds. As opposed to indirect N_2O emissions originating from activities on terrestrial lands or as wastewater treatment, coastal wetland aquaculture occurs as a direct source of N_2O from coastal wetlands, including mangroves and tidal marshes from aquaculture pond use. In seagrass meadows, this direct N_2O source arises from N added to fish cages (e.g. off-shore installations). While this differentiation should assure no double-counting, it is *good practice* to evaluate this assessment considering national circumstances. As such, this new activity fills a gap in the current reporting on direct and indirect sources of N_2O emissions. A country can exclude N_2O emissions from estimation that occur during aquaculture activities where no mangroves, tidal marsh or seagrass meadows exist (i.e. outside of coastal wetland areas).

N_2O is emitted as a by-product of the conversion of ammonia (contained in fish urea) to nitrate through nitrification and nitrate to N_2 gas through denitrification (Hu *et al*., 2012; Annex 4A.5). N_2O emissions can readily be estimated from fish production data.

4.3.2.1 CHOICE OF METHOD

TIER 1

N_2O emissions from aquaculture ponds can be estimated based on fish/shrimp production of the aquaculture activity. N_2O emission estimation follows a modified form of Equation 11.1 from Chapter 11, Volume 4 of the *2006 IPCC Guidelines* and is presented in Equation 4.10.

EQUATION 4.10
DIRECT N_2O EMISSIONS FROM AQUACULTURE USE

$$N_2O\text{-}N_{AQ} = F_F \bullet EF_F \text{ (based on fish production)}$$

Where:

$N_2O\text{-}N_{AQ}$ = annual direct N_2O-N emissions from aquaculture use; kg N_2O-N yr^{-1}

F_F = annual fish production; kg fish yr^{-1}

EF_F = emission factor for N_2O emissions from fish produced; kg N_2O-N (kg fish produced)$^{-1}$

TIER 2

Tier 2 estimation methodology follows that of Tier 1 with the added information provided by country-specific data.

TIER 3

Tier 3 estimation methodology could include the consideration of fish/shrimp type, type of feed and stocking density, category of aquaculture (fish/shrimp species or feed stuff), aquaculture use intensity, and impact of environmental factors (e.g. climate zone, season, and salinity).

4.3.2.2 CHOICE OF EMISSION FACTORS

TIER 1

Hu *et al.* (2012) used the relationship between in-coming nitrogen loads and N_2O emissions from wastewater plants to estimate that 1.8% of the N is emitted as N_2O (0.00169 kg N_2O-N is emitted per kg fish produced). The EF_F is applied during the 'in use' phase of aquaculture (Table 4.15). In the construction and discontinued phases, non-CO_2 emissions are assumed negligible with EF=0. At Tier 1, countries could consider applying this EF to other species groups under aquaculture production. Because the EF is developed for fish, wider application may introduce additional uncertainty.

TIERS 2 AND 3

Under the Tier 2 method, country specific emission factors for N_2O are applied. At Tier 2, these country-specific emission factors could incorporate a different value for the proportion of N emitted as N_2O. For Tier 3 emission factors, comprehensive understanding and representation of the dynamics based on direct field measurements or models is involved, which estimates emission factors considering the category of aquaculture (fish/shrimp species or feed stuff), aquaculture use intensity, and impact of environmental factors e.g. climate zone, season, and salinity.

TABLE 4.15
EMISSION FACTOR (EF_F) FOR N_2O EMISSION FROM AQUACULTURE USE IN MANGROVES, TIDAL MARSHES AND SEAGRASS MEADOWS

Default EF (kg N_2O-N per kg fish produced)	95% CI[1]	Reference
0.00169 kg N_2O-N per kg fish produced	0, 0.0038	Hu *et al.*, 2012

[1]95% CI of the geometric mean.

Note: Approach used by Hu *et al.* (2012) using N in feed to fish biomass: Hargreaves, 1998; Protein content of fish biomass: USDA nutrient database for Standard Reference Nutrient Data Laboratory; N content of protein: Nelson and Cox, 2013; N to N_2O conversion: Hu *et al.*, 2013; Kong *et al.*, 2013; Kampschrew *et al.*, 2008; Ahn *et al.*, 2010 (refer to Annex 4A.5)

4.3.2.3 CHOICE OF ACTIVITY DATA

Data for fish and shrimp production are needed. These data can be obtained from FAO (http://www.fao.org/fishery/statistics/global-aquaculture-production/en). For additional guidance, see Section 4.2.1.

4.3.2.4 UNCERTAINTY ASSESSMENT

Emission factors for N_2O emissions from aquaculture systems are based on protein content of fish, relationships between total nitrogen content and wet weight of fish and the percent of nitrogen load emitted as N_2O. There are no such data for shrimp production so using fish data as a proxy adds a high level of uncertainty. The fish-related factors can vary greatly, and in part on environmental conditions, so high variation can occur among fish aquaculture systems. Decreased uncertainty can be achieved at Tier 2 and 3 to reflect variability in N_2O emissions based on shrimp and fish species and type of food (pellets vs. trash fish). Uncertainties in N_2O emissions associated with stocking of aquaculture facilities can be reduced greatly by better estimation of shrimp and fish production.

4.4 COMPLETENESS, TIME SERIES CONSISTENCY, AND QUALITY ASSURANCE AND QUALITY CONTROL (QA/QC)

4.4.1 Completeness

General guidance on completeness is provided in Chapter 7 of this supplement.

4.4.2 Time series consistency

It is *good practice* that countries clearly define coastal wetlands and use this definition consistently over time.

Consistent time series require that the same methodology is used for the entire time series. Whenever new methodologies are used previous estimates should be recalculated using the new methods for all years in the time series. It is also *good practice* to report why the new estimates are regarded as more accurate or less uncertain.

One potential problem in recalculating previous estimates is that certain data sets may not be available for the earlier years. There are several ways of overcoming this limitation and they are explained in detail in Chapter 5, Volume 1 of the *2006 IPCC Guidelines*. Time series consistency is discussed further in Chapter 7.6 of the *Wetlands Supplement* and Chapter 5 (Time series consistency and recalculations), Volume 1 of the *2006 IPCC Guidelines*.

4.4.3 Quality Assurance/Quality Control (QA/QC)

Quality assurance/quality control (QA/QC) procedures should be developed and implemented as outlined in Chapter 7 of this supplement.

Annex 4A.1 Salinity-based definitions

SALINITY-BASED DEFINTIONS	
Common description	**Salinity (ppt)[1]**
Tidal fresh water	<0.5
Brackish water	0.5 - 18
Saline water	>18

[1]ppt is parts per thousand (‰) and is roughly equivalent to grams of salt per litre of water

Annex 4A.2 Estimation of above-ground mangrove biomass: higher tier methodology

Because of field conditions and heavy weight of wood, an accurate survey of a mangrove forest is difficult and time-consuming. Allometric methods (Soares and Schaeffer-Novelli, 2005; Komiyama *et al*., 2008) estimate the whole or partial weight of a tree from measurable tree dimensions, notably trunk diameter and height, using allometric relations developed from empirical measurement of weight of individual tree components (leaves, branches, stem). Use of allometric equations is favored because it is non-destructive and is therefore useful for estimating temporal changes in forest biomass by means of subsequent stem diameter measurements over subsequent years.

Up until recently, the major drawback of this method has been the site- and species-specific differences in allometric relations, necessitating the use of different allometric equations for different sites (e.g. Smith and Whelan, 2005) and, at a minimum, different species. However, a number of workers, using global datasets, have developed a common allometric equation applicable for all tropical tree species, with the most applicable equations for above-ground biomass being those developed for all tropical trees by Chave *et al*. (2005) and for all mangrove species by Komiyama *et al*. (2005):

$$W_{top} = 0.168 p DBH^{2.47} \text{ (Chave } et\ al. \text{ 2005)}$$

$$W_{top} = 0.251 p D^{2.46} \text{ (Komiyama } et\ al. \text{ 2005)}$$

where W_{top} = above-ground tree weight in kg dry weight, p = wood specific gravity, D = tree diameter, and DBH = diameter-at-breast height. The relative error of each equation varies among species, but is typically within the range of -10% to +10%. There are, of course, arguments to be made that empirical measurements should be made in all mangrove forests, considering the significant allometric differences between species and for the same species at different locations (Smith and Whelan, 2005; Soares and Schaeffler-Novelli, 2005). However, this idea is impractical for inventory compliers; a relative error of ± 10% is acceptable being within the range of error for allometric relations within a forest where biomass has been weighted.

Comparing the two equations, the Chave estimation gives lower above-ground weight estimates than that of the Komiyama equation. Presuming that a complete census of all trees, with species identified, and their diameter have been undertaken from replicate plots within a given forest, these numbers can then be used in either equation to derive individual tree weight.

Annex 4A.3 Wood density of mangrove species

WOOD DENSITY OF MANGROVE SPECIES			
Species	**n**	**Average density (tonnes m^{-3})**	**Standard error**
Brugueria gymnorrhiza	8	0.81	0.07
Xylocarpus granatum	7	0.61	0.04
Sonneratia apetala	2	0.50	0.01
Sonneratia alba	6	0.47	0.12
Rhizophora mucronata	9	0.83	0.05
Rhizophora mangle	7	0.87	0.02
Rhizophora apiculata	4	0.87	0.06
Laguncularia racemosa	3	0.60	0.01
Heritiera littoralis	6	0.84	0.05
Heritiera fomes	3	0.86	0.14
Excoecaria agallocha	7	0.41	0.02
Ceriops tagal	7	0.85	0.04
Ceriops decandra	2	0.87	0.10
Avicennia officinalis	3	0.63	0.02
Avicennia marina	6	0.62	0.06
Avicennia germinans	5	0.72	0.04
Average		**0.71**	**0.02**
Source: Global Wood Density Database http://datadryad.org/resource/doi:10.5061/dryad.234/1?show=full; Saenger, 2002; Komiyama *et al.,* 2005; Donato *et al.,* 2012			

Annex 4A.4 Percent refractory carbon

Percent refractory carbon in organic/mineral soils were estimated for mangrove soils based on either the amount of phenolic compounds/lignins in soils or % TOC in mangrove soils deeper than 1 m if there was no further decline in TOC concentration.

Percent refractory carbon applied to estimate % C oxidation for mangrove soils (% by soil dry weight)	
Mean	3.98
Median	3.4
N	16
Source: Prasad and Ramanathan, 2009; Marchand *et al.*, 2003; Dittmar and Lara, 2001; Koch *et al.,* 2011; Ranjan *et al.,* 2010; Marchand *et al.,* 2005, which is similar to that in tidal marshes (Filip *et al.*, 1988; Alberts *et al.*, 1988; Reddy and DeLaune, 2008).	

Annex 4A.5 Derivation of N_2O emission factor for aquaculture

The emission factor of 0.00169 kg N_20-N per kg fish produced in Table 4.15 is based on the following. Firstly, the protein content of fish is estimated from 80 values in various cultured fish species as 17.72 ± 2.97% (USDA nutrient database for Standard Reference Nutrient Data Laboratory). Using the protein content of fish and the average N content of protein (16%; Nelson and Cox, 2013) implies an N content of 2.84 ± 1.33% of fish biomass; i.e. one metric tonne of fish contains 2.84 x 10^4 g N. Secondly, the % N in aquaculture fish feed that is incorporated into fish biomass averages 23.22 ± 5.88% (Hargreaves, 1998). This value is based on results from four aquaculture production methods in which 18 individual estimates for the conversion of fish biomass to fish N were obtained from 11 different cultured fish species.

Following Hu *et al.* (2012; and references therein), it is assumed that all the feed is ingested by fish and the N input as ammonia to the aqueous phase to produce 1 metric tonne of fish is 12.23 x 10^4 g - 2.84 x 10^4 g = 9.39 ± 4.69 x 10^4 g. Given that on average, during N transformation in the aqueous phase, 1.8 ± 0.7% of the N is converted to N_2O (Kong *et al*., 2013; Kampschreur *et al*., 2008; Ahn *et al*., 2010; Hu *et al*., 2013), the amount of N emitted to the atmosphere as N_2O-N is 1.69 x 10^3 g. Thus the average N_2O emission factor of an aquaculture system is 1.69 g N_2O-N per kg fish or 0.00169 kg N_2O-N per kg fish produced. The uncertainty range is estimated using standard error propagation through the calculations indicated.

Appendix 4a.1 Future methodological development for estimating carbon export

The amount of dissolved and particulate carbon potentially available for export is highly variable among coastal wetlands, depending on a large number of factors such as: net primary productivity, tidal range, the ratio of wetland to watershed area, lateral trapping of tidal water, the presence of high salinity plugs in the tropical dry season, total wetland area, frequency of storms, amount of precipitation, and volume of water exchange. Each ecosystem is unique; some wetlands export DOC but import POC, others import DOC and POC but export DIC, while other systems import or export all forms of dissolved and particulate C. The direction of net exchange also usually varies within the same estuary with change in season. Emerging evidence indicates that DIC (derived from CO_2 by heterotrophic organisms and/or carbonate dissolution) is exported from coastal wetlands by the physical processes of tidal drainage of soils and subsequent advection to adjacent waterways (Alongi, 2009; Perillo *et al*., 2009). For instance, in mangroves, tidal export of respiratory-derived DIC may equate to as much as one-third of carbon fixed by the forests. However, available data are still too few to allow for generalization, and the scant data are highly variable with tidal amplitude being a major driver of soil DIC drainage.

Estimation of tidal exchange in a particular wetland is not a straightforward process. Many workers have provided rough estimates by multiplying carbon concentrations suspended in wetland creeks and waterways by the tidal range multiplied by the creek/waterway cross-sectional area. Estimates derived from such simple calculations are invalid and misleading for a number of reasons, including the inherent assumption that there are differences in carbon concentrations between ebb and flood tide stages and that the tidal prism is symmetrical. In fact, carbon concentrations in many wetland waters do not show significant differences between tides. Further, tides in most wetlands are characterized by a pronounced asymmetry between ebb and flood tides with the ebb most often being of shorter duration but with stronger current velocity than the flood tide. Also, tidal velocities vary across a waterway with faster surface current velocities mid-stream than those just above the creekbed or proximal to the wetland.

For these reasons, it is not possible to make simple generalizations regarding dissolved and particulate organic and inorganic total carbon export from mangroves, seagrasses or tidal marshes and, in fact, comparatively few such measurements have been made properly. The correct method would be to measure water volume and velocity over entire tidal cycles over several seasons in relation to position in the water-column to derive an overall annual estimate of average water flow by volume. This involves fairly complex instrument measurements and sophisticated mathematical modelling as well as extensive and expensive repetitive measurements of dissolved and particulate carbon concentrations. For mangroves, net exchange of carbon has been properly measured in only twelve systems (DIC has only been measured in four systems), with no clear exchange patterns among locations, although it does appear that most mangroves export POC as litter but with rates ranging widely from 0.1-27.7 mol C m^{-2} yr^{-1} (Alongi, 2009). This export equates globally to only about 10% of total carbon fixed by trees; respiration to the atmosphere is by far the largest loss of carbon to the atmosphere. Such appears to be the case for tidal marshes (Chmura *et al*., 2003) and subtidal seagrass beds (Fourqurean *et al*., 2012). Some recent syntheses and literature do hold promise for future development of model relationships that can be used for estimating carbon export (Adame and Lovelock 2011; Maher *et al*., 2013).

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