European Environment Agency

Carbon stocks and sequestration in terrestrial and marine ecosystems: a lever for nature restoration?

A quick scan for terrestrial and marine EUNIS habitat types

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Carbon storage in ecosystems is in the spotlight of environmental policy because of possible mitigating effects on climate change. Carbon uptake by ecosystems may lower atmospheric CO2 concentrations. A short overview is presented of carbon stocks and carbon sequestration rates in terrestrial and marine ecosystems, and possible measures impacting carbon storage. A classification is designed for carbon stocks and carbon sequestration rates which is used to classify the EUNIS habitat types. Although many studies are found presenting relevant information, methodological differences between studies hampers clear interpretation of data. Only a limited number of studies contains information on the carbon pools or carbon sequestration rates of all ecosystem components. There is an expanding literature on carbon storage showing that ecosystems play an important and irreplaceable role in cycling and storing carbon over short, medium and long timescales. Nevertheless, scientific uncertainties surrounding quantitative estimates of carbon storage within many ecosystems remain high. Measures that stimulate carbon storage may have trade-offs to other ecosystem services. Values of biodiversity and ecosystem services have to be taken into account when measures are taken to store carbon in ecosystems.

Keywords: Carbon stock, Carbon sequestration rate, Ecosystem, EUNIS habitat, marine, terrestrial

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Definitions, Acronyms and Units

Definitions

Carbon sequestration is the process of storing carbon in a carbon pool (IPCC 2019b). The rate with which the carbon is stored is referred to as the **carbon sequestration rate**. The units are in mass per time unit (e.g. Mg C yr^{-1}).

Carbon intake is the photosynthetic organisms both take in carbon for tissue growth, and have carbon output as result of their respiration. In literature no clear definition is given for carbon intake. It possibly may refer to gross primary production (GPP), which is the amount of energy fixed in phytomass by photosynthesis mostly expressed as increase in biomass. However, the amount of carbon that is fixed in organisms, is lower due to the respiration, and is called net primary production (NPP). NPP only partly supplement the ecosystem carbon pool (accumulation of net biomass and soil organic carbon) and may be 40% or less of GPP. Because there is no clear definition, we will not use this term in this report.

A **carbon pool** is a reservoir in the earth system where elements, such as carbon, reside in various chemical forms for a period of time. An example is the carbon pool living forest biomass, which is composed of various types of compounds synthesized by trees. A group of pools are linked in a cycle with flows among the pools influenced by both anthropogenic and non-anthropogenic processes. The carbon pools that are usually differentiated in terrestrial ecosystem are (above- and belowground) living biomass, dead organic matter and soil organic matter, in which flows are influenced by non-anthropogenic drivers such as plant production and microbial decomposition, as well as anthropogenic drivers such as fertilization, land use, tree harvest and product use. The units are in mass (e.g. Mg C) (IPCC 2019b).

Carbon stock is the absolute quantity of carbon held within a pool at a specified time. The units of measurement are mass.

Measuring units: To enable classification and mutual comparison, the carbon pools and carbon sequestration rates are expressed per area (respectively Mg C ha^{-1} and Mg C ha^{-1} yr^{-1}). In the water column, where the figures can be very substantial, they may be expressed as Pg C yr^{-1} (1Pg C = 10^{15} gC).

In studies many different measuring units are given. Her conversion from some widely used units is given.

Unit	Converted unit
1 ha	10,000 m^2
1 km^2	100 ha = 10^6 m^2
1 t C	1,000 kg C = 10^6 g C
1 t C	1 Mg C = 10^6 g C
1 kt C	1 Gg C = 1000 t C = 10^9 g C
1 Mg C	10^6 g C = 1 t C = 1000 kg C
1 Gg C	10^9 g C = 1 kt C = 1000 Mg C
1 Tg C	10^{12} g C = 1 Mt C = 10^6 Mg C
1 Pg C	10^{15} g C = 1 Gt C = 10^9 Mg C
1 kg C m^{-2}	10 Mg C ha^{-1} = 10 t C ha^{-1}
1 g C m^{-2}	0.01 Mg C ha^{-1}= 0.01 t C ha-1 = 10 kg ha^{-1}
1 kg ha^{-1}	0.1 g C m^{-2} = 10^{-3} Mg C ha^{-1} = 10^{-3} t C ha^{-1}
1 kg C	44/12 kg CO_2 = 3.66 kg CO_2

1 kg CO_2	12/44 kg C = 0.27 kg C

Conversion from C to CO_2: To convert the sequestration (or loss) of 1 kg of C in a carbon pool to the associated removal (or emission) of CO_2 from the atmosphere the amount of C is multiplied by 44/12, resulting in 3.67 kg of CO_2. The other way around, the amount of 1 kg of CO_2 is multiplied by 12/44 to calculate the corresponding amount of C, resulting in 0.27 kg C.

Conversion from biomass to carbon: The carbon content of living biomass is remarkably constant. Although there is some variation, depending on vegetation type, as rule of thumb it can be assumed that 50% of the dry matter of biomass is carbon (i.e. 1 kg of biomass dry matter represents 0.5 kg of carbon). Information on biomass dry matter content and changes therein thus can be easily converted to carbon content and changes in carbon stocks.

Acronyms

C: Carbon

CO_2: Carbon dioxide

CH_4: Methane

DIC: Dissolved Inorganic Carbon

DOC: Dissolved Organic Carbon

GHG: Greenhouse gasses

GPP: Gros Primary Production

H_2O: Water, di-hydrogen oxide

IPCC: International Panel on Climate Change

POC: Particulate Organic Carbon

SOC: Soil Organic Carbon

LULUCF: Land use, Land use change and Forestry

N_2O: Nitrous oxide

NBP: Net Biome Production

NEP: Net Ecosystem Production

NPP: Net Primary Production

SOM: Soil Organic Matter

UNFCCC: United Nations Framework Convention on Climate Change

Executive summary

I Carbon storage in global terrestrial and marine ecosystems

Global carbon cycle

The total carbon stocks in the ocean have been estimated to amount to ~ 40,853 Pg. This is approximately 50 times greater than carbon stocks in the atmosphere (850 Pg) and approximately 10 times greater than carbon stocks on land (~ 3,900 Pg) (Ciais et al. 2013, Ussiri and Lal et al. 2017).

Carbon stocks and carbon sequestration rates in terrestrial ecosystems

Terrestrial ecosystems (ecosystems on land) can take up carbon from the atmosphere and thereby mitigate the increase in the atmospheric CO_2 concentration. The global amount of carbon stored in vegetation amounts 420-630 Pg C (Ciais et al. 2013). The terrestrial carbon stock was estimated at about 2.6 Pg C in 2010. This stock however, has a high interannual variability due to variation in weather and vegetation. Forests are responsible for about half of the global total terrestrial gross primary production (GPP) of 123 Pg C per year that is the amount of CO 2 fixed as organic compounds by vegetation through photosynthesis at the ecosystem scale. For forests the largest stock is the living biomass pool and not the soil pool. Only between 0.3 and 5.0 Pg C per year remains as net biome production (NBP), as carbon stock, in terrestrial ecosystems, mainly as soil organic carbon (SOC) (Lal et al. 2013).

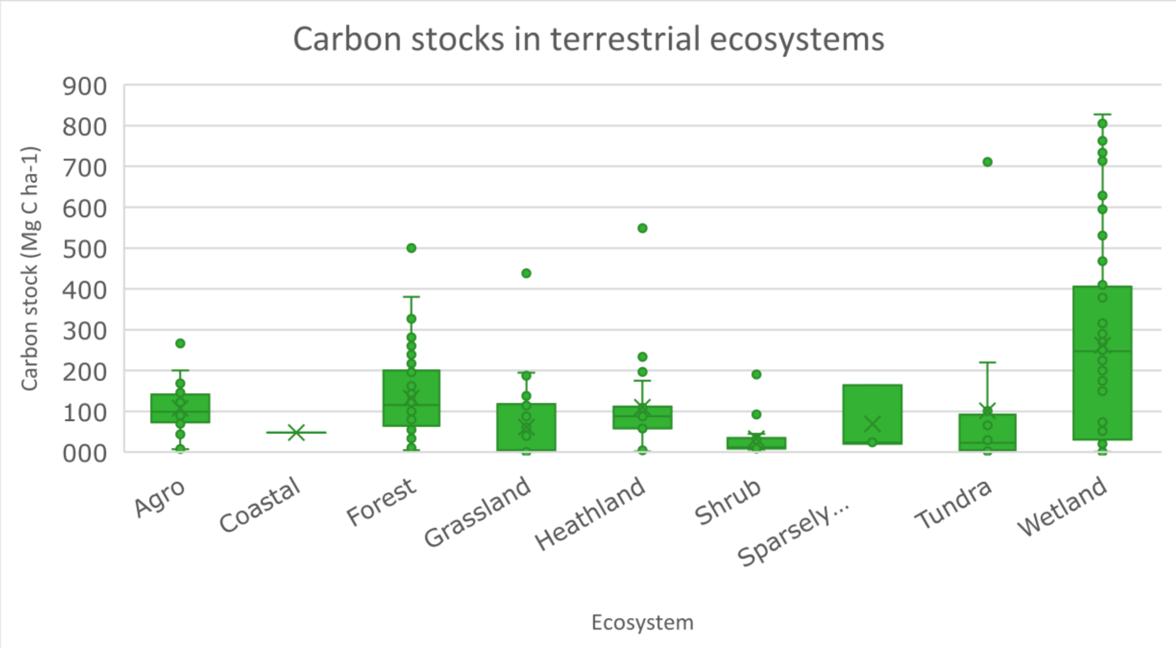
Of all terrestrial ecosystems, the highest carbon stocks are reported for wetlands (Table I).

Table I *Carbon stocks in ecosystems (Mg C ha^{-1}) mean, median, minimum, maximum and number of observations (n). Note: Most of the data is referring to EU27 member states but also UK data is included. Also some data is related to climate zones such as boral forests, which might refer to Scandinavia but to the boreal zone of boreal North America as well. However, the data from outside EU27 is applied to the EUNIS types and therefore can be considered as estimates for the EU27. In some cases there are small number of observations which calls for further validation of the figures.*

Ecosystem	n	mean	median	min	max
Agro	24	107.7	99.0	7.0	266.7
Coastal	1	48.0	48.0	48.0	48.0
Forest	111	133.0	115.5	5.0	500.0
Natural grassland	33	61.3	5.0	0.5	438.0
Heathland	23	110.3	88.0	2.0	548.6
Shrub	14	33.5	12.0	6.9	190.1
Sparsely vegetated	3	69.7	24.0	20.6	164.5
Tundra	12	101.2	23.2	1.5	711.0
Wetland	72	261.8	247.2	0.9	827.1
Total	293	145.7	96.0	0.5	827.1

However, the range in carbon stocks of wetlands is also the largest of all ecosystems (Figure I).

Figure I *Ranges of carbon stocks (Mg C ha^{-1}) in terrestrial ecosystems.*



It are mainly peatlands (with thick peat layers) and salt marshes that have (very) high carbon stocks, while open waters, wet heathlands and shallow peatlands with rocky subsoils can have much lower carbon stocks. Other ecosystems, e.g. forests, heathlands, grasslands, and tundra's, also can have large carbon stocks when growing on peat soils. Forests in general also have large carbon stocks, due to the high above ground (e.g. stems, branches) and below ground (e.g. forest floor, soil organic matter) carbon pools in biomass. Especially (boreal) forests on peat soils have large carbon stocks, but also on sandy soils carbon stocks in forests can be relative high compared to other ecosystems. It is worth noting that forest carbon stocks depend on location, species, age of the stand, management, etc. which explains the variability in the figures. Tundra's have relative low carbon stocks, but can also have very high carbon stocks (Figure I) when occurring on permafrost, which is very vulnerable to temperature rise.

Forests have by far the highest average carbon sequestration rates, up to about 3 times that of wetlands and agroecosystems (Table II).

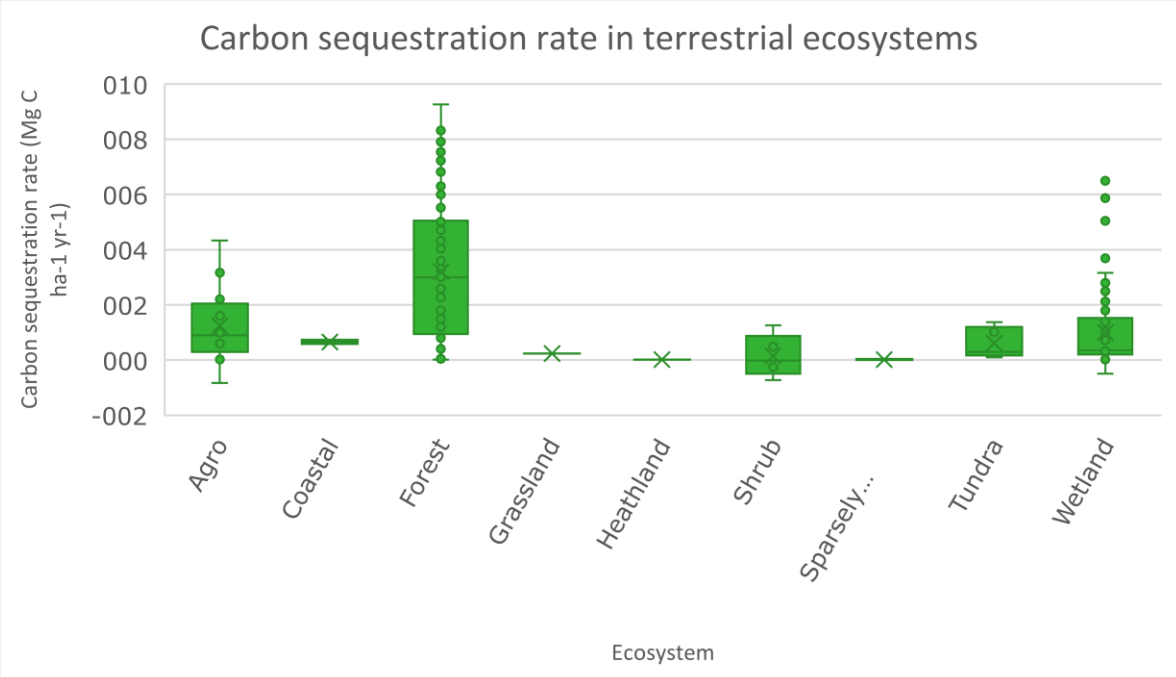
Table II *Carbon sequestration rates in ecosystems (Mg C ha^{-1} yr^{-1}) mean, median, minimum, maximum and number of observations (n). Note: Most of the data is referring to EU27 member states but also UK data is included. Also some data is related to climate zones such as boral forests, which might refer to Scandinavia but to the boreal zone of boreal North America as well. However, the data from outside EU27 is applied to the EUNIS types and therefore can be considered as estimates for the EU27. In some cases there are small number of observations which calls for further validation of the figures.*

Ecosystem	**n**	**mean**	**median**	**min**	**max**
Agro	12	1.25	0.90	-0.83	4.33
Coastal	2	0.66	0.66	0.58	0.73
Forest	73	3.20	3.00	0.02	9.26
Grassland	1	0.24	0.24	0.24	0.24
Heathland	1	0.02	0.02	0.02	0.02
Shrub	5	0.15	-0.02	-0.73	1.26
Sparsely vegetated	2	0.02	0.02	0.00	0.04

Tundra	5	0.60	0.29	0.10	1.37
Wetland	85	1.01	0.35	-0.49	6.50
Total	186	1.83	0.99	-0.83	9.26

This is relevant information to weigh the contribution of different ecosystems to climate policy. Due to the high sequestration rates, forests will store more carbon volumes over a same period compared to other ecosystems (Figure II). Wetlands have relative low carbon sequestration rates. Peatlands have large carbon stocks, but low carbon accumulation rates. It takes hundreds of years or more to build up large carbon stocks that are present in some peatland (Laine and Minkkinen 1996).

***Figure II** Ranges of carbon sequestration rates (Mg C ha^{-1} yr^{-1}) in terrestrial ecosystems.*



Negative sequestration rates are reported for Agroecosystems, Shrubs and wetlands (Table II), although, also other ecosystems can have negative sequestration rates, depending on the site conditions and the measuring method. Negative rates are due to high rates of decomposition of soil organic matter, which for instance may reach high values in drained or dehydrated peat soils. Decompensation rates in such circumstances may exceed carbon sequestration rates, resulting in a negative sequestration rate. In such cases ecosystems then act as a net carbon source.

An overview of the estimated classes of carbon stocks and sequestration rates for the terrestrial EUNIS habitat types are given in Annex 1.

Carbon stocks and carbon sequestration rates in marine ecosystems

The oceans are the largest long-term stock for carbon in the biosphere, as well as storing and cycling an estimated 93% of the Earth's CO_2 which is about 40 Tt (Nellemann et al. 2009). Most of the carbon in the oceans is inorganic carbon (DIC) in the form of bicarbonate, carbonate, dissolved carbon dioxide, and carbonic acid (Hansell et al. 2009). Worldwide the highest concentrations are found in the North-east Atlantic Ocean which has been estimated to store around 23% of anthropogenic CO_2 (Sabine et al. 2004).

A much smaller proportion is organically-bound, biologically 'fixed' carbon i.e. carbon in living organisms, decaying matter in organic compounds in water or in sediments. It has been estimated that approximately 1% of the total organic carbon production at the sea surface is buried in the sediment where it can be stored for thousands and even millions of years (Eppley and Peterson 1979, Nath 2012, Suess 1980). Estimates for inorganic carbon burial in shallow water environments suggest a central value near 150 Pg C per thousand years (Cartapanis et al. 2018).

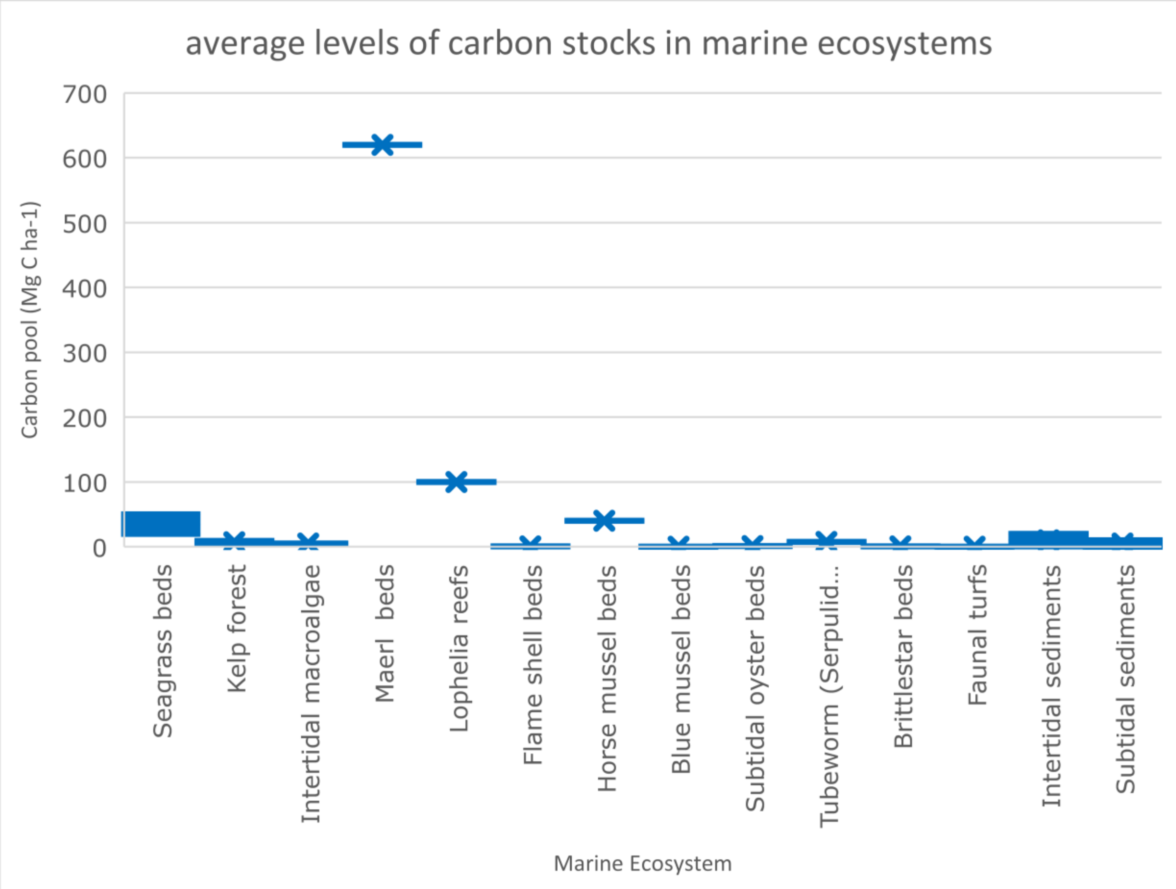
Of the marine habitats, mearl beds have by far the highest carbon stocks, 620 Mg C ha^{-2} (=62,000 g m^{-2}) are found (Table III).

***Table III** Carbon storage and Carbon sequestration rates for marine ecosystems. Note: Most of the data is referring to EU27 Member States including data from outside EU27.*

Habitat type	Carbon storage	Sequestration rates	Notes
Seagrass beds	2,000-5,000 g m^{-2} C_{org}	Global estimate 83 g C m^{-2} yr^{-1}	Majority in the underlying sediment although some storage in roots and rhizomes. Significant differences depending on the species with highest values in *P.oceanica*. Carbon storage ability can also increase with sediment depth
Kelps	500-900 g m^{-2} C_{org}	Contribution to sequestration largely in depositional areas not in the kelp beds	Temporary storage in living material. Exported (offshore and beach cast) and can be sequestered in deep-sea surficial sediments.
Intertidal macroalgae	500 g m^{-2} C_{org}	Contribution to sequestration largely in depositional areas not in the intertidal macroalgae beds	Temporary storage in living material, exported to shelf sediments
Maerl beds	62,000 g m^{-2} C_{inorg}	> 100 g C m^{-2} yr^{-1}	Longer-term store for organic and inorganic carbon. Rates vary between species. E.g. *P.calcareum* sequesters approx one fifth less than *L.glaciale*
Lophelia reefs	10,000 g m^{-2} C_{inorg}	~35 g C m^{-2} yr^{-1}	
Flame shell beds	60-70 g m^{-2} C_{inorg}		
Horse mussel beds	4,000 g m^{-2} C_{inorg}	40 g C m^{-2} yr^{-1}	Beds assumed to be 75cm deep
Blue mussel beds	15 g m^{-2} C_{inorg}	1 to 40 g C m^{-2} yr^{-1} (lowest value based on oyster, highest for horse mussel)	Shellfish beds often considered to be a source of atmospheric CO_2 due to calcification process during shell formation. Source or stocks depends on relative balance between organic and inorganic carbon burial.
Tubeworm (Serpulid reefs)	781.3 g m^{-2} C_{inorg}		
Brittlestar beds	66.2 g m^{-2}	82 g C m^{-2} yr^{-1}	based on *O.fragilis* bed in Dover strait. After death brittlestar skeletons and calcareous plates incorporated into bottom sediments
Faunal turfs	14 g m^{-2}	Not applicable as mostly found on rock	
Intertidal sediments	500-2000 g m^{-2} (top 10cm)	11-37 g C m^{-2} yr^{-1}	Higher levels in sediments with higher mud fractions. Based on accretion rate of 2mm yr^{-1}
Subtidal sediments	<1000 g m^{-2} (top 10cm)	0.3 - 0.9 g C m^{-2} yr^{-1}	Surficial sediments, and particularly deep-sea sediments, are the primary marine store of biologically-derived carbon. Higher levels in sediments with higher mud fractions. Based on 0.1mm accretion per year.

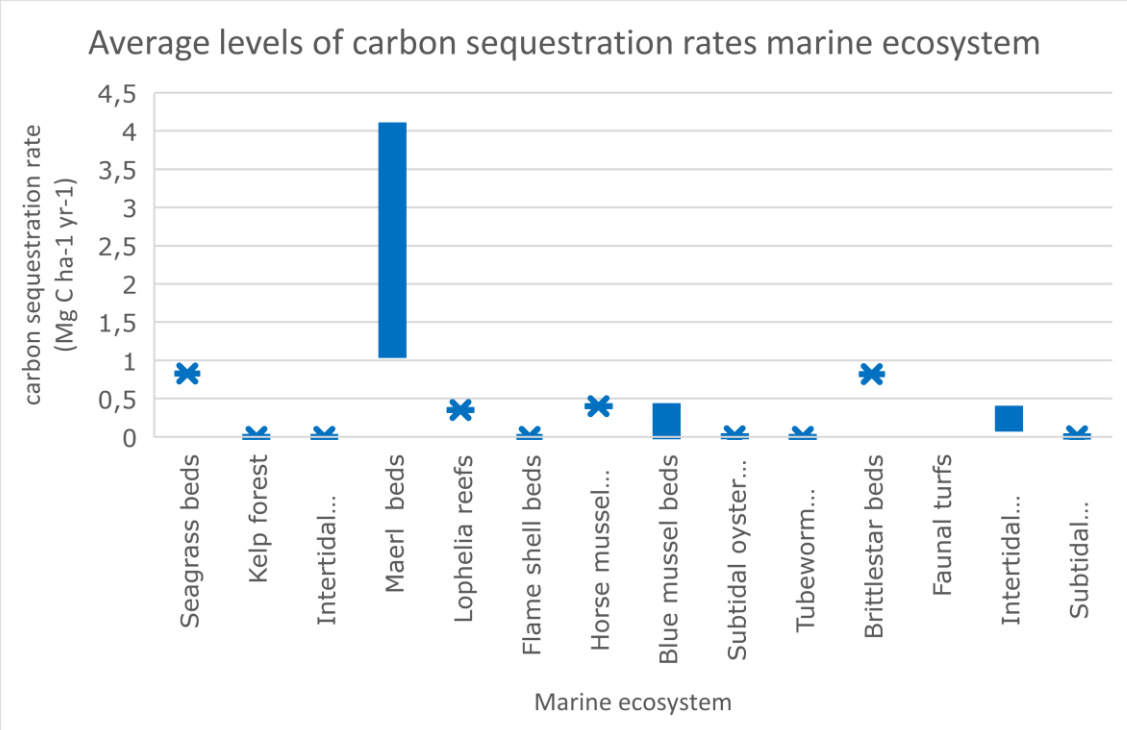
Lophelia reefs also have high carbon stocks, 100 Mg C ha^{-2} (=10,000 g m^{-2}). Flame shell beds, blue mussel beds, brittlestar beds and faunal turfs all have quite low carbon stocks, 0.14-0.70 Mg ha^{-2} (= 14-70 g m^{-2}) (Figure III).

Figure III *Average levels of carbon stocks (Mg C ha^{-1}) in marine ecosystems.*



Mearl beds also have the highest carbon sequestration rate of the marine ecosystems > 1 Mg C ha^{-1} yr^{-1} (> 100 g C m^{-2} yr^{-1}) (Figure IV). Kelp forests, intertidal macroalgae, and faunal turfs have very low or negligible carbon sequestration rates (Table III). Kelp forests and intertidal macroalgae do produce biomass C, but this contributes largely in depositional areas and not in the kelp beds and macroalgae beds themselves.

__Figure IV__ Average levels of carbon sequestration rates (Mg C ha^{-1} yr^{-1}) in marine ecosystems.



An overview of the estimated classes of carbon stocks and sequestration rates for the marine EUNIS habitat types are given in Annex 2.

II Classification of terrestrial and marine ecosystems

Based on the ranges for carbon stocks and carbon sequestration rates reported in literature five classes were defined. Because the large differences between terrestrial and marine estimates, separate classes were defined for the terrestrial and marine ecosystems. The classes are presented in table IV to VII.

Table IV *Applied classes for carbon stocks of terrestrial habitats.*

CLASS number	Class range in carbon stocks (Mg ha^{-1})	Habitat type
1	<75	Sand beach, coastal dune, sea cliff, water body, ice sheet, glacier, spring brook, watercourse, tidal river, rocky grassland, Mediterranean dry grassland
2	75-150	Coastal dune shrub, coastal dune forest, bog, fen mire, dry to mesic grassland, wooded pasture, alpine heath, wet heath, dry heath, maquis, Fagus-forest, Mediterranean deciduous forest, Mediterranean evergreen forest, plantation forest
3	150-225	Coastal dune forest, bog, fen mire, helophyte bed, mountain hay meadow, temperate and boreal grassland, Fagus forest, Mediterranean deciduous forests, taiga Pinus forest, plantation forest
4	225-300	Salt marches, palsa mire, aapa mire, helophyte bed, Abies forest, Picea forest, taiga Pinus forest
5	>300	Salt marches, palsa mire, aapa mire, tundra (permafrost)

Table V *Applied classes for carbon sequestration of terrestrial habitats.*

CLASS number	Class range in carbon sequestration rate (Mg ha^{-1} yr^{-1})	Habitat type
1	<1.5	Sand beach, coastal dunes, dune forest, water body, ice sheet, glacier, spring brook, water course, tidal river, bog, fen, mire, dry grassland, Mediterranean wooded pasture, scrub, tundra, heath
2	1.5-3.0	Salt marshes, helophyte beds, Mediterranean deciduous forest,
3	3.0-4.5	Fagus-forest, broadleaved plantation forest, coppice
4	4.5-6.0	Deciduous plantation forest, coniferous plantation forest
5	>6.0	Coniferous plantation forest, deciduous plantation forest, biomass plantation forest

Table VI *Applied classes for carbon stocks for Marine habitats.*

CLASS number	Class range in carbon stocks (Mg ha^{-1})	Habitat type
1	<10.00	Kelp forest, intertidal macroalgae, flame shell beds, serpulid reefs, brittlestar beds, blue mussel beds, faunal turfs, subtidal shelf sediments. subtidal oyster beds
2	10.00-49.99	Seagrass beds, horse mussel beds, intertidal sediments
3	50.00-99.99	-
4	100.00-149.99	*Lophelia* reefs
5	>150	Maerl beds

Table VII *Applied classes for the carbon sequestration rate of Marine habitats.*

CLASS number	Class range in carbon sequestration rate (Mg C ha^{-1} yr^{-1})	Habitat type
1	negligible	Kelp forest, intertidal macroalgae, faunal turfs, flame shell, serpulid reefs
2	<0.01	Subtidal shelf sediments
3	0.01-0.50	*Lophelia* reefs, horse mussel beds, blue mussel beds, intertidal sediments, subtidal oyster beds
4	0.50-1.00	Seagrass beds, brittlestar beds
5	>1.00	Maerl beds

III Management measures to store carbon in ecosystems

Management measures in terrestrial ecosystems

There are roughly three different types of measures aimed at improving the condition of natural habitats:

1) measures to conserve a habitat type (e.g. preventing succession, reducing possible negative impacts from outside the system)
2) measures to restore a habitat type (e.g. improving biotic and abiotic conditions)
3) land-use change, increasing the area of a habitat type (e.g. to extent existing habitats, making them more robust, or to connect existing habitats)

In general measures aiming at removing nutrients or biomass from a system (for examples to restore eutrophicated systems, or to convert forest land to a more biodiverse heathland to connect areas or to make a habitat more robust) will result in losses of carbon stocks, and hence will contribute to accounted emissions from the land-use sector. Measures that improve water management and rewet soils in nature areas will usually have a positive effect both on biodiversity and on the carbon storage, particularly in areas with organic soils it will result in a reduction of CO_2 emissions from the soil. Although temporary wetting can lead to an increase in CH_4 emissions from the soil. Some sources indicates that it can take several decades before the reduced CO2 emissions will compensate for the increased CH_4 emissions. It should be noted that CH_4 emissions is considered to be 28 times stronger than CO_2 according to IPCC AR5.

Both biodiversity and climate are under pressure. Partly these pressures are similar and some measures and solutions to improve one are also beneficial for the other. Wetlands and forest are two important terrestrial ecosystems for the carbon stocks and carbon sequestration rates because of the large areas covered by these ecosystems.

Wetlands, and especially peatlands usually contain large carbon stocks. Land use changes and drainage of the wetlands cause substantial CO_2 emissions. While wetlands can be restored and carbon sequestration increased, it does not compensate for the net C accumulation in the original ecosystem before drainage (Waddington and Price 2000) meaning wetland conservation is preferable to restoration.

Forest management and tree species selection have a significant impact on the storage of carbon in forests (Nabuurs et al. 2018). Read et al. (2009) reported large carbon stocks of 218 Mg C ha^{-1} in an unmanaged nature forest reserve. Although the carbon stock was large, the carbon sequestration rate was relative low: 1.6 Mg C ha^{-1} yr^{-1}. Conversely, in an intensively managed even-aged forest a carbon stock of 109 Mg C ha^{-1} was reported while the carbon sequestration rate was 6 Mg C ha^{-1} yr^{-1}, and in a wood biomass forest plantation carbon stock was 55 Mg C ha^{-1} and the carbon sequestration rate was 7.9 Mg C ha^{-1} yr^{-1}.

If large carbon stocks are pursued for the long term, unmanaged forest might be a good option. If there is a short term objective to rapidly store carbon, then intensive forest management might be a good option, however then sustainable use of wood and wood products (e.g. for construction applications) is needed to sustainable store carbon for the long term.

It is also clear, however, that there may be cases where trade-offs occur between nature conservation and restoration objectives and climate mitigation actions. These will need to be carefully weighted to make sure that climate mitigation policy and related actions will not (or at least minimize) negatively impact nature conservation and restoration objectives, or the other way around.

Management measures in marine ecosystems

There are similarities between approaches to the management of terrestrial and marine habitats however in the case of the marine environment, there are typically fewer opportunities for active intervention. In most cases marine management is likely to centre around regulation and guidance on how particular activities should be carried out to prevent or minimise anthropogenic impacts. The establishment of Marine Protected Areas (MPAs) compliment such measures by focusing conservation action in particular locations as well as having the potential to act as reference or control areas to study impacts and changes in the marine environment including from climate change such as sea level rise and changes in species distribution.

The IPCC identify two management approaches that are more specific to climate change (IPCC, 2019). Firstly, actions that maintain the integrity of natural carbon stores, thereby decreasing their potential release of greenhouse gases, whether caused by human or climate-drivers; and secondly, actions that enhance the long term (century-scale) removal of greenhouse gases from the atmosphere by marine systems, primarily by biological means.

For example through protection of habitats such as seagrass and maerl beds or enhancing the natural carbon uptake of some marine habitats, not only by increasing their spatial coverage through habitat restoration and new habitat creation, but also by taking management measures to maximise the carbon uptake and storage for existing coastal ecosystems. Such measures include reducing anthropogenic nutrient inputs and other pollutants; restoring hydrology, by removing barriers to tidal flow and sediment delivery; and reinstating predators (to reduce carbon loss caused by some bioturbators) (IPCC 2019).

At the global scale, synthesis studies have estimated the potential additional sequestration achieved by cost effective coastal blue carbon restoration as ~0.05 Gt C yr^{-1} (Griscom et al. 2017) and 0.04 Gt C yr^{-1} (National Academies of Sciences, Engineering, and Medicine 2019), assuming that a relatively high proportion of vegetated ecosystems can be re-instated to their 1980–1990 extents.

Measures to stimulate and/or safeguard carbon storage in the marine environment to date have considered just a small number of marine habitats. These are benthic habitats, the focus of this review, however it is critical to also note that ecologically degraded ocean waters lose their capacity to support the carbon cycle and act broadly as a carbon stock (IUCN 2017). The measures are relevant to habitat protection and restoration. Other approaches such as ocean fertilisation with the addition of iron and macronutrients and injection of captured CO2 into geological reservoirs are being investigated as potential mitigation measures for climate change (e.g. Brewer et al. 2018) but are not discussed in this review.

Of the habitat types reviewed, subtidal sediments with a high mud fraction have the greatest potential to store carbon. Relevant management measures for this habitat are those which either maintain such capacity to store carbon or restore it where it has been degraded. Anthropogenic activities such as fishing, dredging and the installation of offshore structures that affect the mixing of sediments, including disturbing the infauna, will affect carbon storage in shelf sea sediments (Alonso et al. 2012, Hale, R. et al. 2017). Preventing or reducing such disturbance from human activities is therefore a management option to consider.

The protection and restoration of seagrass beds for biodiversity conservation has also been investigated for their role in carbon storage and sequestration. Per unit area of habitat created, restored or rehabilitated, it has been calculated (Isensee et al. 2019) that in the case of seagrass ecosystems, carbon removal rates could be as much 138 ± 38 g C m^{-1} yr^{-1} although there is considerable variation between the species. In a study where seagrass was seeded it was concluded that within 12 years of seeding, the restored seagrass beds would be expected to accumulate carbon at a rate that is comparable to measure ranges in natural seagrass beds.

IV Discussion

Scientific literature shows a wide range of information on carbon stocks and carbon sequestration rates, both qualitative and quantitative. It, however, also shows a very wide range of methods applied. For example, studies have focus on different ecosystem components and carbon pools, different demarcation of ecosystem components, carbon pools or ecosystem productivity (GPP, NPP, NEP), different time scales, or report measured or modelled data. These methodological differences influence the range of the carbon pools and sequestration rates reported and complicate mutual comparison. In our study we mainly used expert assessment for the comparison. A more elaborated scientific basis was beyond the scope of this study, but is recommended for further studies.

Besides these methodological restrictions, some other issues are of influence on the outcomes. Most of the publications found do not describe the studied ecosystem in terms of EUNIS habitat type but in more general terms of present species or on ecosystem level (e.g. boreal forest, Mediterranean shrub, circalittoral mud). Further the classification of ecosystems in publications is overlapping. For example heathlands are classified both as heathland, peatland and shrub, and forested mires are reported both as forests and peatlands. Therefore the reported information on ecosystems including the related EUNIS habitat types are based primarily on expert judgement. With this approach some uncertainty should be recognised. Moreover, most of the data is referring to EU27 Member States but also UK data is included and some data from Ukraine. Also some data is related to climate zones such as boral forests, which might refer to Scandinavia but to the boreal zone of boreal North America as well. However, the data is partly from outside EU27 and is applied to the EUNIS types and therefore they can only be considered as estimates for the EU27.

Although relatively many publications were found with information on carbon pools and carbon sequestration rates in natural vegetation, the number of publications that cover all ecosystem components is low (e.g. only information was given on one carbon pool of the biomass, only biomass of the trees, or of the soil carbon). Of many ecosystems there were no publication with information on all ecosystem components. These gaps were filled with information, if available, of ecosystems which are more or less comparable. This approach influences the accuracy and reliability of the classification and could not be done without substantial expert assessment through interpretation and extrapolation of the fragmented information on the different ecosystems that could be taken representative for the EUNIS habitats.

For terrestrial ecosystems there are many studies found on forests and wetlands. Information on carbon pools and carbon sequestration rates for some other ecosystems (e.g. coastal, tundra, shrubs) are relatively scarce. It is recommended to increase the data on these ecosystems in future studies. Differences in methods result in large differences in values for carbon pools and carbon sequestration rates that are reported. This wide range is also influencing the definition of classes and the classification of the carbon pools and sequestration rates. It is recommended that in future studies attention is given to clarify this in more detail in order to create a more complete and more reliable picture of total carbon stocks and sequestration rates. For marine ecosystems the carbon pools and sequestration rates have only been examined in detail for a small number of habitat types. Seagrass beds, for example, have been the focus of the largest number of studies whereas there is far less information on carbon sequestration and storage on the large number of benthic habitat associated with different subtidal sediments.

Given the uncertainties mentioned above, the classification of the EUNIS habitat types carried out in this study must be seen as a first attempt of classification which is subject to many improvements and must be handled with care when applied in other studies. Some possible improvements that can be undertaken are:

- Find more data on specific ecosystems of which in this research only few data were found (e.g. shrubs, taiga, tundra ecosystems and benthic habitats on subtidal sediments).
- Combine data of different publications to create full-ecosystem records containing information for all ecosystem components to estimate total ecosystem carbon storage and sequestration rates (e.g. data on living biomass carbon storage from publication a,b,c and soil organic matter pools from publication x,y,z.
- Soil organic matter in many ecosystems is the largest carbon ecosystem and at the same time this ecosystem is heavily depending on the soil type and climate and sampling depth. Additional research can give more insight in the contribution of soil type to carbon storage and carbon sequestration rates related to EUNIS habitat types.
- Geographical information can be of use in future steps to improve the classification of the carbon storage and sequestration rates, e.g. geographical information on soil organic matter, soil type, ground water, climate, vegetation, etc.

Measures to store carbon in ecosystems may have trade-offs for biodiversity and ecosystem services. Therefore measures to store carbon should be taken with care. In many cases it holds that conservation of existing ecosystems is preferable to restoration as with regards to carbon stocks.

V Conclusions

Terrestrial ecosystems
A large number of scientific studies is found that describe the pools and sequestration rates of carbon in terrestrial ecosystems. Many of them show the importance of terrestrial ecosystems in the carbon cycle and in perspective of climate change. The studies vary from very general to very detailed on the figures presented. The quantitative estimates of both the carbon stock and carbon sequestration show a wide range for similar ecosystem types. This wide range on the one hand presents real world differences, but on the other hand they are also partly due to methodological differences used in the different studies, and the focus of some studies on exceptional habitat conditions, resulting in difficult interpretation and uncertainty of the estimates.

Whether terrestrial habitats are reported in literature as net stocks or sources of carbon, depends – amongst others – on the method applied and whether the total ecosystem is considered or only phytomass or other single ecosystem components (e.g. soil organic matter). Some studies report present carbon pools at only one moment, which does not illustrate changes in the size of the pools over time, or they report just Phyto mass production, not taking into account decomposition of soil organic matter. Especially in peat soils this may cause the difference between habitats acting as source or stock for carbon.

Most estimates on carbon storage and carbon sequestration rates in literature are found for forests. This is probably due to the assumed importance of forest in the climate change debate, but also to the extended forest area. About 43% of the European Union land surface is covered with forest. There are however large differences between carbon storage and carbon sequestration rates of forests. Climate, soil, tree species, management and anthropogenic influences (land use change, forest fires etc.) all greatly influence the carbon cycle of forests. Further research on these factors and measures may help in better understanding their effects on the carbon storage in forests.

Literature estimates show the highest carbon storage in wetlands, followed by forests. Sparsely vegetated ecosystems, shrubs, and tundra habitats have the lowest carbon stocks. Carbon sequestration rates are highest in forest habitats and lowest in natural grasslands, heathland, semi desert, shrub and tundra habitats. This results show that it is very important to conserve the large carbon stocks stored in wetlands and forests and to adapt management strategies with carbon friendly measures. The results also show that forest have high potential to store large amounts of carbon in relative short periods of time, where other ecosystems need longer periods to build up similar carbon volumes. This may, however, be different for individual ecosystems, depending on site conditions such as climate, soil type and management.

Marine ecosystems
There is an expanding literature on 'blue carbon' relating to both carbon storage and sequestration rates showing that marine ecosystems have an important and irreplaceable role in cycling and storing carbon over short medium and long timescales. Nevertheless, scientific uncertainties surrounding quantitative estimates of carbon storage within many marine ecosystems remain high.

Marine habitats where carbon sequestration occurs can be net sources or stocks influenced by factors such as season, sea-surface temperature, stratification, ocean currents and turbulence from storms. Sequestration rates will also be affected by climate change because of the predicted changes in parameters such as sea water temperature, ocean circulation and frequency of storms.

One of the best studied benthic habitats in terms of carbon storage and sequestration is seagrass beds. Carbon pools in seagrass beds are associated with the plants and the underlying sediments. Accumulation rates and storage depend on the species, sediment characteristics, depth range of the habitat, age of the seagrass bed, depth of the sediment being sampled and remineralization rates. There is also much variability in carbon storage capacity between geographical areas.

Sediment type has a significant influence on carbon storage with subtidal sediments that have a high mud fraction having the greatest potential to store carbon. Anthropogenic activities such as fishing, dredging and the installation of offshore structures that affect the mixing of sediments, including disturbing the infauna, will affect carbon storage in shelf sea sediments.

Macroalgae do not directly transfer carbon to marine sediments, unlike rooted coastal vegetation. Nevertheless, seaweed detritus can deliver carbon to sedimentary sites and may provide a source of refractory dissolved organic carbon. Recent studies indicate that globally important amounts of carbon may be involved in these processes.

Of the benthic habitats reviewed sequestration rates were highest in seagrass beds, brittlestar beds and maerl beds. Storage rates were highest for deep water coral (*Lophelia*) reefs and maerl beds.

1 Introduction

1.1 Background

Anthropogenic greenhouse gas (GHG) emissions since the pre-industrial era have driven large increases in the atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). Between 1750 and 2011, cumulative anthropogenic CO_2 emissions to the atmosphere were 2040 ± 310 Gt CO_2 (556 Pg ± 85 Pg C). About 40% of these emissions have remained in the atmosphere (880 ± 35 Gt CO_2, 240 ± 10 Pg C); the rest was removed from the atmosphere and stored on land (in plants and soils) and in the ocean. The ocean has absorbed about 30% of the emitted anthropogenic CO_2, causing ocean acidification. About half of the anthropogenic CO_2 emissions between 1750 and 2011 have occurred in the last 40 years (IPCC 2014). Global atmospheric CO_2 concentrations increased from around 285 ppm in 1850 to about 410 ppm CO_2-eq in 2020 (IPCC 2014, Dlugokencky and Tans 2020).

Mitigation scenarios reaching about 450 ppm CO_2-eq in 2100 (consistent with a likely chance to keep warming below 2°C relative to pre-industrial levels) typically involve temporary overshoot of atmospheric concentrations, as do many scenarios reaching about 500 ppm CO_2-eq to about 550 ppm CO_2-eq in 2100. Depending on the level of overshoot, overshoot scenarios typically rely on the availability and widespread deployment of bioenergy with carbon dioxide capture and storage (BECCS) and afforestation in the second half of the century.

Global C cycling involves the exchange of C between its four main reservoirs: the atmosphere, the terrestrial biosphere, oceans and sediments (Ussiri and Lal 2017). In the light of CO_2 driven climate change, besides reduction of emissions, the sequestration of CO_2 from the atmosphere and the uptake of CO_2 by marine and terrestrial ecosystems can have significant impact reducing atmospheric CO_2 concentrations and with that climate change. Mitigation options are available in every major sector. Mitigation can be more cost-effective if using an integrated approach that combines measures to reduce energy use and the greenhouse gas intensity of end-use sectors, decarbonize energy supply, reduce net emissions and enhance carbon stocks in land-based sectors (IPCC 2014).

Environmental policy has great interest in carbon storage in natural ecosystems, as it contributes to lower carbon dioxide concentrations in the atmosphere and in that way is relevant for targets set for atmospheric carbon concentrations to mitigate impacts of climate change. Well-functioning and intact ecosystems may store and conserve large amounts of carbon. Restoration of degraded ecosystems (e.g. drained peatlands) may contribute significantly to reduce further carbon dioxide emissions from these systems or even remove it from the atmosphere and sequester the carbon in biomass and soil. For example, in the European green deal, reforestation is mentioned as an option for increasing removals of CO_2, while also marine ecosystems (e.g. seagrass meadows) are known significant carbon stocks. Such climate regulating is an example of an ecosystem service. There is a growing awareness that nature contributes to human well-being by means of ecosystem services. Specifically on carbon storage, an increasing number of studies has become available in recent years. However, no summarizing overview is available yet on the carbon storage in the total range of ecosystems that occur in Europe. This study may be seen as a first step in providing such an overview, based on a quick scan of existing literature. The presented information will help policy makers and nature conservation organisations to implement actions that follow European, national and regional strategies on carbon storage, and which are elements of a joint biodiversity-climate change roadmap.

Figure 1.1 *Global averaged greenhouse gas concentrations (IPCC 2014)*

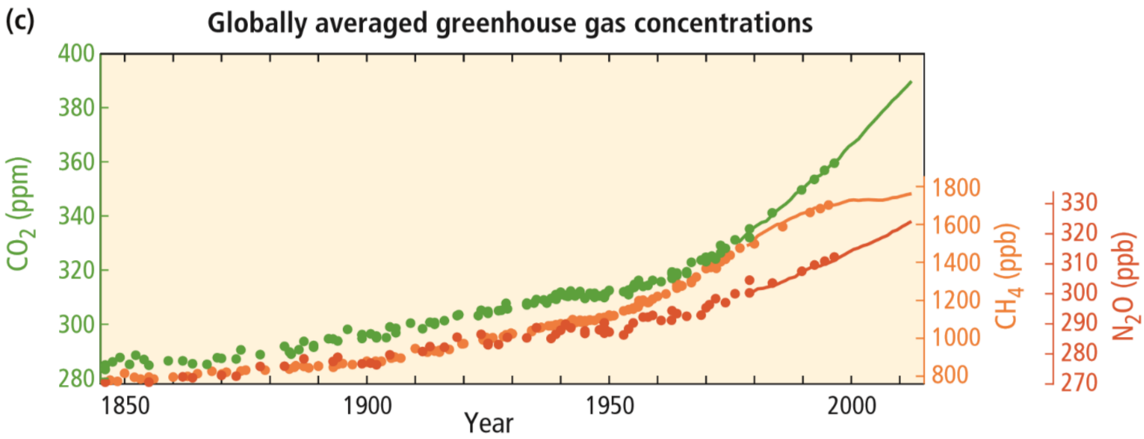
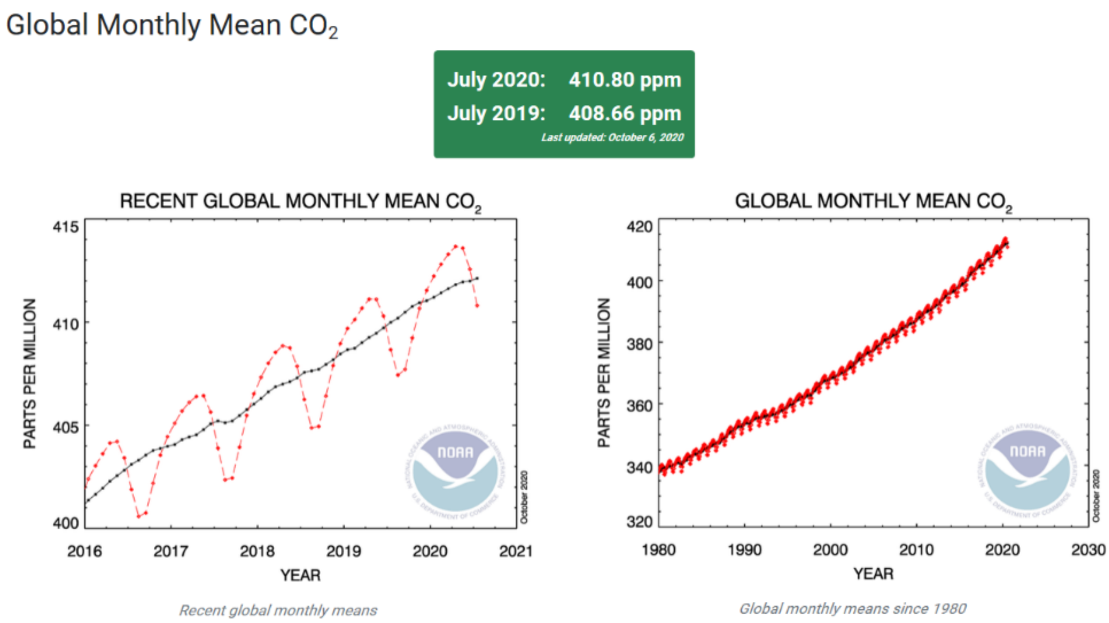


Figure 1.2 *Global monthly mean CO2 concentrations in the atmosphere (Dlugokencky and Tans 2020)*



1.2 Objective

The aim of the study is to (i) provide an overview of relative levels of carbon pools and carbon sequestration (yearly increase) in marine and terrestrial European ecosystems, and (ii) indicate how CO_2 storage and sequestration can be affected by land and sea use.

1.3 Method

The revised classification of EUNIS habitats was used as a basis for European ecosystems (EUNIS marine habitat classification 2019 and EUNIS habitat classification 2017 for terrestrial ecosystems, EEA 2020).

EUNIS is the only classification system in Europe that completely covers all natural and semi-natural habitats, and includes both the marine and terrestrial realm.

First a literature scan was carried out bringing together current knowledge for different types of terrestrial and marine ecosystems and their observed or modelled carbon stocks and carbon sequestration rates in the major carbon pools. Data was listed in an excel worksheet. The data found in literature was then used to define relevant boundaries for five classes of carbon stock values and five classes of carbon sequestration rates. Because different quantities and ranges of carbon sequestered in marine and terrestrial systems different class ranges were defined for terrestrial and marine ecosystems to estimate levels of carbon storage and sequestration rate of the EUNIS habitats.

As a second step, based on the literature scan and complemented with expert-knowledge, the EUNIS habitat types were linked to ecosystems and habitat types as identified in the literature review. Because in most literature no reference to EUNIS types is provided this linking was on the basis of expert knowledge of the EUNIS types and expert interpretation of the descriptions of vegetation type, location and specific conditions that were provided in the different studies. Using this link each EUNIS habitat type was classified into one or a range of classes for the carbon stock and carbon sequestration rate as found for the studies that were linked to a EUNIS habitat type.

Measures taken in natural ecosystems may have large impact on the carbon pools of these ecosystems, both positive and negative. Therefore an assessment of the potential of measures to store carbon in natural ecosystems is carried out. On the base of experience in previous studies and literature the impact of measures to store carbon in natural ecosystems is described.

Results from the literature scan, method development for classification, and classification of the EUNIS habitats are described in this report. The classified EUNIS habitats are reported in Annex 1 and 2 and more extensively in a separate excel worksheet for the terrestrial and marine habitat types, in which also corresponding habitat types of the Habitats Directive have been listed. The excel worksheet can be made available on request.

1.4 Reading guide

In Chapter 2 a general introduction is presented to carbon storage in ecosystems which include some definitions. Also impact of management measures is given. In Chapter 3 levels of carbon storage and carbon sequestration are described for different broadly defined terrestrial and marine ecosystems. Chapter 4 group the different EUNIS habitat types to these broader ecosystems. Finally, the findings and results are discussed in Chapter 5 and conclusions are presented in Chapter 6.

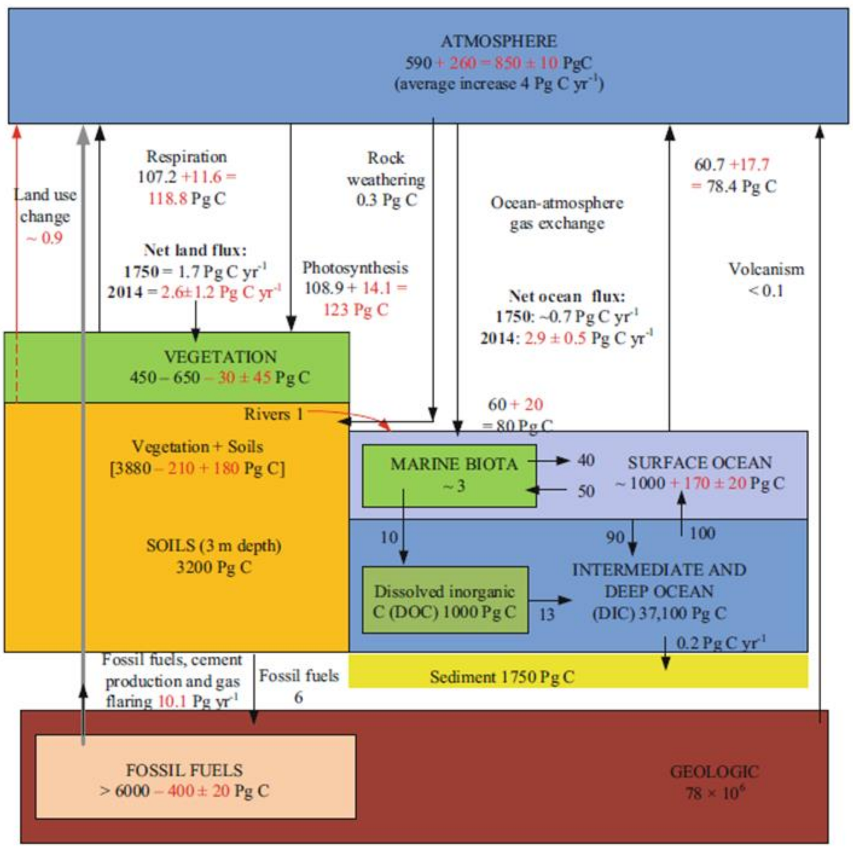
2 Carbon storage in ecosystems

2.1 Carbon storage in ecosystems

2.1.1 introduction

Plants, with the energy from sunlight, use CO_2 from the atmosphere in combination with H_2O to produce carbohydrates, which are partly used to build biomass. Through respiration, a part of the CO_2 is emitted again to the atmosphere. At the end of their life, or through litterfall, the living biomass is transformed to dead organic matter, which as a result of decomposition will gradually result in emissions of CO_2. The remaining parts of the dead organic matter will contribute to the soil organic matter (SOM), which determines soil condition and ecosystem productivity. Through decomposition and oxidation of the organic matter, the sequestered C is returned to the atmosphere, ready for renewed uptake by organisms. Due to the biotic origin this C content in the ecosystem is referred to as organic carbon. In ecosystems with little soil disturbance, usually the carbon inputs from dead organic matter and the carbon losses resulting from decomposition and oxidation are considered to be in equilibrium.

Figure 2.1.1.1 *The global carbon cycle before and after the anthropogenic influence. All units are in petagrams (Pg) of carbon. Numbers in black are natural (i.e., prior to anthropogenic influence in 1750); while numbers in red shows the anthropogenic change by 2014. Black arrows indicates fluxes of C (Pg C yr−1). (Sources of data Ciais et al. 2013, Houghton 2014, Le Quéré et al. 2015, 2016) (Figure from Ussiri and Lal, 2017).*



The carbon storage in the worlds terrestrial vegetation living biomass is estimated to be between 450 and 700 Pg C (Prentice et al. 2001, Ussiri and Lal 2017), which is less than the carbon reservoir of the atmosphere which amounts about 850 Pg C (Ciais et al. 2013, Ussiri and Lal 2017) (Figure 2.1.1.1).

Global net primary production (NPP) on the terrestrial ecosystem is estimated at 123 Pg C yr^{-1}. The carbon content in litter and dead organic matter in soils (Soil organic carbon (SOC) is estimated at about 1500–2400 Pg C for the top 1 m depth (Batjes 1996, Ciais 2013) and an additional amount in old soil carbon in wetlands (300 to 700 Pg, Bridgeham et al. 2006) and in permafrost soils (~1700 Pg, Tarnocai et al. 2009). Inorganic C contents stored in terrestrial soils (SIC) are estimated at 720–930 Pg C (Schlesinger 1982, Sombroek et al. 1993). The geologic carbon reservoir is immense, but largely immobilized in solid soil minerals (Figure 2.1.1.1, Ussiri and Lal 2017).

The total carbon stocks in the ocean have been estimated to amount to ~ 40,853 Pg C (Surface ocean C ~ 1000 Pg, DIC = 37,100 Pg C, DOC = 1000 Pg C, marine biota = 3 Pg C and ocean floor sediments = 1750 Pg C) (Fig. 2.1.1.1). This is approximately 50 times greater than carbon stocks in the atmosphere and approximately 10 times greater than on land (Ciais et al. 2013, Ussiri and Lal et al. 2017).

The large C content of the ocean results from C chemistry. When CO_2 dissolves in the ocean it reacts with water and carbonate (CO_3^{-2}) to form bicarbonates (HCO_3^{-}). Due to the chemical origin, this C content is referred to as inorganic carbon (Ussiri and Lal 2017).

2.2 Current knowledge on carbon storage in ecosystems

2.2.1 Terrestrial ecosystems

Terrestrial ecosystems (ecosystems on land) can take up carbon from the atmosphere which can mitigate the increase in the atmospheric CO_2 concentration. The terrestrial C stock was estimated at about 2.6 Pg C in 2010. The stock however, has a high interannual variability. Forests are responsible for about half of the global total terrestrial gross primary production (GPP) of 123 Pg C per year. However, only between 0.3 and 5.0 Pg C per year remains as net biome production (NBP) in terrestrial ecosystems, mainly in the soil as soil organic carbon (SOC). Terrestrial C stocks can be enhanced by soil and land-use management practices. The CO_2 mitigation potentials of croplands and grasslands for instance, may be about 0.8 Mg C ha^{-1} $year^{-1}$ and 0.2 Mg C ha^{-1} $year^{-1}$, respectively (Lal et al. 2013).

Agroecosystems

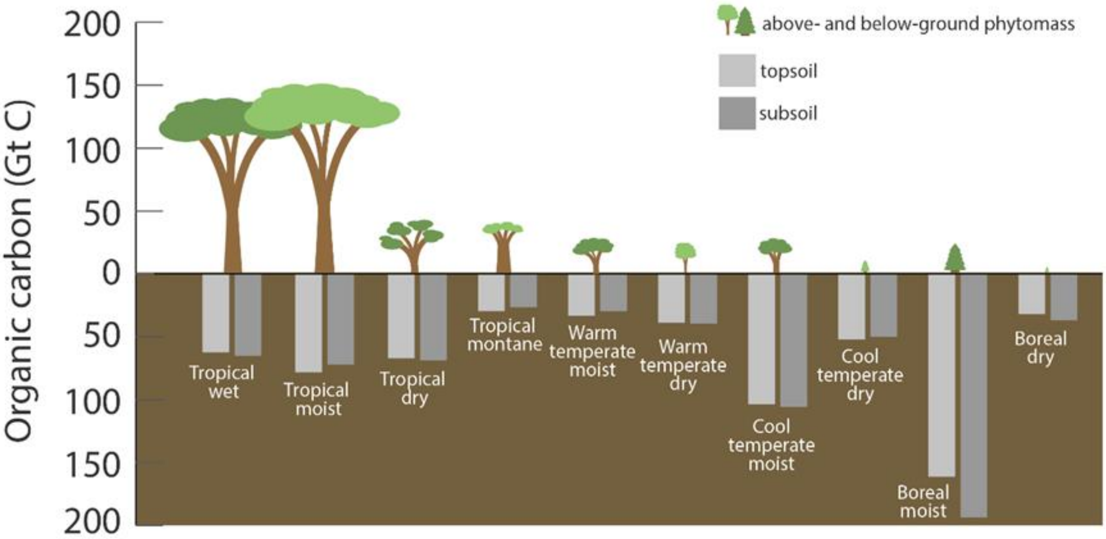
Carbon pools in grasslands are generally higher than in croplands. Lesschen et al. (2012) reported 94 Mg C ha^{-1} for SOC in croplands and 122 Mg C ha^{-1} for SOC in grassland in the Netherlands. This is similar to Nieder and Benbi (2008) who report 145-168 Mg C ha^{-1} for the total C pool (in crop and soil) of agroecosystems in temperate regions. The C pool in the above ground biomass ranges from 10% to 25% of the total C pool for most climate regions. In the boreal region the aboveground biomass might be much larger. Nieder and Benbi (2008) report 33-100 Mg C ha^{-1} for the above ground biomass on a total C pool of 200-267 Mg C ha^{-1} of agroecosystems in the boreal zone.

Concerning the C sequestration rate, most studies report on the sequestration rate of SOC only. This is mainly due to the temporarily sequestration in the aboveground biomass which is largely removed after harvesting, while changes in soil C sequestration rates much more express C uptake from the atmosphere. Soil C sequestration rates in agroecosystems ranges from 0.2 to 1.6 Mg C ha^{-1} yr^{-1} (Freibauer et al. 2004, Kayranli et al. 2004, Lorenz 2013). The sequestration rate varies depending on the management of the agricultural land. De Deyn et al. 2010 found C sequestration rates of 0.6 Mg ha^{-1} yr^{-1} for regular maintained grazed grassland and 3.2 Mg C ha^{-1} yr^{-1} for improved grassland with white clover.

Forests

The potential of C pool in forest is vast, also because the litter layer and soil carbon, in which large C can be stored. While tropical forests have much higher above ground carbon pool than temperate and boreal pools, the latter two forest type have large soil carbon pools (Figure 2.2.1.1).

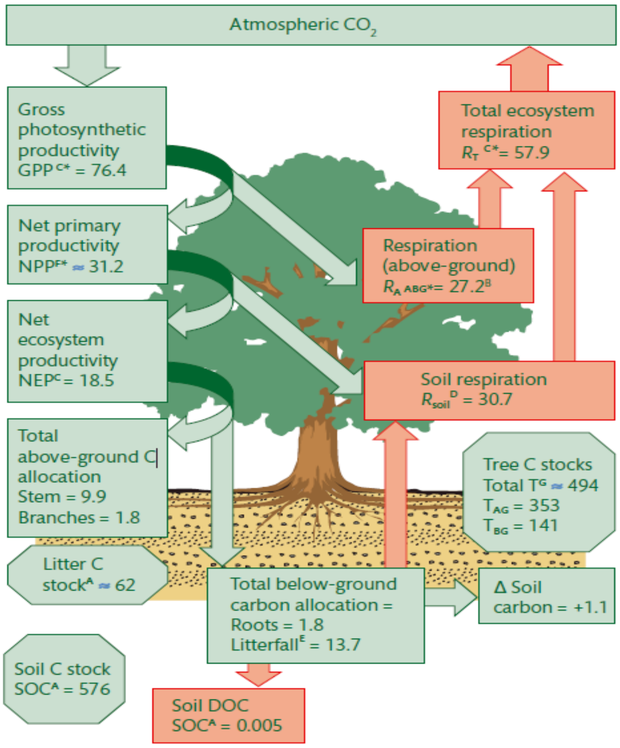
Figure 2.2.1.1 *Carbon stored in different forest ecosystems (Janowiak et al. 2017)*



Studies on carbon pools in forests show a large variation in those pools. This is partly due to real differences in the ecosystems, but in many cases due to different methods or different components that are studied. Forest ecosystems have different components in which carbon is stored (stem, branches, leaves, roots, litter, soil). Only few studies found present figures for all these components at the same time. Also studies differ in reporting gross or net biomass sequestration. This can cause large difference in values reported, and in fact can make the difference between ecosystems being a carbon stock or a carbon source (Beier et al. 2009).

The carbon uptake of forest is much larger than the carbon storage in the ecosystem as shown in Figure 2.2.1.2. From the amount of carbon that is taken up by forest (76.4 t CO_2 ha^{-1} yr^{-1} = 20.8 Mg C ha^{-1} yr^{-1}) in this example only about 25% is allocated in the living biomass above ground (stem, branches) and below ground (roots, litter that feed the soil organic matter). This means that most carbon (75%) that is taken up in the ecosystem (gross photosynthetic productivity) is also returned to the atmosphere due to respiration. Some studies make extensive mass flow measurements related to all components (e.g. Beier et al. 2009), while others determine carbon contents in only one or two ecosystem components (e.g. Read et al. 2009, Crabtree et al. 1997, Schultz 2000). Figures presented in this study may differ because of these different methodological approaches.

Figure 2.2.1.2 *Carbon fluxes and stocks (both in t CO_2 ha^{-1} yr^{-1}) in a 70-80 year old oak forest in the UK (Morison et al. 2012)*



Carbon pool levels shown in most studies fit in the range from 68-212 Mg C ha^{-1} (Liski et al. 2002, Olson et al. 1985, Nieder and Benbi 2008, Lesschen et al. 2012, Dybala et al. 2018). However, much lower C pools are found for some Mediterranean forests (Liski et al. 2002) and even some boreal forests (Nieder and Benbi 2008), both with C pools of 15 Mg C ha^{-1}. Liski et al. (2002) however found low values for North-Western and Central European forest ranging from 0.02 to 0.2 Mg C ha^{-1} yr^{-1} for Mediterranean forests in Greece, Spain. Ranges may differ because of a wide range of one or more of the different ecosystem components. Schulz (2000) found an exceptional high C content of the litter layer of 500 Mg C ha^{-1} in boreal old forest stands, and in above ground biomass of boreal mature coniferous forest he found a C pool of 126 Mg C ha^{-1}. This is in large contrast to the pool found in Mediterranean forests in Greece and Spain, where a C pool of 11 and 8 Mg C ha^{-1} was found (Liski et al. 2002). Most studies found present aboveground biomass C pools in the range of about 20-100 Mg C ha^{-1}. In many cases however, it is not clear whether the aboveground biomass is referring to the stem biomass, stem and course branch biomass, total tree biomass or total living above ground biomass (including ground vegetation and shrubs). Read et al. (2009) found a whole tree C content of 218 Mg C ha^{-1} in unmanaged forest in the United Kingdom, which suggests that the C pool levels in many other studies, which are in most cases (much) lower, are not referring to the whole C tree pool level.

The median C pool in forest soils of studies found amount 74 Mg C ha^{-1}, with most ecosystems fitting in the range of about 30-110 Mg C ha^{-1}. There is no clear regional distinction in the soil C pool however there seems a slight tendency in the boreal forest soils having higher soil C pools then Mediterranean forests. Soil type and tree species however, as well as stand age and management type have large impact on soil C pools and interfere with the level of the C pool related to the climate region.

C sequestration rates found in literature show large variation, ranging from 0.02-9.26 Mg C ha^{-1} yr^{-1} and a median of 2.9 Mg C ha^{-1} yr^{-1}. Schelhaas (2020) calculated, on the base of model simulations over a 50 year period, highest values for alpine, central-European and west-Atlantic forests ranging from 6-9 Mg C ha^{-1} yr^{-1}. C sequestration in litter contributes for the largest part to these high values. Larcher

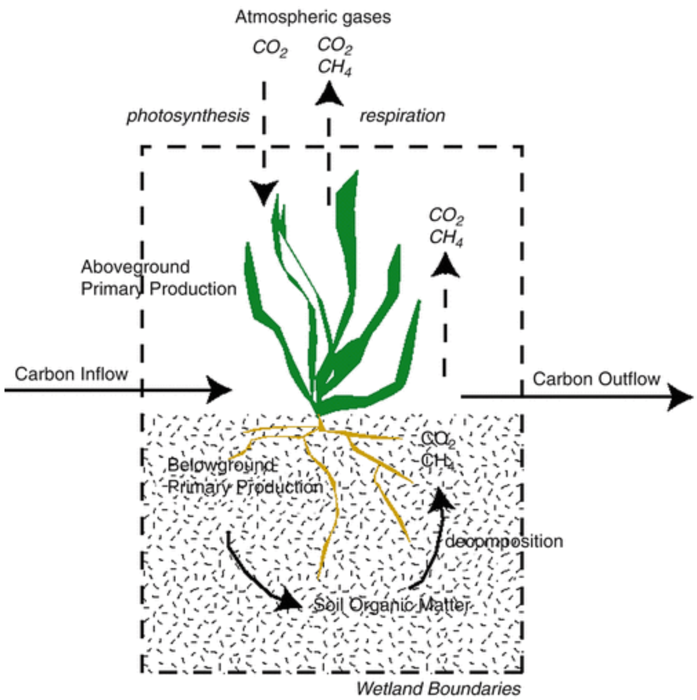
(2003) and Nieder and Benbi (2008) also reported high C sequestration rates (6.3 Mg C ha^{-1} yr^{-1}), but for other ecosystem components, namely soil C and above ground C in living biomass respectively. Liski et al. (2002) found low C sequestration rates for Mediterranean forests ranging from 0.02 Mg C ha^{-1} yr^{-1} for Greece and 0.13 Mg C ha^{-1} yr^{-1} for Portugal to 0.22 Mg C ha^{-1} yr^{-1} for forest in Spain.

Forest management also influences the C sequestration rate by selection of tree species, cutting cycles, intensity of management etc. Read et al. (2009) found increasing C sequestration rates of tree biomass with the intensity of the forest management: C sequestration rate in unmanaged forest nature reserves 1.64 Mg C ha^{-1} yr^{-1}, for close to nature forestry 3.00 Mg C ha^{-1} yr^{-1}, for combined objective forestry 4.36 Mg C ha^{-1} yr^{-1}, for intensive even-aged forestry 6.00 Mg C ha^{-1} yr^{-1} and 7.91 Mg C ha^{-1} yr^{-1} for wood biomass plantations.

Wetlands

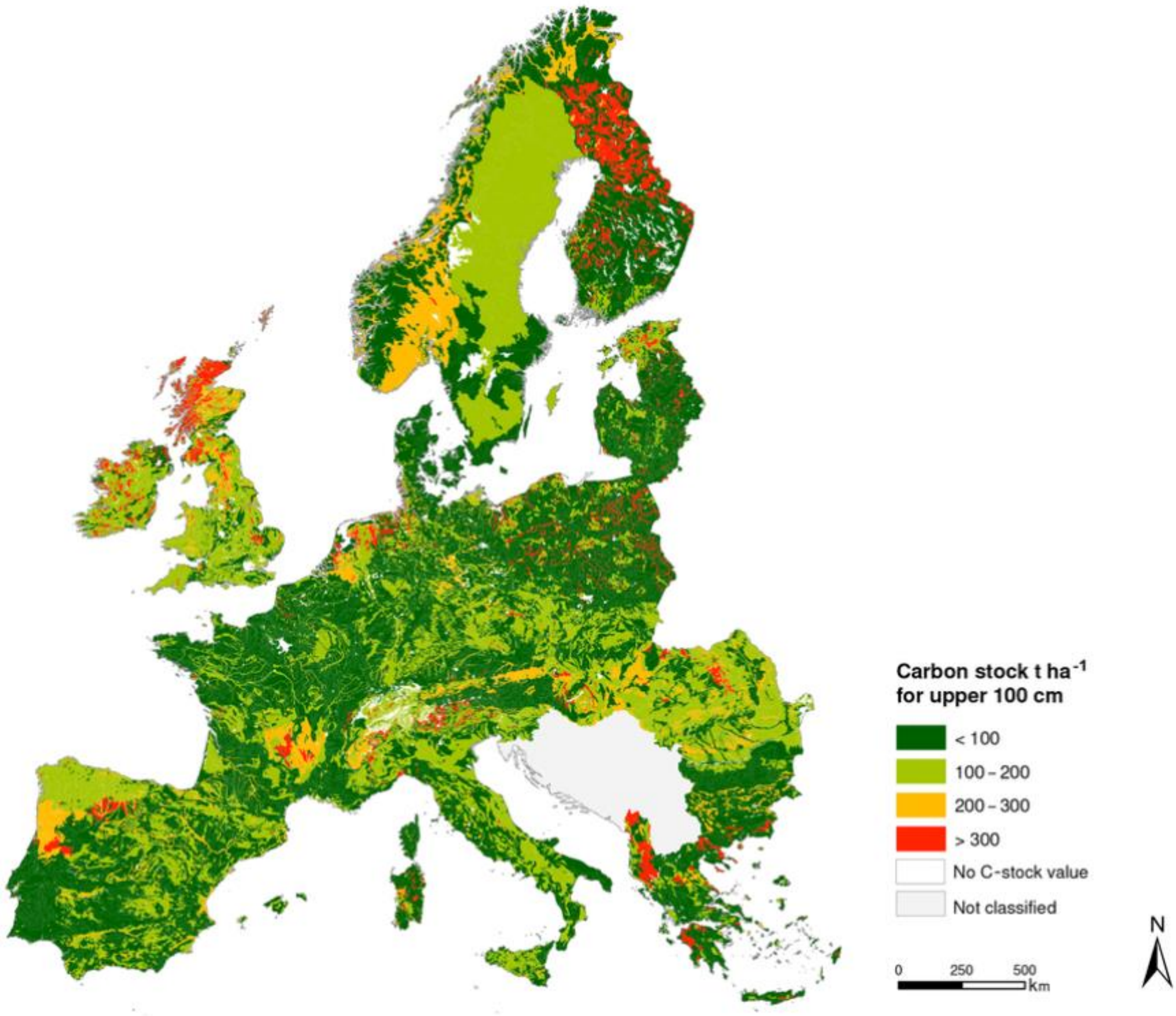
Wetland ecosystems consist out of a broad range of different sub-types such as peatlands, fresh water reed marshes, intertidal marshes, salt marshes, riparian ecosystems and so on. This broad range of different sub-ecosystems also has a broad range of carbon pools and carbon sequestration rates.

Figure 2.2.1.3 *Carbon cycle in wetlands showing carbon fluxes between ecosystem components and the atmosphere (Fennessy 2014).*



In general, peatlands have high carbon pool, however this strongly depends on the thickness of the peat layer, the thicker the layer the more carbon is stored. In the boreal zone extended and thick peatlands occur with thick layers of peat, which may contain over 300 Mg C ha^{-1} (fig. 2.2.1.4). Turunen et al. (2002) found C pools of mires in Finland ranging from 186 Mg C ha^{-1} to 883 Mg C ha^{-1}. Bogs in general had a higher C accumulation rate than fens, and undrained bogs and fens had higher C pools than drained systems. Alonso et al. 2012 reports for bog in the United Kingdom C pools ranging from 74 to 259 Mg C ha^{-1}. For the Netherlands, Lesschen et al. (2012) reports 75 Mg C Ha-1 for quaking bogs. The C pools reported for the living biomass in these peatlands in general are low 1 to 2 Mg C ha-1, however Nieder and Benbi (2008) and Olson et al. (1985) report C pools of around 20 Mg C ha-1 for bogs and mires in cool and cold climate zones. Reported carbon sequestration rates are all lower than 1 Mg C ha^{-1} yr^{-1}, and in the range of 0.1 to 0.9 Mg C ha^{-1} yr^{-1}.

Figure 2.2.1.4 *Soil organic carbon stocks in Europe (t ha^{-1}= Mg ha^{-1}, soil layer 0-100 cm, Kristensen et al. 2019).*



Reed marshes may have large amounts C stored in layers below the surface. Lesschen et al. (2012) reports C pools for the soil layer of 150 to 330 Mg C ha^{-1}. Above ground and below ground living biomass C pool may vary from roughly 2 to 10 Mg C ha^{-1} and 12 to 47 Mg C ha^{-1} respectively (Brix et al. 2001, Mander et al. 2008). Sequestration rates found in literature showed a rather broad range from 0.15 to 5.0 Mg C ha^{-1} yr^{-1} (Brix et al. 2001, Mander et al. 2008).

Salt marshes also contain large amounts of Carbon in the soil layers and are referred to as blue carbon, however, the high carbon storage may not always be the result of in-situ production of carbon by the present vegetation but may be transported from elsewhere and settled near coastal areas (Chmura et al. 2003, Teunisen and Didderen 2018). C pools range mainly from 200 to 400 Mg C ha^{-1} with an average of 311 Mg C ha^{-1} (Chmura et al. 2003, Teunisen and Didderen 2018, Alongi 2018). Also much higher values are found for instance for the Rhone delta in France with an C pool of 730 Mg C ha^{-1} (Chmura et al. 2003, Alongi 2018) and also much lower C pool, for example in Spain with 30 Mg C ha^{-1} (Alongi 2018) and the Netherlands with 38 and 52 Mg C ha^{-1} (Kiehl et al. 2012). The C sequestration rates are mainly in between 1.5 and 2.5 Mg C ha^{-1} (Chmura et al. 2003, Teunisen and Didderen 2018, Alongi 2018), however also higher values up to 6.5 Mg C ha^{-1} were found for the Netherlands (Chmura et al. 2003).

Natural Grasslands

Carbon pools of grasslands found in literature vary from 61 to 193 Mg C ha^{-1} (e.g. Alonso et al. 2012, Lesschen et al. 2012). Differences depend largely on differences in the soil carbon pool which built up steadily under (natural) grassland management. In many natural grasslands the living biomass carbon pool is low (less than 5 Mg C ha^{-1}) due to low soil quality (Nieder and Benbi 2008, Lesschen et al. 2012, Alonso et al. 2012). In grassland systems where the grass is harvested (e.g. for fodder purposes), the carbon in the grass is not accounted for in the carbon pool.

Steppe ecosystems occur in dry areas with long periods without rain. Net primary production in general is low and due to climate condition the sequestration rates are also low resulting in low carbon pools (less than 10 Mg C ha^{-1}). In forest steppes carbon pool can be much higher due to the carbon in the forest trees (40 to 120 Mg C ha^{-1}, Schulz 2000).

Heathlands

Just like grassland, the carbon pools of heathland vary widely depending on the soil carbon content. Heath may grow perfectly on both nutrient poor mineral soils and peat soils. In peat soils, carbon pools of course are much larger than in sandy soils. Carbon pools found in literature of heathlands vary roughly between 58 and 111 Mg C ha^{-1} (Sowerby et al. 2008, Lesschen et al. 2012, Alonso et al. 2012). On peat soils in Denmark, Sowerby et al. (2008) found high carbon pools up to 548 Mg C ha^{-1} mainly due to the soil C pool (496 Mg C ha^{-1}). No clear differences in carbon pools are found between *Calluna* and *Erica* vegetation.

Other ecosystems

Nieder and Benbi (2008) report low C pools for sparsely vegetated ecosystems such as polar deserts (24 Mg C ha^{-1}) but relatively high C pools for polar semi-desert (164.5 Mg C ha^{-1}). Arctic tundra may contain relatively large (more than 100 Mg C ha^{-1}) to very large carbon pools in permafrost areas (over 700 Mg C ha^{-1}).

Mediterranean shrub systems in general have low carbon poolse due to the open structure of the vegetation. Nieder and Benbi (2008) report living biomass C storage around 10 Mg C $ha\text{-}^{1}$.

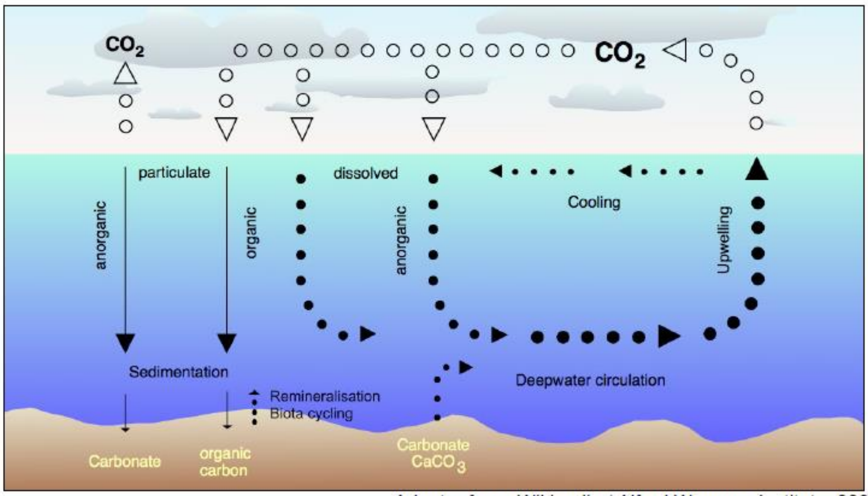
Lesschen et al. (2012) reports a carbon pool of 24 Mg C ha^{-1} for open sand dunes and drifting sand.

2.2.2 Marine ecosystems

The oceans are the largest long-term stock for carbon in the biosphere, as well as storing and cycling and estimated 93% of the Earth's CO_2 (40 Tt) (Nellemann et al. 2009). Most of the carbon in the oceans is dissolved inorganic carbon (DIC) in the form of bicarbonate, carbonate, dissolved carbon dioxide, and carbonic acid (Hansell et al. 2009). Worldwide the highest concentrations are found in the North Atlantic which has been estimated to store around 23% of anthropogenic CO_2 (Sabine et al. 2004) [1]. A much small proportion is organically-bound, biologically 'fixed' carbon i.e. carbon in living organisms, decaying matter in organic compounds in water or in sediments. This may be particulate organic carbon (POC) or dissolved organic carbon (DOC). Both particulate and dissolved organic matter (POM & DOM) are subject to microbial mineralization and most of the organic carbon will be returned to dissolved organic carbon within a few decades (Raven and Falkowski 1999). Some DOM is also transformed into more recalcitrant DOM and is eventually exported to the deep ocean where it is stored for millennia (Jiao et al. 2010, Hach et al. 2020). It has been estimated that approximately 1% of the total organic carbon production at the sea surface is buried in the sediment where it can be stored for thousands and even millions of years (Eppley and Peterson 1979, Nath 2012, Suess 1980). Estimates for inorganic carbon burial in shallow water environments suggest a central value near 150 Pg C per thousand years (Cartapanis et al. 2018).

[1] CO_2 emitted by human activity since the beginning of the industrial period in the late 18th century. Sabine et al. 2004.

The total carbon stocks in the ocean have been estimated to amount to ~ 40,453 Pg C (DIC = 38,000 Pg C, DOC = 700 Pg C, marine biota = 3 Pg C and ocean floor sediments = 1750 Pg C). This is approximately 50 times greater than in the atmosphere and approximately 10 times greater than on land (Ciais et al. 2013)[2].



Adapter from: Wikipedia / Alfred Wegener Institute, 2006
(Remineralisation and biota cycling inserted by ABPmer)

***Figure 2.2.2.1** – Marine biological and physical pumps of carbon (dioxide) from Armstrong et al. 2020)*

The term 'Blue Carbon' has been coined to refer to organic carbon that is captured and stored by marine living organisms (Nellemann et al. 2009). Marine species use carbon in sea water to build their soft tissues (organic carbon), while many of them - calcifiers - build solid skeletons made of inorganic carbon (mineral carbon, i.e. calcium carbonate). The planktonic and benthic organisms that live in the water column and on the ocean floor, respectively, account for the main source of particulate organic carbon and play a very important role in marine carbon storage (Laffoley and Grimsditch 2009). This takes place over different time scales. In coastal wetlands, for example, carbon is stored short-term[3] in living biomass and long-term in the soil and sediment. In the open ocean long-term carbon sequestration takes place over millions of years, when microbial degradation of organic matter gives rise to gas hydrates, and carbon from decomposed plankton is mineralised to form oil (Thompson et al. 2017). Transport of sediment to deeper waters effectively sequesters carbon over long time scales in a process referred to as the shelf sea carbon pump (Thomas et al. 2004). Most scientists refer to carbon held within the biomass of animals as being 'temporary' carbon storage. The ocean contains as much organic carbon (mostly in the form of dissolved organic matter) as the total vegetation on land (Jiao et al. 2010, Hansell 2013).

Scientific uncertainties surrounding quantitative estimates of carbon storage within many marine ecosystems remain high, but they have an important and irreplaceable role in cycling and storing carbon over short medium and long timescales. This review is focused on benthic habitats on the continental shelf of European seas. However, it is essential to note that the amount of carbon in the oceans and its sequestration is inextricably linked to processes in the water column, the open ocean, the deep sea and across all ocean basins. For example, a significant fraction of macroalgal production is exported to eventually reach shelf sediments and the deep ocean where it can be stored over significant time scales (Krause-Jensen and Duarte 2016, Duarte and Cebrian 1996, Barrón and Duarte 2015). It is also the case that areas of the seabed where carbon sequestration occurs can be net sources or stocks depending on season, sea-surface temperature, ocean currents and turbulence from storms. Sequestration rates

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[2] Terrestrial carbon stock estimates range from 3 950 - 5 450 Pg C (vegetation living biomass = 450 - 650 Pg C, dead organic matter in soil = 1500 - 2400 Pg C, wetland soils = 300 - 700 Pg C and permafrost soils = 1700 Pg C,). Atmospheric carbon stocks amount to ~ 830 Pg C

[3] decades

will also be affected by climate change because of the predicted changes in parameters such as sea water temperature, ocean circulation and frequency of storms.

The open ocean

In open ocean environments the uptake of atmospheric carbon is primarily controlled by biological activity and by seasonal and long-term changes in ocean heat content, as well as by the chemistry of surface and deep waters. The biological carbon pump (coupled with the solubility pump) is an important process in the ocean-wide (water column) sequestration of carbon. It refers to the photosynthetic uptake of CO_2 by marine plankton in surface waters, which results in a fraction of produced biomass being transferred to the deep ocean and subsequently buried. Open ocean calcifiers such as the foraminifera lock away carbon in the form of calcium carbonate through shell formation and transport it to the deep sea. They have been estimated to account for as much as 80% of the global marine $CaCO_3$ production and transport to the deep sea although their exact role as carbon storage remains to be quantified (Laffoley and Grimsditch 2014).

Diatoms fix CO_2 and export carbon to the deep ocean via the 'biological pump'. Whilst the majority of diatom production is used by upper and mid-ocean food webs with release of CO_2 back into the ocean and atmosphere through respiration, some dead diatom cells and faecal matter from marine consumers stocks through the water column. Deep-sea sediments are the main long-term repositories for carbon fixed by oceanic diatoms although only 1-2% of diatom production has been predicated to escape grazing and microbial degradation, and eventually reach the deep ocean (>1000m) where it is stored for thousands of years or longer (Figure 2.2.2.2).

Estimates of water column carbon stores derived from a modelling study carried out in Welsh waters using the Plymouth Marine Laboratory's European Regional Seas Ecosystem Model (ERSEM) are shown in Table 2.2.2.1. This indicates that in any given year the Welsh water column holds at least 48.7 Mt C mostly in the form of Dissolved Organic Carbon (DIC). Figure 2.2.2.3 maps the peak months for DOC and DIC in Welsh waters.

Figure 2.2.2.2 *Fate of diatom production in the ocean. Values represent mass of carbon (x1015 gC), NPP = net primary production. Food-webs include microbial degradation, and each component of the food-web will liberate CO_2 via respiration and produce faecal matter that sinks to the deep ocean (Figure 3.3.4 from Laffoley and Grimsditch, 2014). References: 1 (Ciais et al. 2013), 2 (Field et al. 1998), 3 (Duarte and Cebrian 1996), 4 (Jin et al. 2006), 5 (Nelson et al. 1996), 6 (Ragueneau et al. 2006), 7 calculated from % NPP.*

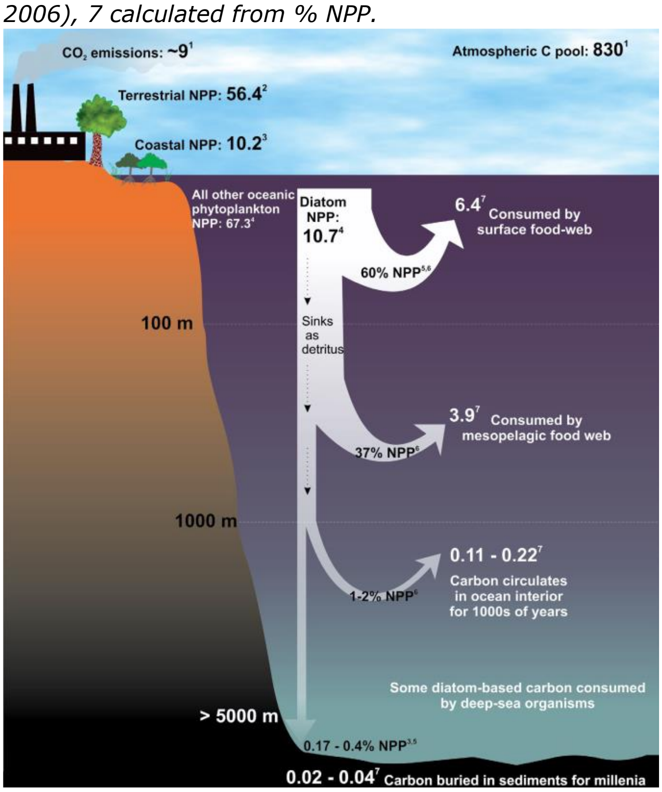


Figure 2.2.2.3 *Peak months for Dissolved organic carbon and non-living particulate carbon in Welsh waters. (Armstrong et al. 2020)*

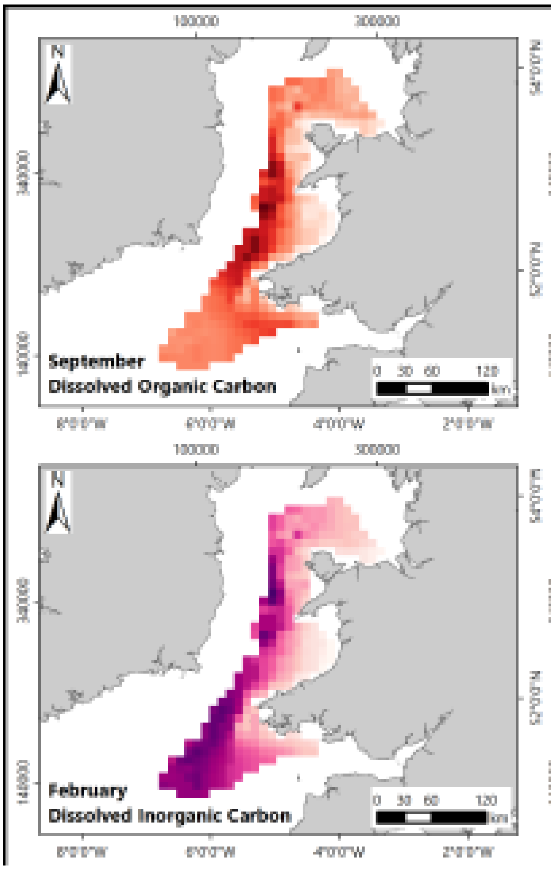


Table 2.2.2.1 *Water column carbon stores in Welsh waters derived from ERSEM model (Armstrong et al. 2020)*

Variable	Peak month	Lowest month	Peak C (Mt C)*	Lowest C (Mt C)*	Average C (Mt C)*
DIC	February	August	47.06	45.75	46.41
DOC	September	March	2.44	1.47	1.95
Non-living POC	July	February	0.17	0.02	0.09
Zooplankton Biomass	June	February	0.10	0.01	0.05
Phytoplankton Biomass	April	January	0.17	0.03	0.09
Total	-	-	**49.95**	**47.28**	**48.59**

* Values derived from 10-year (2011-2021) average of monthly means, based on Representative Concentration Pathway (RCP) 4.5. Please note that the model does not cover Welsh inshore waters, see, for example, Figure 1.

Shelf sea sediments

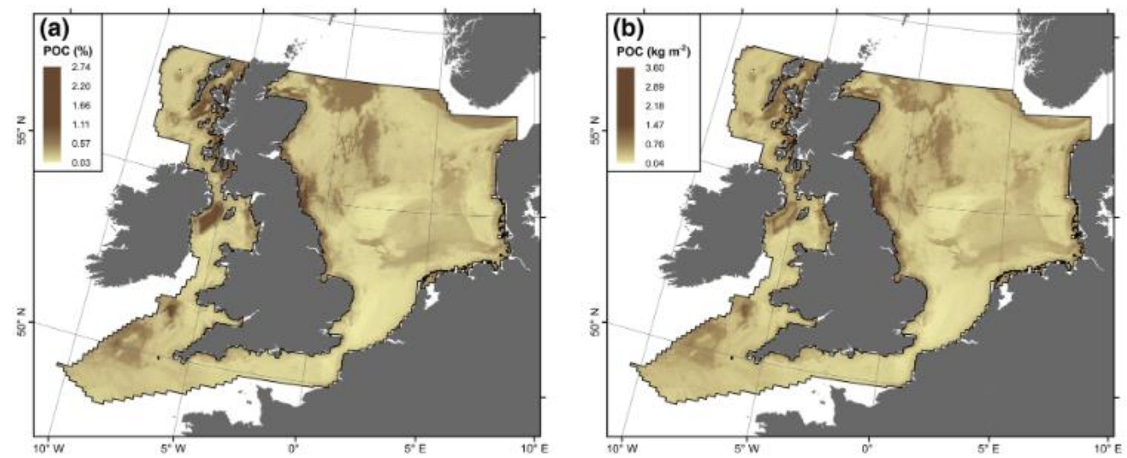
The sedimentation of particulate organic carbon (POC) is a key process in transferring CO_2 from the atmosphere to the seabed where it may be stored long term (decades–centuries). The amount which is incorporated into sediments is affected by many natural mechanisms from physical process such as particle movement or bedform migration during storms and tides or water temperature, and biological processes such as the activity and feeding by the infauna. Most carbonate degradation is believed to take place at the sediment-water interface, and long-term preservation (i.e. with the potential to enter the geological record) requires burial below this "Taphonomically Active Zone" (TAZ), typically by a sediment slide or other large-scale physical event.

Terrestrial organic carbon washed into the ocean is generally more efficiently sequestered in sediments than organic carbon produced in open ocean surface waters by phytoplankton. This efficiency is largely because soils and terrestrial plants contain a greater amount of substances that are relatively resistant to microbial degradation, such as humus, lignin or cellulose. Human activities that affect the mixing of the sediments such as benthic trawling, can also change the amount of carbon in the food web and how much goes into detritus.

Sediment type has a significant influence on carbon storage. Fine sediments are often associated with high natural organic matter loading due to proximity to terrestrial inputs, sedimentary hydrographic environments of low natural disturbance or because they create an environment where POC that is deposited naturally accumulates due to the diffusional environment that the higher mud percentage creates. Substrates with lower proportion of mud have more open structures so POC drawn into the sediments is more rapidly respired.

Figure 2.2.2.4 shows the results of a study using a combination of observational and modelling data to estimate POC in the surface sediments (0-10cm) of the North West European continental shelf. An estimated 250 Mt carbon is stored in surficial sediments in the study area (633,000 km^2). Scaling this up to the area of the NW European continental shelf (1,111,812 km^2) gave a carbon storage figure of 476 Mt (230-882 Mt).

Figure 2.2.2.4 *(a) Predicted concentrations of POC across the study site (b) Predicted mass of POC per unit area of seabed to a depth of 10cm. (Diesing et al. 2017)*



The most important variable in predicting POC concentrations was the mud content, with an increase in POC with increasing mud content. It should be noted however, that this does not necessarily translate into highest values in terms of mass per unit area as the dry bulk densities of muddy sediments are usually lower than that of sand and gravelly sands (Table 2.2.2.2). POC also increased with decreases in the annual average water column bottom temperature in the range of 7-12 °C.

Table 2.2.2.2. *POC dry bulk densities by Folk sediment class. (Diesing et al. 2017)*

Folk class	Area (km^2)	POC (%)				Dry bulk density ($kg\ m^{-3}$)				
		P5	P95	Mean	SD	P5	P95	Mean	SD	POC stock (Mt)
Mud	3080	0.59	1.11	0.88	0.20	536	624	580	29	1.56
Sandy mud	13,656	0.54	1.11	0.78	0.21	646	1011	828	120	8.81
Muddy sand	64,043	0.27	0.92	0.54	0.22	1111	1429	1323	99	45.49
Sand	323,200	0.10	0.50	0.24	0.12	1454	1535	1511	25	116.24
Slightly gravelly sandy mud	122	0.55	0.93	0.67	0.16	789	1030	945	73	0.08
Slightly gravelly muddy sand	5772	0.32	0.82	0.54	0.22	1192	1433	1357	80	4.20
Slightly gravelly sand	92,414	0.07	0.43	0.22	0.11	1467	1534	1512	21	31.13
Gravelly mud	2	0.70	1.69	0.91	0.51	845	1080	1011	102	0.00
Gravelly muddy sand	1638	0.30	0.77	0.49	0.23	1287	1447	1397	51	1.12
Gravelly sand	90,987	0.12	0.44	0.23	0.10	1486	1534	1515	16	32.35
Muddy gravel	1	0.62	0.62	0.62	0.01	1234	1394	1314	125	0.00
Muddy sandy gravel	802	0.16	0.45	0.29	0.10	1438	1510	1482	25	0.34
Sandy gravel	35,222	0.12	0.35	0.19	0.09	1492	1534	1521	13	10.33
Gravel	1942	0.13	0.25	0.18	0.05	1511	1535	1529	8	0.55
Sum	632,881									252.21

Using the figures in Table 2.2.2.3, the following standing stock rates have been used to calculate the storage values in different subtidal sediments in Wales.

Table 2.2.2.3 *Soil standing stock of POC for subtidal sediments in Wales (Armstrong et al. 2020)*

Sediment type	Standing stock ($kg\ m^{-2}$ top 10cm)
Subtidal mud	0.51040
Subtidal sandy mud	0.64584
Subtidal muddy sand	0.71442
Subtidal sand	0.36264
Subtidal slightly gravelly sandy mud	0.63315
Subtidal slightly gravelly muddy sand	0.73278
Subtidal slightly gravelly sand	0.33264
Subtidal gravelly mud	0.92001
Subtidal gravelly muddy sand	0.68453
Subtidal gravelly sand	0.34845
Subtidal muddy gravel	0.81468
Subtidal muddy sandy gravel	0.42978
Subtidal sandy gravel	0.28899
Subtidal gravel	0.27522

The need for further research on storage of POC in coarse-grained sediments with low mud contents was also highlighted.

Burrows et al. (2014) estimated a carbon store of 18 Mt of organic carbon in the top 10 cm of sediments in Scotland's seas and a standing stock of biogenic carbonate in sands and gravels of 1,739 Mt, although they note there is a considerable range of uncertainty around these estimates. These figures have since been updated by Smeaton et al. (2020) who have estimated that the surficial sediments (top 10 cm) of the mapped extended Scottish EEZ (i.e. area = 554,755 km^2) holds an estimated 1,515 ± 252 Mt C. For maps of the distribution of both sedimentary inorganic and organic carbon stocks around Scotland see Figures 2.2.2.5 and 2.2.2.6.

__Figure 2.2.2.5__. Spatial distribution of organic carbon across Scotland's continental shelf sediments (Smeaton et al. 2020)

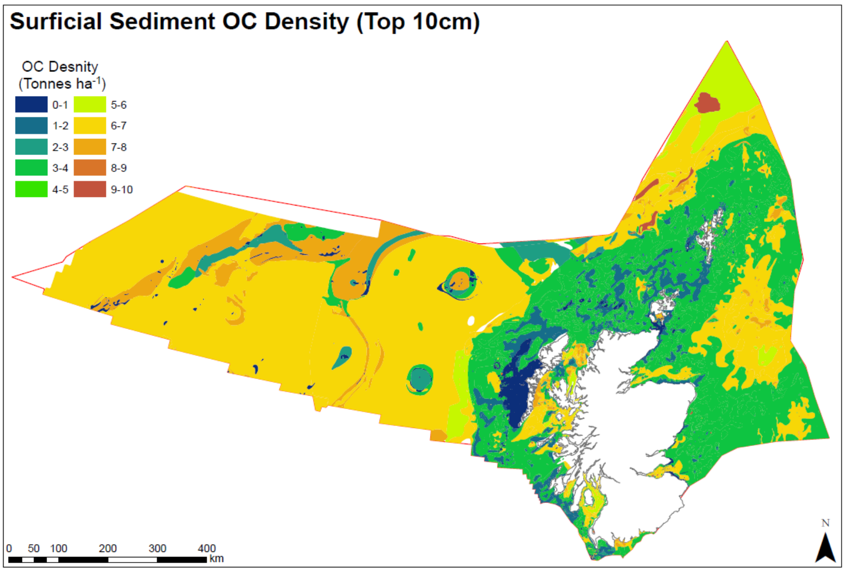
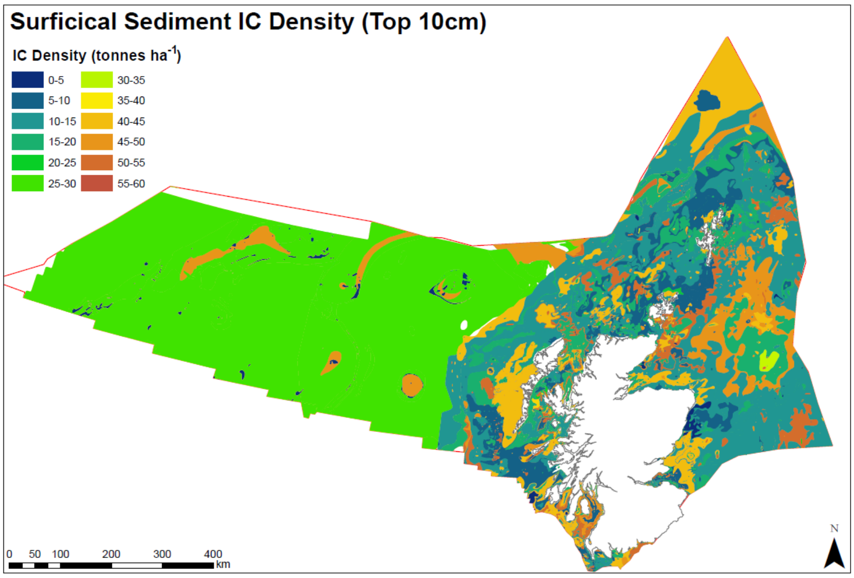


__Figure 2.2.2.6__. Spatial distribution of inorganic carbon across Scotland's continental shelf sediments (Smeaton et al. 2020)



Intertidal sediments

Intertidal sediments can store and sequester carbon in both organic and inorganic forms. This includes carbon from organic matter that is carried on to mudflats and sandflats from adjacent habitats such as saltmarsh.

Based on the work by Diesing et al. (2017) the standing stock rates in Table 2.2.2.4 were used to calculate the storage values in different subtidal sediments in Wales. The sequestration rate was estimated as 0.011-0.037 kg m^{-2} yr^{-1}, assuming an accretion rate of 2mm yr^{-1}.

__Table 2.2.2.4__ Standing stock of POC for intertidal sediments in Wales (Armstrong et al. 2020)

Sediment type	Standing stock (kg m^{-2} top 10cm)
Intertidal mud	1.02080
Intertidal sandy mud	1.29168

Intertidal muddy sand	1.42884
Intertidal sand	0.72528
Intertidal slightly gravelly sandy mud	1.26630
Intertidal slightly gravelly muddy sand	1.46556
Intertidal slightly gravelly sand	0.66528
Intertidal gravelly mud	1.84002
Intertidal gravelly muddy sand	1.36906
Intertidal gravelly sand	0.69690
Intertidal muddy gravel	1.62936
Intertidal muddy sandy gravel	0.85956
Intertidal sandy gravel	0.57798
Intertidal gravel	0.55044

Benthic biotopes in shelf seas

Carbon pools in seagrass beds are associated with the plants and the underlying sediments. Accumulation rates and storage depend on the species, sediment characteristics, depth range of the habitat, depth of the sediment being sampled and remineralization rates. There is also much variability in carbon storage capacity between geographical areas.

Most of the organic carbon in seagrass beds is stored in the underlying sediment because of the generally anoxic nature of these sediments along with continual accumulation of seagrass leaves. Where there is a dense seagrass canopy this also reduces fine-grained sediment resuspension, helping to trap sediments rich in organic matter. The combination of these processes can preserve organic carbon in seagrass sediments over decadal to even millennial time scales. A conservative estimate by Fourqurean et al. (2012) was that around 10 Pg C is stored in the top 1m of seagrass sediments giving a global estimate of stored carbon of between 25,200 to 84,000 t C/km^2.

Organic carbon (Corg) stored in the seagrass plants is mostly held in the rhizomes and roots with the larger seagrass species tending to have higher production rates, higher carbon burial rates, and higher sediment Corg stores due to a taller plant canopy, which enhances particle trapping and growth of larger, more persistent below ground tissues. The largest stores have been reported from Mediterranean meadows dominated by *Posidonia oceanica*, which is a large seagrass with extensive, long-lived rhizome mats. The carbon stored in some mats formed by *P. oceanica* are also believed to date back up to 12,500 years, while Corg stocks of other seagrass species, such as *Zostera marina* and *Cymodocea nodosa*, have typically formed within shorter time scales of up to several centuries. Carbon cannot be considered truly sequestered on a greater than 100 year timescale until it has been buried below the remineralization depth.

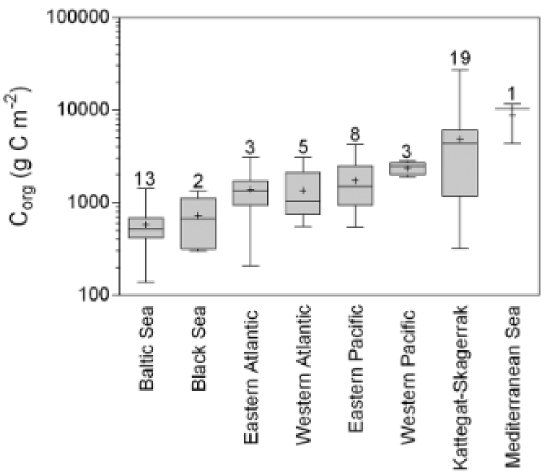
Regional studies show considerable variation in carbon storage in seagrass beds due to different factors affecting carbon stocks and accumulation rates (see Table 2.2.2.5 and Figure 2.2.2.7).

Table 2.2.2.5 *Estimates of Carbon storage in seagrass beds*

Geographical location	Seagrass species	Estimated C stock	Reference
Finland and Denmark	*Zostera marina*	627-6005 g C km^2 in the top 25cm.	Rohr et al. 2016
Kattegat-Skagerrak (19 sites)	*Zostera marina*	Projected C_{org} stock of 194.5 Mg C ha^{-1}	Rohr et al. 2018
United Kingdom (13 sites)	*Zostera marina*	500 ± 50.00 g C m² to 4,324.50 ± 1,188.00 g C m^2 in the top 25 cm of sediment. With an average carbon stock of 3,372.47 ± 1,625.79 g C m$^{2.}$ Soil standing stock: 1.35 kg m^2 (top 10 cm).	Green et al. 2018
Mediterranean (57 /29 studies)	*Posidonia oceanica*	7.29 ± 1.52 Mg C ha^{-1} living seagrass biomass and 372.4 ±	Fourqurean et al. 2012

		74.5 Mg C ha^{-1} Soil organic carbon	
Spain, Canary Islands	*Cymodocea nodosa*	total estimated stock of C_{org} 86.20 ± 19.06 Mg C ha^{-1}	Bañolas et al. 2020
Black Sea (2 sites)	*Zostera marina*	Projected C_{org} stock of 29 Mg C ha^{-1}	Rohr et al. 2018
Baltic Sea (13 sites)	*Zostera marina*	Projected C_{org} stock of 23.1 Mg C ha^{-1}	Rohr et al. 2018

Figure 2.2.2.7 *Seagrass (Z. marina) sediment organic carbon stocks (C_{org} g C m^{-2}) across the ocean margins and seas in the top 25 cm of the sediment. Box plots represent first and third quartiles and are shown with medians (horizontal line), means (+). Bars represent the 2.5-97.5th percentiles. Number of sites per ocean margin/sea are given above the bars. (Rohr et al. 2018)*



Macroalgae

Macroalgae, including kelps are not thought to be long term carbon pools but they contribute substantially to Corg export to the open ocean. Most of the primary production is either consumed by herbivores and detritivores, re-mineralised through respiration or decomposition by microorganisms and metazoans, buried in sediments, or exported away as detritus to other habitats. Their contribution to carbon sequestration and storage therefore largely occurs in depositional areas beyond the macroalgal beds.

The amount of Corg that is stored in the short term varies depending on the species of macroalgae and also the standing stock which, in the case of kelp, reduces with depth. In a study of 12 UK kelp forests dominated by *Laminaria hyperborea*, for example, there were marked differences in regional averages between the northernmost and southernmost regions with the suggestion that Scottish values were higher due to a combination of cooler water temperatures, higher light levels, longer summer days and often increased wave exposure, all of which promote greater kelp biomass (see Table 2.2.2.6).

Table 2.2.2.6 *Estimates of carbon stocks in macroalgae beds. NB most rates for kelp apply to shallow water in optimum depths of growth*

Geographical location	Species	Estimated C stock	Reference
UK (12 sites)	Predominately *Laminaria hyperborea*	Average 721 ± 140 g C m^{-2}, with the vast majority (~86%) stored in canopy-forming, rather than sub-canopy, plants.	Smale et al. 2016
UK - Scotland	Kelp	187.7 g organic carbon m^{-2} for areas where kelp was identified as being 'abundant' (>20% cover).	Burrows et al. 2014, Burrows et al. 2017

UK - Scotland	Intertidal macroalgae	489 g organic carbon m^{-2}	Burrows et al. 2017
UK - Wales	Intertidal macroalgae	Standing stock of 0.047 kg m^{-2} (representing 10% of subtidal value)	Armstrong et al. 2020

Much of the carbon originating from kelp is consumed by suspension feeders, detrital grazers and general consumers of organic material in soft sediments, and it has been estimated that more than 80% ends up as detritus and as dissolved organic matter. Its fate is likely to depend on the refractory nature of kelp detritus and its incorporation into sediments.

Krause-Jensen and Duarte (2016) reviewed available evidence of the presence of macroalgal carbon in shelf sediments and concluded that burial of macroalgal carbon beyond macroalgal habitats is at least 4 times greater than burial in macroalgal beds occurring in soft sediments - 14 and 35 Tg C yr^{-1} respectively. They made a first-order global estimate of 173 Tg C yr^{-1} of macroalgal C potentially sequestered in sediments and deep-sea waters, which amounts to about 11% of macroalgal net C production.

Biogenic reefs

Biogenic reefs have very different capacities for carbon storage. The potential for carbon storage in a variety of biogenic reefs have been investigated and, in some cases, combined with data on the extent of these habitat types to estimate carbon storage (Table 2.2.2.7).

Table 2.2.2.7*. Estimates of Carbon storage in biogenic reefs in Scotland (from Burrows et al. 2014 and Burrows et al. 2017).*

Species	Estimated C stock
Maerl – varies between species (*L.glaciale* and *P.calcareum*) and depth	Average 721 ± 140 g C m^{-2}, with the vast majority (~86%) stored in canopy-forming, rather than sub-canopy, plants. 0.8667 t C m^{-3}
Maerl	62,402.4 g C m^{-2} inorganic carbon
Lophelia pertusa reefs	Net carbon sequestration rate of ~35 g C m^{-2} yr^{-1} with a tentative estimate of standing stock of stored carbon for the Darwin Mounds of ~13500 t and for the Mingulay Reef complex ~112,000 t
Lophelia pertusa	9,375 g C m^{-2} inorganic Carbon stock
Serpulid reefs	Estimated carbonate production rate of Loch Creran reefs ~420 g C m^{-2} yr^{-1}
Serpulid reefs	781.3 g C m^{-2} inorganic carbon stock
Flame shell (*Limaria hians*) beds	63.8 g C m^{-2} inorganic carbon stock
Horse mussel (*Modiolus modiolus*) beds	Estimate carbon sequestration rate (Noss head) sequestration capacity) equivalent to ~40 g C m^{-2} yr^{-1}; estimated standing stock ~15,400 t.
Horse mussel (*Modiolus modiolus*) beds	For a mean thickness of 75cm of Modiolus beds and based on 5-7cm deep grab samples of 2 219 g $CaCO_3$ m^{-2} and a 12% inorganic carbon percentage of $CaCO_3$, the inorganic carbon stock estimate was 4,000 g C m^{-2}
Mytilus edulis beds	15.4 g C m^{-2} inorganic carbon stock using the same values as Modiolus beds
Brittlestar beds	Based on carbonate production rates for Ophiothrix fragilis in the Dover Strait an inorganic carbon production rate of 82 g C_{inorg} m^{-2} yr^{-1}

Shellfish beds

Shellfish assimilate carbon in the form of calcium carbonate, via shell production but during the calcification process CO_2 is released to the atmosphere. There is growing evidence indicating that biocalcification can contribute substantially to temperate near-shore coastal ecosystems carbon cycling, and that numerous calcifying organisms living in such ecosystems are CO_2 generators.

The role of shellfish reefs as CO_2 sources or stocks ultimately depends on the relative balance between organic and inorganic carbon burial. For example, shellfish bed habitats such as blue mussel (*Mytilus edulis*) and Horse mussel (*Modiolus modiolus*) are often considered to be a source of atmospheric CO_2 however accumulations of relict shells of dense beds may be important repositories of biogenic carbonate and may store carbon for as long as they remain undisturbed. A study of oyster reefs in the USA (*Crassostrea virginica*) found that decade-old oyster reefs had captured 0.3-2.7 Mg Corg ha^{-1} yr^{-1}, were essential for long-term carbon burial in the sandy environment as there Corg was almost completely absent in areas of similar sediment without reefs, and that burial of both organic and inorganic Carbon was related to live oyster density.

Horse mussel beds

Modiolus modiolus is a large long-lived and relatively slow growing bivalve with a robust shell. Dense beds may develop on a range of substrata from cobbles through to muddy gravels and sands, with the mussels that are partly buried in the sediment tending to have a stabilising effect, due to the production of byssal threads. Recruitment is very sporadic and therefore there is a low area-specific carbonate production rate. An assessment of Blue Carbon resources in Scotlands' inshore Marine Protected Area network estimated inorganic carbon storage in Modolius beds of 4000 g Cinorg m^{-2}.

Mytilus beds

There are several species of Mytilus in European seas and when growing in abundance they can form extensive mussel beds (principally *Mytilus edulis* and *Mytilus galloprovincialis*). Growth rates show considerable variation particular between intertidal and subtidal beds. Standing stock biomass and carbonate production rate will therefore be heavily dependent on local conditions and no single set of values can accurately represent all cases. Without detailed site-specific information (on bed/reef thickness, mussel population size structure and shell growth rate) a study of carbon storage and sequestration in marine habitats around Wales concluded that it was not possible to assign figures for individual Marine Protected Areas. Blue mussel beds were therefore treated as a "data deficient" category in this study. Stocks and rates of production and sequestration of carbon were assumed to the same as for Modiolus beds in the absence of any appropriate alternative information.

Flame shell beds

The flame shell *Limaria hians* is an epifaunal bivalve that constructs a "nest" of byssal threads interwoven with shell and algal fragments and partially infilled with trapped sediment. In dense populations these nests can form continuous reef-like structures 10-20 cm thick and several hectares in extent. The thin, delicate shells of *Limaria hians* are likely to persist for timescales of only years to decades. For this reason, and owing to the lack of data on rates of shell production, carbon sequestration was assumed to be zero in a study of carbon storage in different biogenic habitats around Scotland, but shell densities suggest a standing stock of 63.8 g Cinorg/m^2 (Burrows et al. 2014).

Serpulid reefs

The serpulid polychaete *Serpula vermicularis* is common and widespread throughout Scottish waters but the formation of reefs composed of masses of aggregated tubes is a very localised phenomenon. However, on a local scale they can form an important biogenic habitat and their calcareous tubes (occupied or relict) are a potential blue carbon stock.

Brittlestar beds

As echinoderms, brittlestars have an endoskeleton of calcareous plates, and due to their abundance in virtually all benthic environments they may play an important (and largely overlooked) role in the marine carbon cycle (Lebrato et al. 2010). Brittlestar skeletal fragments will be subject to the same processes of bioerosion and chemical dissolution as carbonates produced by corals, serpulids or bivalves, and the timescale of their persistence in sediments will depend on the local environment and the potential for burial below the Taphonomically Active Zone (Walker and Goldstein 1999).

Off Keppel Pier, Great Cumbrae, Aronson (1989) recorded densities of *Ophiocomina nigra* in excess of 2 000 individuals m^{-2}. On this scale, brittlestar beds represent substantial concentrations of benthic biomass. Like all echinoderms, brittlestars have an endoskeleton of calcareous plates, and owing to their abundance in benthic environments throughout the oceans, carbonate-producing echinoderms may play an important (and largely overlooked) role in the marine carbon cycle (Lebrato et al. 2010). The potential contribution of brittlestar beds to carbon storage in Scotland's inshore MPA network therefore warrants consideration.

Maerl beds

Maerl is a collective term for several species of coralline red algae which secrete a calcareous skeleton and grow as unattached nodules (rhodoliths), often with a complex branching structure. The calcium carbonate skeleton of maerl persists after the death of the living algal tissue and accumulates to form long-lasting deposits. These deposits act as a long-term store for inorganic carbon and lock-up associated calcifying biota in their matrix-like structure. As maerl beds are long-lived this is a continuous standing stock of organic and inorganic carbon which has likely been accreted since the Holocene deglaciation.

Production and sequestration of inorganic carbon was taken as 74 g C_{inorg} m^{-2} yr^{-1}, the average of rates reported for *Lithothamnion glaciale* and *Phymatolithon calcareum*, assuming the beds were 60cm deep. Stock and production rates of organic carbon were assumed to be negligible.

Deep water coral reefs (Lophelia pertusa)

Lophelia pertusa, is a deep water coral that forms reef under certain conditions particularly related to water temperature and currents. In Europe such reefs are known to occur in deep waters off Scandinavia, the British Isles and the Mediterranean Sea. Around the North-East Atlantic margin they are present in the approximate depth range 100-1,500 m.

Estimates of carbon storage requires a figure for the mass per unit volume of *Lophelia pertusa*. Using calculations based on dried specimens and mapping data on the extent and size of mounds, the standing stock of stored carbon has been calculated for two areas of Lophelia reef in Scottish waters: the Darwin Mounds (~13500t) and the Mingulay Reef complex (~11200t). The carbon storage capacity of the Darwin Mounds is represented solely by the living coral colonies as cores did not contain carbonate mud or concentrated accumulations of dead coral. The Mingulay Reef Complex includes both living coral framework and accumulations of relict calcareous material which collectively represent a carbon stock operating over a timescale of up to 7.7 thousand years ago, based on radiocarbon dating of coral fragments. It has therefore acted as a repository of stored carbon over a timescale of several millennia.

Using calculation of coral mass per unit area, the carbon stock on this reef has been estimated as 9 375 g Cinorg m^{-2}. Rates of accumulation of *Lophelia pertusa* mounds, based on growth rates on Norwegian reefs and on North Sea oil/gas platforms suggested a net sequestration rate of 35 g Cinorg m^{-2} yr^{-1}, once loss by bioerosion and chemical dissolution is taken into account.

2.3 Management measures to store carbon in ecosystems

2.3.1 Terrestrial Ecosystems

There are roughly three different types of measures aimed at improving the condition of natural habitats:

1) measures to conserve a habitat type (e.g. preventing succession, reducing possible negative impacts from outside the system)
2) measures to restore a habitat type (e.g. improving biotic and abiotic conditions)
3) land-use change, increasing the area of a habitat type (e.g. to extent existing habitats, making them more robust, or to connect existing habitats)

In general measure aiming at removing nutrients or biomass from a system (for examples to restore eutrophicated systems, or to convert forest land to a more biodiverse heathland to connect areas or to make a habitat more robust) will result in losses of carbon stocks, and hence will contribute to accounted emissions from the land-use sector. Measures that improve water management and rewet soils in nature areas will usually have a positive effect, particularly in areas with organic soils, and will result in a reduction of CO_2 emissions from the soil. Although temporary wetting can lead to an increase in CH_4 emissions from the soil. Both biodiversity and climate both are under pressure. Partly these pressures are similar and measures and solutions to improve one are also beneficial for the other. Wetlands and forest are two important terrestrial ecosystems important for the carbon stocks and carbon sequestration rates and because of the large areas covered by these ecosystems.

Wetlands, and especially peatlands may contain large carbon stocks. Land use changes and drainage of the wetlands cause substantial CO_2 emissions. While wetlands can be restored and carbon sequestration increased, it does not compensate for the net C accumulation in the original system before drainage (Waddington and Price 2000) meaning wetland protection is preferable to restoration.

Forest management and tree species selection have a significant impact on the storage of carbon in forests (Nabuurs et al. 2018). Read et al. (2009) reported large carbon stocks of 218 Mg C ha^{-1} in an unmanaged nature forest reserve. Although the large carbon stock was, the carbon sequestration rate was relative low: 1.6 Mg C ha^{-1} yr^{-1}. In an intensively managed even-aged forest this was the other way around. A carbon stock of 109 Mg C ha^{-1} was reported while the carbon sequestration rate was 6 Mg C ha^{-1} yr^{-1}, and in a wood biomass forest plantation carbon stock was 55 Mg C ha^{-1} and the carbon sequestration rate was 7.9 Mg C ha^{-1} yr^{-1}. So if large carbon stocks are pursued for the long term, unmanaged forest could be a good option. If there is a short term objective to rapidly store carbon, then intensive forest management could be a good option.

It is also clear, however, that there may be cases where trade-offs occur between nature conservation and restoration objectives and climate mitigation actions. These will need to be carefully weighted to make sure that climate mitigation policy and related actions will not negatively important nature conservation and restoration objectives, and the other way around.

2.3.2 Marine ecosystems

There are similarities between approaches to the management of terrestrial and marine habitats however in the case of the marine environment, there are typically fewer opportunities for active intervention. In most cases marine management is likely to centre around regulation and guidance on how particular activities should be carried out to prevent or minimise anthropogenic impacts. The establishment of Marine Protected Areas (MPAs) compliment such measures by focusing conservation action in particular locations as well as having the potential to act as reference or control areas to study impacts and changes in the marine environment including from climate change such as sea level rise and changes in species distribution.

The IPCC identify two management approaches that are more specific to climate change (IPCC, 2019). Firstly, actions that maintain the integrity of natural carbon stores, thereby decreasing their potential release of greenhouse gases, whether caused by human or climate-drivers; and secondly, actions that enhance the long term (century-scale) removal of greenhouse gases from the atmosphere by marine systems, primarily by biological means. For example through protection of habitats such as seagrass and maerl beds or enhancing the natural carbon uptake of some marine habitats, not only by increasing their spatial coverage through habitat restoration and new habitat creation, but also by taking management measures to maximise the carbon uptake and storage for existing coastal ecosystems. Such measures include reducing anthropogenic nutrient inputs and other pollutants; restoring hydrology, by removing barriers to tidal flow and sediment delivery; and reinstating predators (to reduce carbon loss caused by some bioturbators). (IPCC 2019).

At the global scale, synthesis studies have estimated the potential additional sequestration achieved by cost effective coastal blue carbon restoration as ~0.05 Gt C yr^{-1} (Griscom et al. 2017) and 0.04 Gt C yr^{-1} (National Academies of Sciences, Engineering, and Medicine 2019), assuming that a relatively high proportion of vegetated ecosystems can be re-instated to their 1980–1990 extents.

Measures to stimulate and/or safeguard carbon storage in the marine environment to date have considered just a small number of marine habitats, the details of which are summarised below. These are benthic habitats, the focus of this review, however it is critical to also note that ecologically degraded ocean waters lose their capacity to support the carbon cycle and act broadly as a carbon stock (IUCN 2017).

The measures described below are relevant to habitat protection and restoration. Other approaches such as ocean fertilisation with the addition of iron and macronutrients and injection of captured CO_2 into geological reservoirs are being investigated as potential mitigation measures for climate change (e.g. Brewer et al. 2018) but are not discussed in this review.

Subtidal sediments

Of the habitat types reviewed, subtidal sediments with a high mud fraction have the greatest potential to store carbon. Relevant management measures for this habitat are those which either maintain such capacity to store carbon or restore it where it has been degraded.

Anthropogenic activities such as fishing, dredging and the installation of offshore structures that affect the mixing of sediments, including disturbing the infauna, will affect carbon storage in shelf sea sediments (Alonso et al. 2012, Hale, R. et al. 2017). Preventing or reducing such disturbance from human activities is therefore a management option to consider.

Bottom trawling can shift the infauna of sedimentary biotopes towards short lived small species and can therefore change the amount of carbon in the associated food webs and how much carbon goes into detritus (Duplisea et al. 2001). Mixing the top layers of sediment also has implications for carbon mineralisation. Pusceddu et al. (2014) showed trawling affecting sediments to a depth of 10 cm with a 52% reduction in organic carbon storage, slower carbon turnover and reduced meiofauna (or mesofauna) abundance and biodiversity.

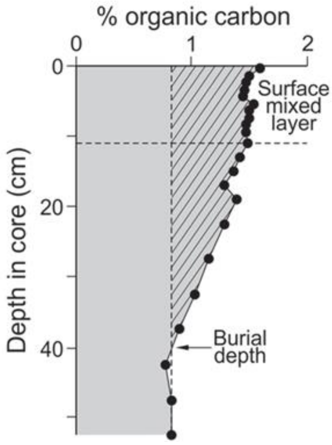
In areas with low natural disturbance, such as parts of the central North Sea, it has been suggested that trawling disturbance is likely to account for a significant proportion of total disturbance removing bioturbators from the system and acting as a strong physical mixing force that will affect how a soft sediment system will mineralise carbon (Duplisea et al. 2001).

Luisetti et al. (2019) have proposed that cessation of bottom trawling would promote improved carbon storage in subtidal sedimentary habitats. However, Armstrong et al. (2020), in examining carbon storage potential of marine habitats in Welsh waters, note that there is a lack of data and understanding of the complex processes that affect carbon storage in the potentially mobile fraction of marine sediments. They conclude that due to these uncertainties, there is currently low confidence that control of sediment disturbance can be used for climate mitigation.

Seagrass

The protection and restoration of seagrass beds for biodiversity conservation has also been investigated for their role in carbon storage and sequestration. Per unit area of habitat created, restored or rehabilitated, it has been calculated (Isensee et al. 2019) that in the case of seagrass ecosystems, carbon removal rates could be as much 138 ± 38 g C m-1 yr^{-1} although there is considerable variation between the species (see above). Longer term storage only takes place when the carbon is incorporated into the underlying sediment and calculating this potential requires reliable determination of sediment accumulation and knowledge of the burial depth (Figure 2.3.2.1) (Johannessen and Macdonald 2016).

Figure 2.3.2.1 *Typical organic carbon concentration profile in a coastal sediment core. Organic carbon continues to be remineralized below the surface mixed layer of the sediment. The concentration becomes approximately constant at the burial depth, below which it is only minimally remineralized. Carbon is not sequestered over the long term until it reaches the burial depth. (Johannessen and Macdonald 2016).*



The age of seagrass beds is also relevant to its carbon storage potential. An investigation into carbon storage of restored *Zostera marina* beds revealed higher rates of carbon accumulation in 10 year seagrass beds relative to a 4 year bed and bare sediment (Greiner et al. 2013). After 4 years there was little change because the shoot densities were insufficient to reduce resuspension and shallow mixing of sediment compared to bare sediments but within 10 years the seagrass had stabilized and trapped sediment more effectively allowing for sediment accretion. The study concluded that within 12 years of seeding, the restored seagrass beds would be expected to accumulate carbon at a rate that is comparable to measure ranges in natural seagrass beds (Figure 2.3.2.2 and Figure 2.3.2.3).

Figure 2.3.2.2 *Vertical average down-core profiles of sediment characteristics in the top 10 cm. A) Percent organic matter (% OM);* ***B****) Percent organic carbon (% C);* ***C****) Percent nitrogen (% N) for 4 age treatments (0- (HI), 4-, 0- (SB), and 10-year) in top 10 cm of sediment, where error bars indicate standard error. Averages for each variable were calculated in 1-cm intervals to a depth of 10 cm. (Greiner et al. 2013)*

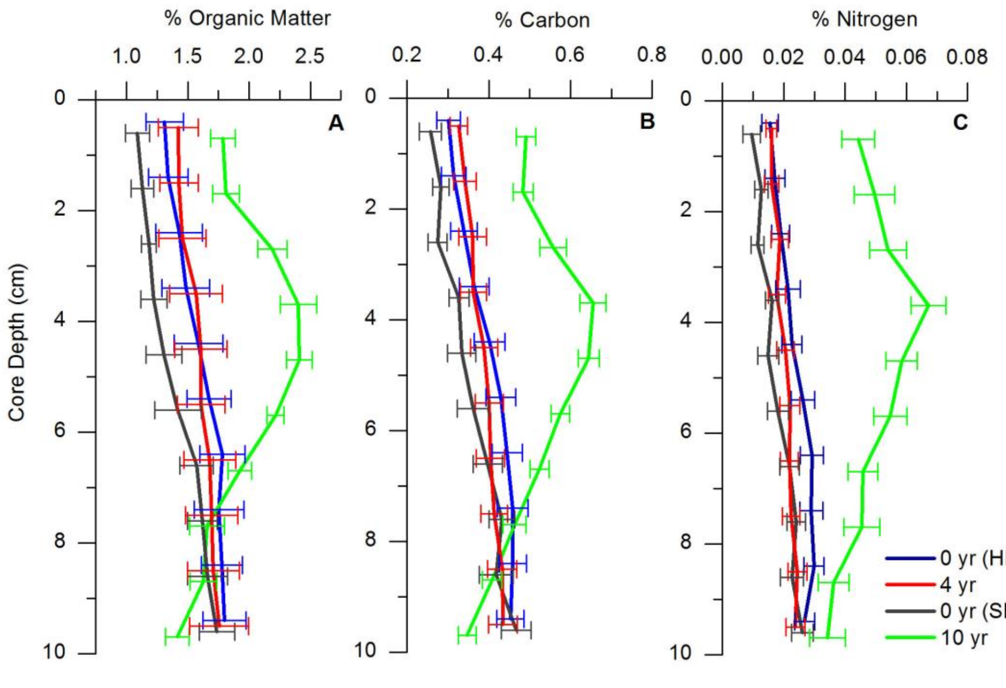
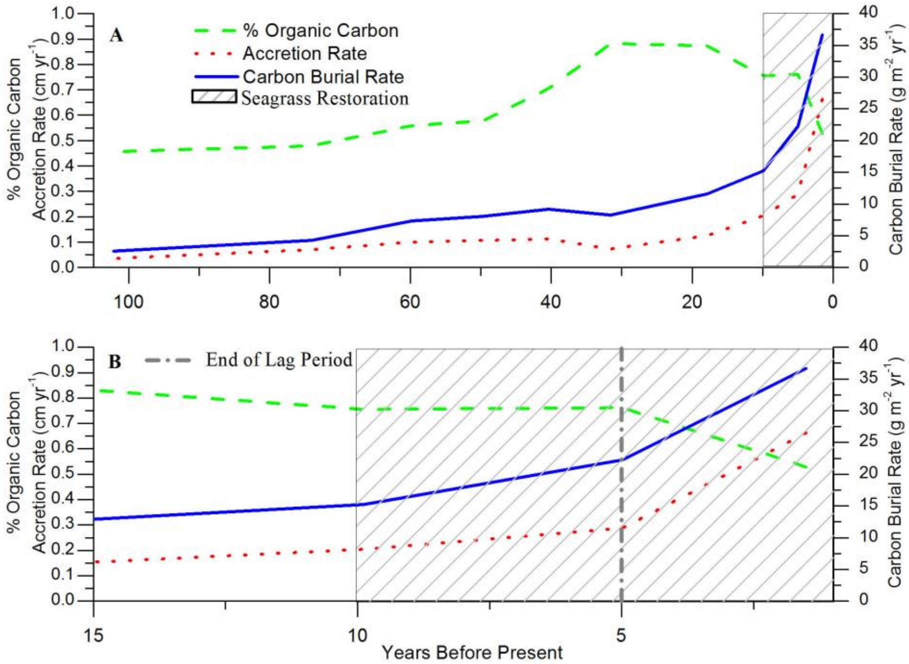


Figure 2.3.2.3 *Record of sediment accretion rate, percent organic carbon, and carbon burial rate in 10-year treatment. A) Historical record in the 10-year treatment (SB) of sediment accretion rate, percent organic carbon, and carbon burial rate with years before present starting in 2011 (= 0 on x-axis). B) Recent record in the 10-year treatment of sediment accretion rate, percent organic carbon, and carbon burial rate with years before present starting in 2011. Time influenced by seagrass restoration (10 years) is enclosed in box with grey diagonal lines. The vertical, grey hyphenated line at 5 years before present indicates the end of the 5-year lag period, where before there was little change in carbon burial rates due to low seagrass density. (Greiner et al. 2013).*



Macroalgae
Seaweeds do not directly transfer carbon to marine sediments, unlike rooted coastal vegetation. Nevertheless, seaweed detritus can deliver carbon to sedimentary sites and may provide a source of refractory dissolved organic carbon (Hill et al. 2015, Krause-Jensen and Duarte 2016). Recent studies indicate that globally important amounts of carbon may be involved in these processes (Krause-Jensen and Duarte 2016, Krause-Jensen et al. 2018, Smale et al. 2018). Armstrong et al.(2020), in examining the carbon storage potential of marine habitats in Welsh waters, considered there was low confidence that enhancement of natural seaweed production would provide a significant mitigation response, due to large uncertainties relating to sequestration duration and effectiveness. Such considerations relate to transport pathways, the fate of material transported to deeper water, and the timescales of its subsequent return to the atmosphere over decadal to century timescales.

Shellfish beds
A number of studies have discussed or investigated the benefits of conserving or restoring shellfish beds for their role in carbon storage (E.g. Fodrie et al. 2017, Armstrong et al. 2020). The rates of accretion of a study of oyster reefs (C.virginica), for example, vary depending on factors such as the stage of reef growth (e.g initial rapid accretion) as well as where they fit into the landscape (e.g. intertidal reefs that are isolated or fringing saltmarsh). However, the net effect of habitat destruction for all reefs, regardless of whether they function as sources or stocks before disturbance, is probably CO2 release (Fodrie et al. 2013). In the case of the farmed Mediterranean mussel Mytilus galloprovincialis, estimates of sequestration for shell formation and fluxes due to respiration and calcification, indicate that mussel farming appeared to be a significant additional source of CO2 to sea water and should therefore not be considered as part of carbon trading systems (Munari et al. 2013).

3 Classification of ecosystems according to their potential for carbon storage and sequestration

3.1 Terrestrial ecosystems

Ecosystems differ largely with respect to their carbon stocks and carbon sequestration rates. Wetlands may store large stocks of carbon. Open sand dunes on the other hand, store very low amounts of carbon and due to the lack of vegetation, no carbon is sequestered. But also within one ecosystem type carbon stocks may vary widely. For instance in peatlands, where the total amount of carbon depends mainly on the thickness of the peat layer which may vary from only a couple of centimetres to several meters. The amount of stored carbon thus may vary strongly for the same habitat types. This may also hold for other ecosystems of which in many cases the soil carbon pool is the largest stock of the different ecosystem components. In general many ecosystems occur on a broad range of soil types, implying also a wide range of carbon ecosystems. This wide range in carbon stocks of one ecosystem and of comparable ecosystems makes it difficult to distinguish clear class borders.

On the base of the literature results found, classes were designed for the carbon stocks and carbon sequestration rates of terrestrial ecosystems. Meaningful classes were shaped, which are not too broad and which are based on an adequate number of observations. An odd number of classes were designed so it could contribute to a qualitative classification like high-moderate-low. Following these criteria and the number of observations found, 5 classes were designed both for the carbon storage and the carbon sequestration rate. Class ranges and number of values per class are given in Figure 3.1.1 and Figure 3.1.2 for the carbon pool and carbon sequestration rate respectively.

Figure 3.1.1 *Classes used to categorise carbon stocks of terrestrial ecosystems (with number of literature references of ecosystems in the classes)*.

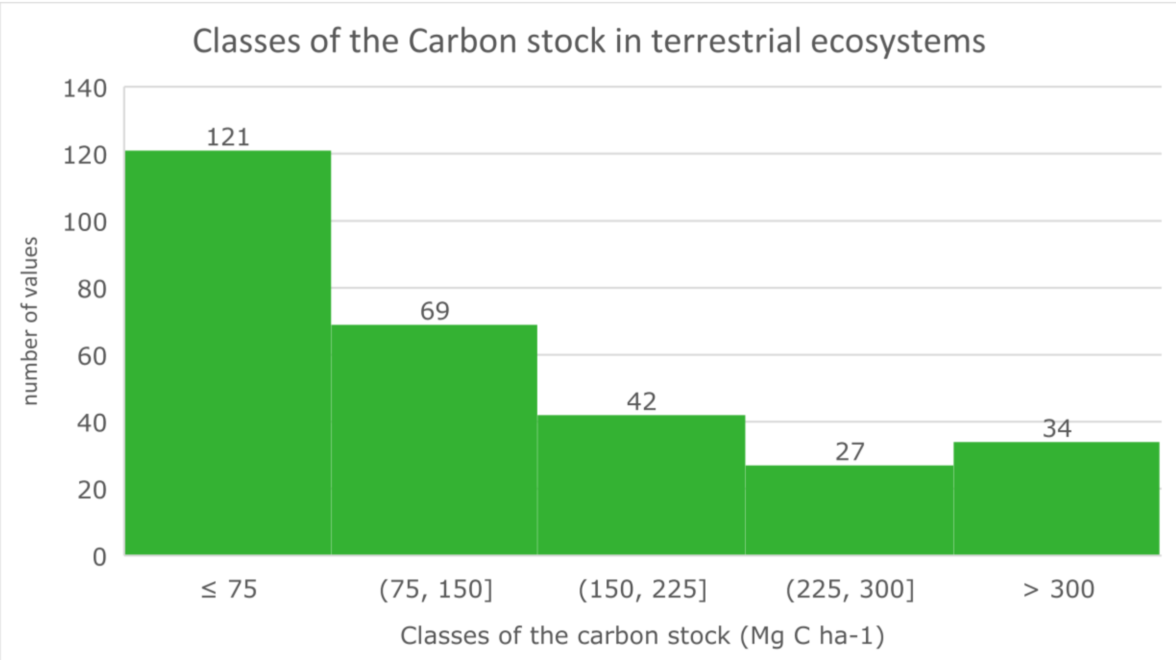


Table 3.1.1 *Applied classes for carbon stocks of terrestrial habitats.*

CLASS number	Class range in carbon stocks (Mg C ha^{-1})
1	<75
2	75-150
3	150-225
4	225-300
5	>300

Figure 3.1.2 *Classes used to categorise carbon sequestration rate of terrestrial ecosystems (with number of literature references of ecosystems in the classes).*

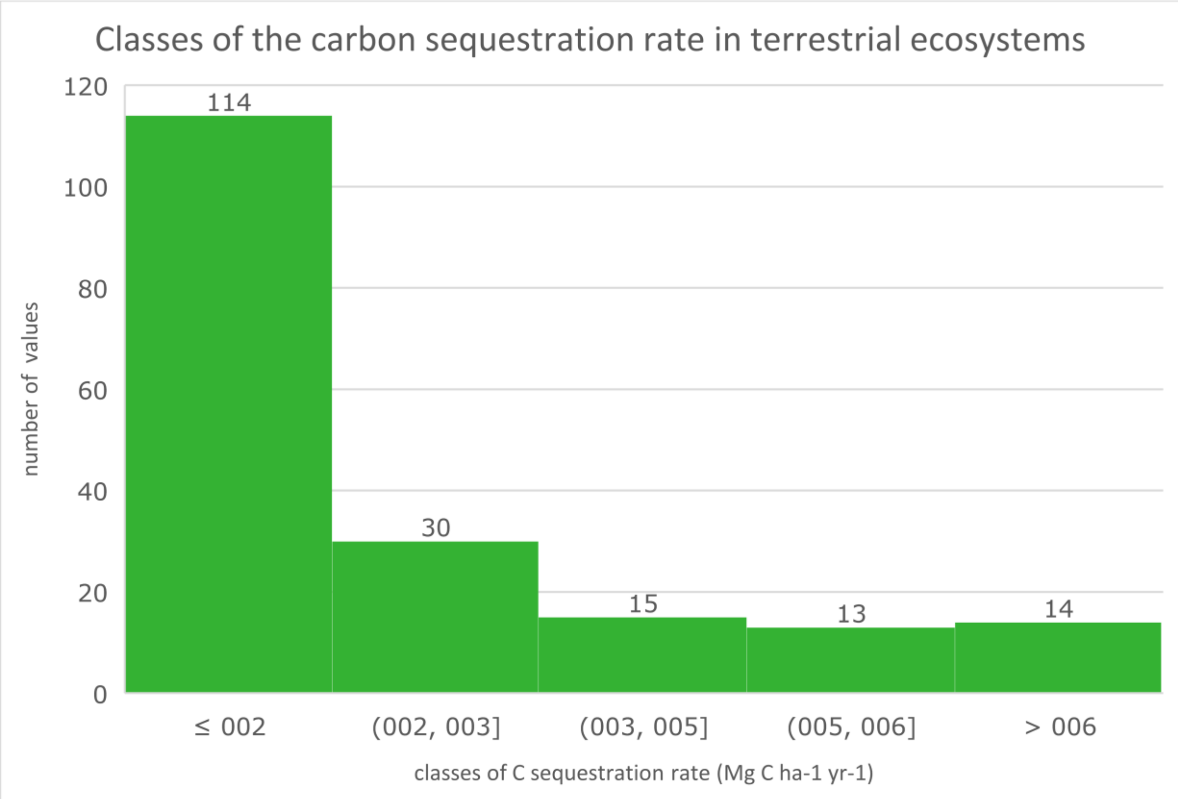


Table 3.1.2 *Applied classes for carbon sequestration of terrestrial habitats.*

CLASS number	Class range in carbon sequestration rate (Mg C ha^{-1} yr^{-1})
1	<1.5
2	1.5-3.0
3	3.0-4.5
4	4.5-6.0
5	>6.0

3.2 Marine ecosystems

The ocean is the largest carbon stock on Earth and investigations into the potential of different marine habitats to store and sequestrate carbon has been the subject of an increasing numbers of studies in the last two decades. Despite this, there remain considerable gaps in our knowledge of this potential across marine habitats. There is also scientific uncertainty and different degrees of confidence in our understanding to date. The results of this review illustrate these points as data have only been found for a small number of marine habitats (especially when they are cross-referenced to the EUNIS classification scheme), and even in these cases can show considerable variation across studies. The categorisation into five classes, presented below is therefore based on limited data with these various shortcomings. For both carbon stocks and carbon sequestration rates, the classes have been selected to cover the full range of data available, in evenly divided classes. As data are refined and information becomes available about other marine habitats, the division of these classes may need to be adjusted however they provide a good overview, based on current knowledge, for the present analysis.

The distinguished classes for the carbon pools and carbon sequestration rates are presented in Table 3.2.1 and 3.2.3 respectively.

Table 3.2.1 *Applied classes for carbon stocks of Marine habitats.*

CLASS number	Class range in carbon stocks (Mg C ha^{-1})
1	<10.00
2	10-50
3	50-100
4	100-150
5	>150

Table 3.2.2 *Applied classes for the carbon sequestration rate of Marine habitats.*

CLASS number	CLASS range in carbon sequestration rate (Mg C ha^{-1})
1	negligible
2	<0.01
3	0.01-0.50
4	0.50-1.00
5	>1.00

4 Carbon stocks and sequestration rates

The observations of carbon stocks and carbon sequestration rates found in literature are very diverse because of different methods applied in the underlying studies. We have tried to interpret the data as accurately as possible, but still there are restrictions to the comparability of the different observations. Also studies vary in the carbon pools considered. For terrestrial ecosystems for example some only focus on living biomass, while other focus on soil organic matter. Relatively few studies cover all relevant terrestrial carbon storage of the ecosystem studied. Therefore, the results presented here have to be interpreted as indicative estimates.

The results of the classification of the EUNIS habitat types on their carbon storage and carbon sequestration rate is given in Annex 1 for terrestrial ecosystems and in Annex 2 for the marine ecosystems.

4.1 Terrestrial ecosystems

Large differences are found in the carbon observed stocks between and within the ecosystems (Figure 4.1.1). The range of carbon stocks are reflecting the amount of carbon stored in the living biomass (above and below ground), dead biomass (stems, branches, litter) and soil organic matter. Soil organic matter in most ecosystems forms the largest sub-storage of the total carbon pool. In some studies very large soil carbon pools were found. Nieder and Benbi (2008) report a soil carbon content of 638 Mg C ha^{-1} for an artic tussock/sedge dwarf shrub vegetation and a living biomass C content of 73 Mg C ha^{-1}. This is the one but highest carbon pool mentioned we found in literature. The highest was found for a herb-rich sedge fen in boreal Finland where a carbon pool of 827 Mg C ha^{-1} was reported (Turunen et al. 2002). However, also studies were found where only one or two carbon pools of biomass were reported. This might lead to misinterpretation if not taken into account. For instance Schlesinger 1997) reports a C content of 80 Mg C ha^{-1} for broadleaf forest of the temperate zone, and which is referring to the C pool in living trees. Lesschen et al. report for a comparable forest type 81 Mg C ha^{-1} which is quite comparable, but also the C contents of the other sub-pools are mentioned summing up to a total C stock in the ecosystem of 201 Mg C ha^{-1}.

The C stocks presented in Figure 4.1.1 includes both the observations of a single or just several sub-pools, and of the total C stock in the ecosystem. This partly explains the wide range in C stocks within the ecosystems. This problem can be overcome by extracting estimations of C pools from literature for the different ecosystem compartments of comparable ecosystems and then calculate averages for each sub-pool and combine them to estimate the total C pool for the regarding ecosystem. This might create more mutual comparable values of the total C stocks and sequestration rates.

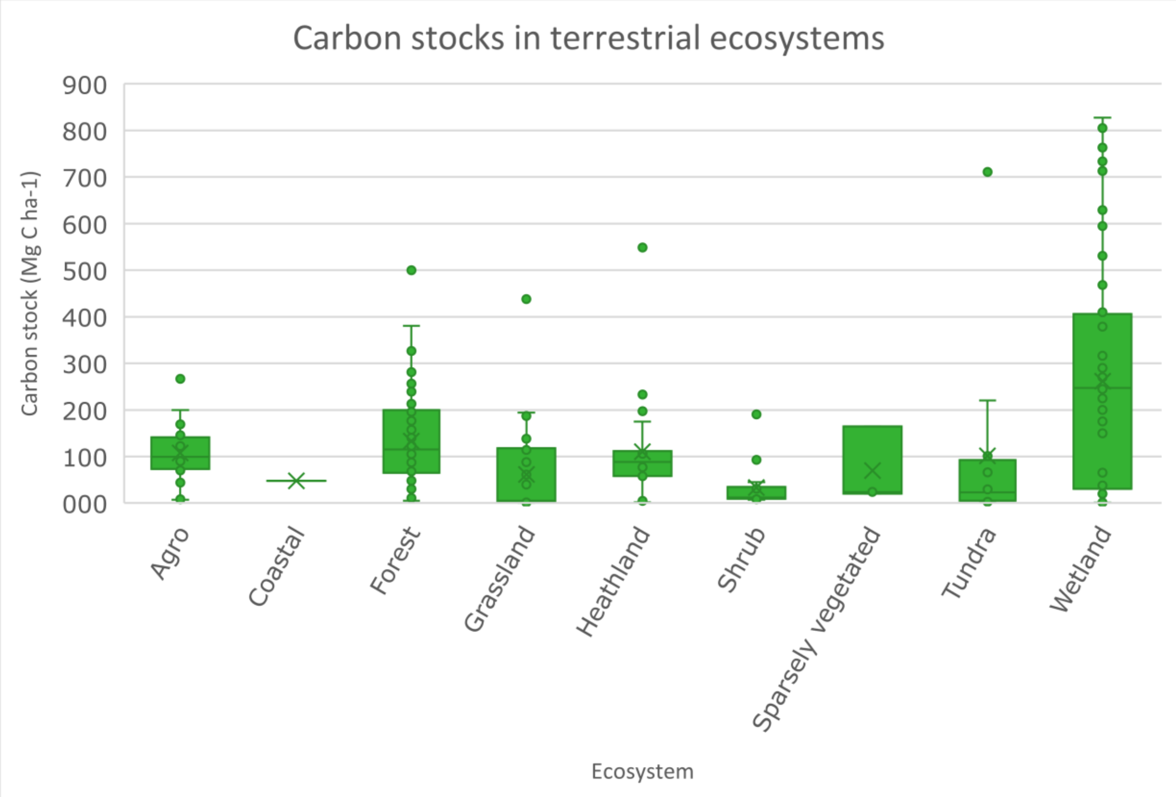


Figure 4.1.1 *Carbon stocks (Mg C ha^{-1}) in terrestrial ecosystems.*

Table 4.1.1 *Carbon stocks in terrestrial ecosystems (Mg C ha^{-1}) mean, median, minimum, maximum and number of observations (n)*

Ecosystem	n	mean	median	min	max
Agro	24	107.7	99.0	7.0	266.7
Coastal	1	48.0	48.0	48.0	48.0
Forest	111	133.0	115.5	5.0	500.0
Natural grassland	33	61.3	5.0	0.5	438.0
Heathland	23	110.3	88.0	2.0	548.6
Shrub	14	33.5	12.0	6.9	190.1
Sparsely vegetated	3	69.7	24.0	20.6	164.5
Tundra	12	101.2	23.2	1.5	711.0
Wetland	72	261.8	247.2	0.9	827.1
Total	293	145.7	96.0	0.5	827.1

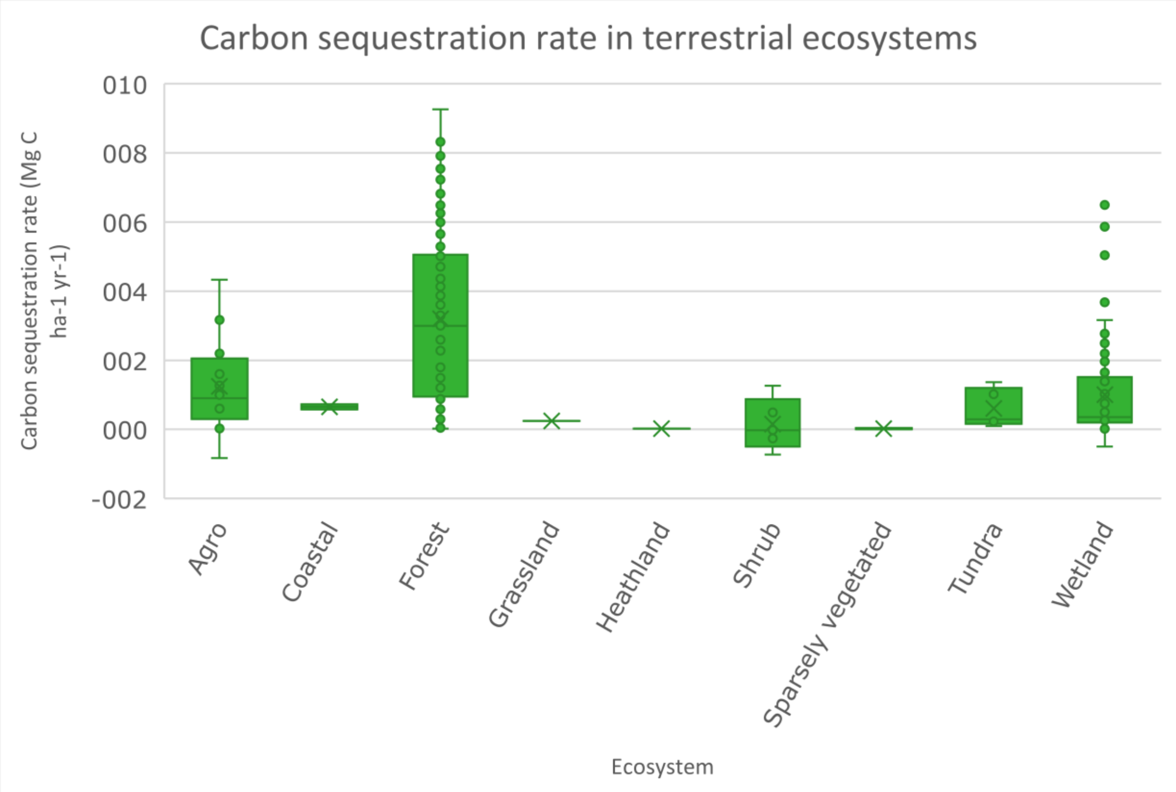


Figure 4.1.2 *Carbon sequestration rate (Mg C ha^{-1} yr^{-1}) in terrestrial ecosystems.*

Table 4.1.2 *Carbon sequestration rates in terrestrial ecosystems (Mg C ha^{-1} yr^{-1}) mean, median, minimum, maximum and number of observations (n)*

Ecosystem	**n**	**mean**	**median**	**min**	**max**
Agro	12	1.25	0.90	-0.83	4.33
Coastal	2	0.66	0.66	0.58	0.73
Forest	73	3.20	3.00	0.02	9.26
Grassland	1	0.24	0.24	0.24	0.24
Heathland	1	0.02	0.02	0.02	0.02
Shrub	5	0.15	-0.02	-0.73	1.26
Sparsely vegetated	2	0.02	0.02	0.00	0.04
Tundra	5	0.60	0.29	0.10	1.37
Wetland	85	1.01	0.35	-0.49	6.50
Total	186	1.83	0.99	-0.83	9.26

From literature we found more observations for carbon stocks (303) than for carbon sequestration rates (196). Highest carbon sequestration rates were found for forest ecosystems in Switzerland, modelled values were calculated of 9.26 Mg C ha^{-1} yr^{-1} (Schelhaas 2020) (Fig. 4.1.2). The high rate is due to a very high input of carbon in the litter layer which amounts 7.55 Mg C ha^{-1} yr^{-1}. This input rate for litter is about 2 to 3 times as high as for forests in Sweden, Finland, Italy, Spain and Ukraine (Schelhaas 2020). Also the carbon sequestration rates in the living tree biomass vary significantly from 0.01 Mg C ha^{-1}yr^{-1} for forest in Greece (Liski et al. 2002) to 7.91 Mg C ha^{-1} yr^{-1} in a biomass production forest in the UK (Read et al. 2009). Most observations found relate to forests, agroecosystems and wetlands. The variation in carbon sequestration rate in most of the other ecosystems was low due to the limited number of observations found.

Negative sequestration rates are reported for agroecosystems, shrubs and wetlands (table 4.1.2). Although, also other ecosystems can have negative sequestration rates, depending on the site conditions and the measuring method. Negative rates are due to high rates of decomposition of soil organic matter, and may reach high values in drained or dehydrated peat soils. Soil respiration rates in such circumstances may be greater than the carbon storage rate, resulting in a negative sequestration rate. These ecosystems then act as a net carbon source.

4.2 Marine ecosystems

On the base of observations for the marine habitats found in literature the marine habitats were classified as shown in table 4.2.1 regarding their carbon pool and in table 4.2.2 regarding their carbon sequestration rate. The classification per EUNIS habitat type is given in Annex 2.

The carbon storage potential of benthic marine habitats that have been studied show considerable variation with flameshell beds and faunal turfs for example, having far lower potential than maerl beds and *Lophelia* reefs. On the other hand it should be noted that carbon is exported from some of these habitats, in particular kelp forest and intertidal macroalgae, to the offshore environment, where they may be incorporated into sediments once decomposed and therefore contribute to the long term storage potential of such sediments. There is also variation within some of the studied habitats which should not be attributed to the method of study or confidence limits. In the case of seagrass beds, for example, the species under investigation makes a significant difference to rates of carbon storage and sequestration. The same is true for intertidal and subtidal sediments where the rates are strongly influenced by the detailed composition (e.g. mud fraction).

Other important considerations when reviewing data on carbon storage and sequestration associated with marine habitats are that while some have a low capacity (e.g. subtidal sediments) they cover large areas of the continental shelf and can therefore make a very significant contribution to carbon storage and sequestration in absolute terms. Changing and long-term storage capacity is also not reflected in these figures. With *Zostera marina* seagrass beds, for example, there appear to be higher rates of carbon accumulation in older beds and, in the case of *Lophelia* reefs where bioerosion and chemical dissolution can take many years, they can act as carbon stocks for thousands of years.

Table 4.2.1 *Applied classes for carbon stocks for Marine habitats.*

CLASS number	Class range in carbon stocks ($Mg\ ha^{-1}$) (based on highest estimates)	Habitat type
1	<10.00	Kelp forest, intertidal macroalgae, flameshell beds, serpulid reefs, brittlestar beds, blue mussel beds, faunal turfs, subtidal shelf sediments. subtidal oyster beds
2	10.00-49.99	Seagrass beds, horse mussel beds, intertidal sediments
3	50.00-99.99	
4	100.00-149.99	*Lophelia* reefs
5	>150	Maerl beds

Table 4.2.2 *Applied classes for the carbon sequestration rate of Marine habitats.*

CLASS number	Class range in carbon sequestration rate ($Mg\ C\ ha^{-1}\ yr^{-1}$) (based on highest estimates)	Habitat type
1	negligible	Kelp forest, intertidal macroalgae, faunal turfs, flame shell, serpulid reefs
2	<0.01	Subtidal shelf sediments
3	0.01-0.50	*Lophelia* reefs, horse mussel beds, blue mussel beds, intertidal sediments, subtidal oyster beds
4	0.50-1.00	Seagrass beds, brittlestar beds
5	>1.00	Maerl beds

5 Discussion

Measures to store carbon in ecosystems may have trade-offs for biodiversity and ecosystem services. Therefore measures to store carbon should be taken with care. In many cases it holds that conservation of existing ecosystems is preferable to restoration as with regards to carbon stocks.

Scientific literature shows a wide range of information on carbon pools and carbon sequestration rates, both qualitative and quantitative. It, however, also shows a very wide range of methods used to gather the information. This range in methodological approaches comprises amongst others:

- Focus on different ecosystem components (e.g. only phytomass or soil organic carbon), different measuring methods (e.g. loss of ignition, measurement of carbon fluxes, or model estimations)
- Different demarcation of carbon pool components (e.g. only tree stems vs. whole trees [leaves, branches, stem, roots] for the determination of living biomass carbon stocks, or different soil or marine sediment depths 0-15 cm, 0-30 cm, 0-100 cm for determination of the soil organic carbon).
- Use different carbon sequestration entities. Some studies use Gross Primary Production (GPP), others Net Primary Production (NPP), others Net Ecosystem Production (accounting for SOM and litter decomposition), others Net Biome Production (NBP) taking into account CO_2 loss caused by fires, drought, pests, human activities etc. (Fig. 5.1).

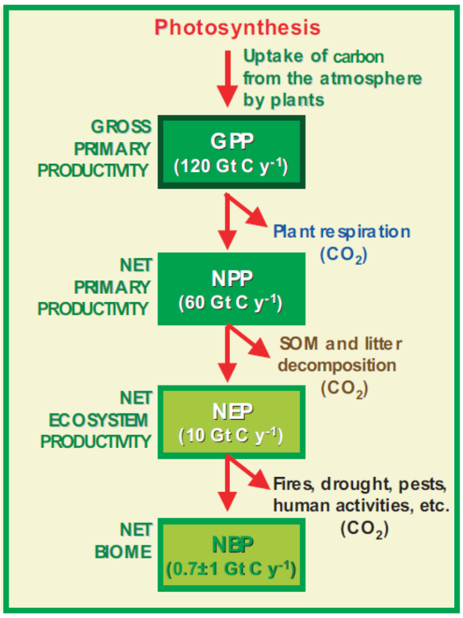


Figure 5.1 Terrestrial global carbon balance and different productivity entities (FAO 2004)

While all these productivity entities somehow relate to how much carbon enters the system, for assessing carbon stocks and carbon sequestration from a climate mitigation point of view, NEP would be the correct process to look at. For instance grasslands and other ecosystems dominated by annual plant species may have a high NPP, but since at the end of the growing season all living biomass dies part of the carbon in biomass is released again through decomposition processes. Although part of this carbon enters the dead organic matter and soil organic matter pools, in undisturbed ecosystems this usually is in balance with the decomposition occurring in these carbon pools, resulting in a dynamic equilibrium. Hence some ecosystems with a high NPP actually over longer periods of time do not store additional carbon, while other (perennial and forest) systems continue to store carbon in biomass with relatively limited NPP values.

- Different time scales. Some studies measure just at one moment in time, others measure over one or more years. Some (model) studies even estimate carbon pools and sequestration rates even over hundreds of years. Carbon sequestration rates however may vary largely over years due to climatological and biological influences such as dry or wet years, forest fires etc.

- Land use changes may have large impact on carbon pools and carbon sequestration rates. It is known that land use change from agricultural use to forest will increase the carbon pool stored in the vegetation as well in the soil. To reach a new equilibrium however, may take 20 years or more. In the marine environment, disturbance of benthic habitats has also been shown to have an impact on carbon storage and sequestration.
- Some carbon pools may exist for decades or even hundreds of years (e.g. soil organic matter). In some ecosystems carbon is stored for much longer periods, e.g. peatlands and oceans when carbon from decomposed plankton is mineralised to form oil. The carbon cycle period of the carbon pools is not taken into account in many studies.
- Differences in values also occur between field measurements and modelled outcomes.
- Development stage of ecosystems influence the carbon pool and especially the carbon sequestration rate. Young forest has a significantly lower carbon sequestration rate than mature forest types and the same applies to seagrass beds with older beds having higher rates of carbon accumulation.
- Soil carbon is for most ecosystems the largest carbon pool of the total carbon stock. Soil carbon may differ greatly between different soil types and climate for the same or comparable ecosystem types.
- In water bodies carbon is seasonally sequestered in water vegetation. This vegetation however, dies mostly in wintertime after which the carbon will flow back to the atmosphere or enriches the sediment. A similar pattern is apparent in the plankton. In floating water, the debris will not be sequestered locally but will drift with the flow and sediment elsewhere, e.g. in salt marshes or beach cast macroalgae.
- Overlapping ecosystems. The classification of ecosystems (e.g. forests, wetlands, shrubs, tundra etc.) may be somewhat arbitrary since the ecosystems can be classified on more than one ecosystem. Forested peatland in some publications is classified as forest while in others it is classified as peatland (wetland). The same holds for heathlands which is classified as heathland, peatland and shrub.

Besides these methodological restrictions, there are other issues that are of influence on the outcomes which we briefly summarize below.

- Most of the publications found do not describe the studied ecosystems in terms of EUNIS habitat types but in more general terms of present species or on ecosystem level (e.g. boreal forest, Mediterranean shrub, circalittoral mud). Therefore we interpret the reported information on the ecosystems and assessed the related EUNIS types on the base of expert judgement. With this approach we introduced some uncertainty.
- Although we found relatively many publications with information on carbon pools and carbon sequestration rates in natural vegetation, the number of publications that cover all ecosystem components is low (e.g. only information was given on one carbon pool of the biomass, only biomass of the trees, or of the soil carbon). For many ecosystems we did not have any publication with information on all ecosystem components. These gaps were filled with information of ecosystems which we thought were somewhat comparable, when available, and with expert judgement. This influences the accuracy and reliability of the classification which could not be done without substantial expert assessment through interpretation and extrapolation of the fragmented information on the different ecosystems that could be taken representative for the EUNIS habitats.
- For terrestrial ecosystems there are many studies found of forests and wetlands. Information on carbon pools and carbon sequestration rates for some other ecosystems (e.g. taiga, tundra, shrubs) are relatively scarce.
- Differences in methods result in large differences in values for carbon pools and carbon sequestration rates that are reported. This wide range is also influencing the definition of classes and the classification of the carbon pools and sequestration rates. For marine ecosystems the carbon pools and sequestration rates have only been examined in detail for a small number of habitat types. Seagrass beds, for example, have been the focus of the largest number of studies

whereas there is far less information on carbon sequestration and storage on the large number of benthic habitat associated with different subtidal sediments.

Given the uncertainties mentioned above, the classification of the EUNIS habitat types must be seen as a first attempt of classification which is subject to many improvements and must be handled with care when applied in other studies. Some possible improvements that can be undertaken are:

- Find more data on specific ecosystems of which in this research only few data were found (e.g. shrubs, taiga, tundra ecosystems and benthic habitats on subtidal sediments).
- Combine data of different publications to create full-ecosystem records containing information for all ecosystem components to estimate total ecosystem carbon pools and sequestration rates (e.g. data on living biomass carbon pools from publication a,b,c and soil organic matter pools from publication x,y,z.
- Soil organic matter in many ecosystems is the largest carbon pool and at the same time this pool is heavily depending on the soil type and climate. Additional research can give more insight in the contribution of soil type to carbon storage and carbon sequestration rates related to EUNIS habitat types.
- Geographical information can be of use in future steps to improve the classification of the carbon pools and sequestration rates, e.g. geographical information on soil organic matter, soil type, ground water, climate, vegetation, etc.

6 Conclusions

6.1 Terrestrial ecosystems

A large number of scientific studies is found that describe the pools and sequestration rates of carbon in terrestrial ecosystems. Many of them show the importance of terrestrial ecosystems in the carbon cycle and in perspective of climate change. The studies vary from very general to very detailed on the figures presented. The quantitative estimates of both the carbon stock and carbon sequestration show a wide range for similar ecosystem types. This wide range on the one hand presents real world differences, but on the other hand they are also partly due to methodological differences used in the different studies, and to focus of some studies on exceptional habitat conditions, resulting in difficult interpretation and uncertainty of the estimates.

Whether terrestrial habitats are reported in literature as net stocks or sources of carbon, depends – amongst others – on the method applied and whether the total ecosystem is considered or only phytomass or other single ecosystem components (e.g. soil organic matter). Some studies report present carbon pools at only one moment, which does not illustrate changes in the size of the pools over time, or they report just phytomass production, not taking into account decomposition of soil organic matter. Especially in peat soils this may cause the difference between habitats acting as source or stock for carbon.

Most estimates on carbon storage and carbon sequestration rates in literature are found for forests. This is probably due to the assumed importance of forest in the climate change debate, but also to the extended forest area. About 43% of the European Union land surface is covered with forest. There are however large differences between carbon pools and carbon sequestration rates of forests. Climate, soil, tree species, management and anthropogenic influences (land use change, forest fires etc.) all greatly influence the carbon cycle of forests. Further research on these factors and measures may help in better understanding their effects on the carbon storage in forests.

Literature estimates found show the highest carbon pools in wetlands, followed by forests. Sparsely vegetated ecosystems, shrubs, and tundra habitats have the lowest carbon stocks. Carbon sequestration rates are highest in forest habitats and lowest in natural grasslands, heathland, semi desert, shrub and tundra habitats. This results show that it is very important to conserve the large carbon stocks stored in wetlands and forests and to adapt management strategies with carbon friendly measures. The results also show that forest have high potential to store large amounts of carbon in relative short periods of time, where other ecosystems need longer periods to build up similar carbon volumes. This may, however, be different for individual ecosystems, depending on site conditions such as climate, soil type and management.

Restoration of habitats may cause large differences in present carbon pools and carbon sequestration rates. Studies found in general show higher carbon pools and sequestration rates for intact and restored habitats. Especially in peatlands this can make large differences, but also for other habitats.

6.2 Marine ecosystems

There is an expanding literature on 'blue carbon' relating to both carbon storage and sequestration rates showing that marine ecosystems have an important and irreplaceable role in cycling and storing carbon over short medium and long timescales. Nevertheless, scientific uncertainties surrounding quantitative estimates of carbon storage within many marine ecosystems remain high.

Marine habitats where carbon sequestration occurs can be net sources or stocks influenced by factors such as season, sea-surface temperature, stratification, ocean currents and turbulence from storms. Sequestration rates will also be affected by climate change because of the predicted changes in parameters such as sea water temperature, ocean circulation and frequency of storms.

One of the best studied benthic habitats in terms of carbon storage and sequestration is seagrass beds. Carbon pools in seagrass beds are associated with the plants and the underlying sediments. Accumulation rates and storage depend on the species, sediment characteristics, depth range of the habitat, age of the seagrass bed, depth of the sediment being sampled and remineralization rates. There is also much variability in carbon storage capacity between geographical areas.

Sediment type has a significant influence on carbon storage with subtidal sediments that have a high mud fraction having the greatest potential to store carbon. Anthropogenic activities such as fishing, dredging and the installation of offshore structures that affect the mixing of sediments, including disturbing the infauna, will affect carbon storage in shelf sea sediments.

Macroalgae do not directly transfer carbon to marine sediments, unlike rooted coastal vegetation. Nevertheless, seaweed detritus can deliver carbon to sedimentary sites and may provide a source of refractory dissolved organic carbon. Recent studies indicate that globally important amounts of carbon may be involved in these processes.

Of the benthic habitats reviewed sequestration rates were highest in seagrass beds, brittlestar beds and maerl beds. Storage rates were highest for deep water coral (Lophelia) reefs and maerl beds.

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Annex 1 Classification of terrestrial EUNIS habitat types according to classes of carbon stock and carbon sequestration rate

Table A 1.1 *Applied classes for carbon stocks of terrestrial habitats.*

CLASS number	Class range in carbon stocks ($Mg\ C\ ha^{-1}$)
I	<75
II	75-150
III	150-225
IV	225-300
V	>300

Table A1.2 *Applied classes for carbon sequestration of terrestrial habitats.*

CLASS number	Class range in carbon sequestration rate ($Mg\ C\ ha^{-1}\ yr^{-1}$)
I	<1.5
II	1.5-3.0
III	3.0-4.5
IV	4.5-6.0
V	>6.0

NB. in case expert assessment is mentioned in the table below, no or little data was available on the concerning habitat type

Level	EUNIS Code 2018	EUNIS Name 2018	Carbon stock class (table A1.1)	Lable number in raw table (excel file)	Carbon sequestration rate class (table A1.2)	Lable number in raw table (excel file)	Comment
	MARINE (SALT MARSHES)						
4	MA211	Arctic coastal saltmarshes	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA221	Atlantic saltmarsh driftlines	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA222	Atlantic upper saltmarshes	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA223	Atlantic upper-mid saltmarshes and saline and brackish reed, rush and sedge beds	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA224	Atlantic mid-low saltmarshes	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA225	Atlantic pioneer saltmarshes	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large

							of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA232	Baltic coastal meadow	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA241	Black Sea littoral saltmarsh	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA251	Mediterranean upper saltmarshes	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA252	Mediterranean upper-mid saltmarshes and saline and brackish reed, rush and sedge beds	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
4	MA253	Mediterranean mid-low saltmarshes	IV-V	326-354	II	326-354	Sequestration rate depends strongly on the development stage of the salt marsh; in cases of large of sedimentation the sequestration rate is high (stocks), but stable or even eroding salt marshes may form a source of carbon
	COASTAL HABITATS						
3	N11	Atlantic, Baltic and Arctic sand beach	I	210	I	expert assessment	
3	N12	Mediterranean and Black Sea sand beach	I	210	I	expert assessment	
3	N13	Atlantic and Baltic shifting coastal dune	I	210	I	expert assessment	

3	N14	Mediterranean, Macaronesian and Black Sea shifting coastal dune	I	210	I	expert assessment
3	N15	Atlantic and Baltic coastal dune grassland (grey dune)	I	expert assessment	I	expert assessment
3	N16	Mediterranean and Macaronesian coastal dune grassland (grey dune)	I	expert assessment	I	expert assessment
3	N17	Black Sea coastal dune grassland (grey dune)	I	expert assessment	I	expert assessment
3	N18	Atlantic and Baltic coastal Empetrum heath	II	186-208	II	201, 408-410
3	N19	Atlantic coastal Calluna and Ulex heath	II	186-208	II	201, 408-410
3	N1A	Atlantic and Baltic coastal dune scrub	I	expert assessment	I	expert assessment
3	N1B	Mediterranean and Black Sea coastal dune scrub	I	expert assessment	I	expert assessment
3	N1C	Macaronesian coastal dune scrub	I	expert assessment	I	expert assessment
3	N1D	Atlantic and Baltic broad-leaved coastal dune forest	II-III	50, 56, 57, 58, 59	I	expert assessment, 72
3	N1E	Black Sea broad-leaved coastal dune forest	II-III	50, 56, 57, 58, 59	I	expert assessment, 73
3	N1F	Baltic coniferous coastal dune forest	II	46, 48, 60, 61, 62	I	expert assessment, 74
3	N1G	Mediterranean coniferous coastal dune forest	I-II	56, 1120	I	expert assessment
3	N1H	Atlantic and Baltic moist and wet dune slack	I	355-357	I	355-357
3	N1J	Mediterranean and Black Sea moist and wet dune slack	I	355-357	I	355-357
3	N21	Atlantic, Baltic and Arctic coastal shingle beach	I	expert assessment	I	expert assessment
3	N22	Mediterranean and Black Sea	I	expert assessment	I	expert assessment

		coastal shingle beach					
3	N23	Shingle and gravel beaches with scrub	I	expert assessment	I	expert assessment	
3	N24	Shingle and gravel beach woodland	I	expert assessment	I	expert assessment	
3	N31	Atlantic and Baltic rocky sea cliff and shore	I	expert assessment	I	expert assessment	
3	N32	Mediterranean and Black Sea rocky sea cliff and shore	I	expert assessment	I	expert assessment	
3	N33	Macaronesian rocky sea cliff and shore	I	expert assessment	I	expert assessment	
3	N34	Atlantic and Baltic soft sea cliff	I	expert assessment	I	expert assessment	
3	N35	Mediterranean and Black Sea soft sea cliff	I	expert assessment	I	expert assessment	
	AQUATIC HABITATS						
3	?	Permanent oligotrophic waterbody with very soft-water species	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Permanent oligotrophic to mesotrophic waterbody with soft-water species	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Permanent oligotrophic to mesotrophic waterbody with Characeae	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Mesotrophic to eutrophic waterbody with vascular plants	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).

3	?	Permanent dystrophic waterbody	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Permanent inland saline and brackish waterbody	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Temperate temporary waterbody	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Mediterranean temporary waterbody	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Permanent lake of glaciers and ice sheets	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Base-poor spring and spring brook	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Calcareous spring and spring brook	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment;

							water bodies may even function as emission source (for methane).
3	?	Permanent non-tidal, fast, turbulent watercourse of montane to alpine regions with mosses	I	expert assessment	I	expert assessment, 308-309	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Permanent non-tidal, fast, turbulent watercourse of plains and montane regions with Ranunculus spp.	I	expert assessment	I	expert assessment, 308-310	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Permanent non-tidal, smooth-flowing watercourse	I	expert assessment	I	expert assessment, 308-311	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Tidal river, upstream from the estuary	I	expert assessment	I	expert assessment, 308-312	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Temperate temporary running watercourse	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Periodically exposed shore with stable, eutrophic sediments with pioneer or ephemeral vegetation	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Periodically exposed shore with stable,	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly

3		mesotrophic sediments with pioneer or ephemeral vegetation					growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Periodically exposed saline shore with pioneer or ephemeral vegetation	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Unvegetated or sparsely vegetated shore with mobile sediments in montane and alpine regions	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
3	?	Unvegetated or sparsely vegetated shore with mobile sediments in the Mediterranean region	I	expert assessment	I	expert assessment	In water bodies the changes in carbon pools will be near to zero, due to yearly growing and dying of plants; few carbon may be stored in the water body sediment; water bodies may even function as emission source (for methane).
	WETLANDS						
3	Q11	Raised bog	II-III	274, 282-284	I	284, 287-289, 360	It depends strongly which soil depth is calculated in the figures. Bogs may be meters deep, while many figures use just 15 to 30 cm soil depth for carbon rates.
3	Q12	Blanket bog	II-III	274, 282-284	I	278-281, 358	No total biomass data avaliable; we applied general peat/bog values
3	Q21	Oceanic valley bog	II-III	274, 282-284	I	expert assessment 282-284	A complicated EUNIS type; we applied general peat/bog values
3	Q22	Poor fen	II-III	expert assessment	I	253-259	
3	Q23	Relict mire of Mediterranean mountains	II-III	expert assessment	I	253-259	
3	Q24	Intermediate fen and soft-water spring	II-V	251, 256,258	I	253-259	
3	Q25	Non-calcareous quaking mire	II-III	303-305	I	253-259	
3	Q31	Palsa mire	III-V	221, 222, 243, 255, 256	I	253-259	
3	Q32	Aapa mire	III-V	221, 256, 260	I	253-259	

3	Q33	Polygon mire		221, 256, 261	I	253-259	
3	Q41	Alkaline, calcareous, carbonate-rich small-sedge spring fen	II-III	expert assessment	I	253-259	
3	Q42	Extremely rich moss-sedge fen		expert assessment	I	253-259	
3	Q43	Tall-sedge base-rich fen	II-III	expert assessment	I	253-259	
3	Q44	Calcareous quaking mire	II-III	expert assessment	I	253-259	
3	Q45	Arctic-alpine rich fen	II-III	expert assessment	I	253-259	
3	Q46	Carpathian travertine fen with halophytes		expert assessment	I	253-259	
3	Q51	Tall-helophyte bed	III-V	303-305	I-IV	expert assessment 294-296, 355, 356	
3	Q52	Small-helophyte bed	III-V	303-305	I-II	expert assessment 294-296, 355, 356	
3	Q53	Tall-sedge bed	III-V	303-305	I-IV	expert assessment 294-296, 355, 356	
3	Q54	Inland saline or brackish helophyte bed	III	expert assessment	I	expert assessment	Estimation: slightly lower than fresh water reed beds
3	??	Underground standing and running waterbody	I	expert assessment	I	expert assessment	
	GRASSLANDS						
3	R11	Pannonian and Pontic sandy steppe	I	170-175	I	expert assessment, 159	
3	R12	Cryptogam- and annual-dominated vegetation on siliceous rock outcrops	I	expert assessment	I	expert assessment, 159	
3	R13	Cryptogam- and annual-dominated vegetation on calcareous and ultramafic rock outcrops	I	expert assessment	I	expert assessment, 159	
3	R14	Perennial rocky grassland of the Italian peninsula	I	expert assessment	I	expert assessment, 159	
3	R15	Continental dry rocky steppic grassland and dwarf scrub on chalk outcrops	I	expert assessment	I	expert assessment, 159	
3	R16	Perennial rocky grassland of Central and South-Eastern Europe	I	expert assessment	I	expert assessment, 159	

3	R17	Heavy-metal dry grassland of the Balkans	I	expert assessment	I	expert assessment, 159
3	R18	Perennial rocky calcareous grassland of subatlantic-submediterranean Europe	I	expert assessment	I	expert assessment, 159
3	R19	Dry steppic submediterranean pasture of the Amphi-Adriatic region	I	expert assessment	I	expert assessment, 159
3	R1A	Semi-dry perennial calcareous grassland (meadow steppe)	II	151-158	I	expert assessment, 159
3	R1B	Continental dry grassland (true steppe)	I	170-175	I	expert assessment, 159
3	R1C	Desert steppe	I	170-175	I	expert assessment, 159
3	R1D	Mediterranean closely grazed dry grassland	I	expert assessment	I	expert assessment, 159
3	R1E	Mediterranean tall perennial dry grassland	I-II	expert assessment	I	expert assessment, 159
3	R1F	Mediterranean annual-rich dry grassland	I	expert assessment	I	expert assessment, 159
3	R1G	Iberian oromediterranean siliceous dry grassland	I-II	150, 156, 158	I	expert assessment, 159
3	R1H	Iberian oromediterranean basiphilous dry grassland	I-II	150, 156, 158	I	expert assessment, 159
3	R1J	Cyrno-Sardean oromediterranean siliceous dry grassland	I-II	150, 156, 158	I	expert assessment, 159
3	R1K	Balkan and Anatolian oromediterranean dry grassland	I-II	150, 156, 158	I	expert assessment, 159
3	R1L	Madeiran oromediterranean siliceous dry grassland	II	150, 156, 158	I	expert assessment, 159
3	R1M	Lowland to montane, dry to mesic grassland usually dominated by *Nardus stricta*	II	150, 156, 158	I	expert assessment, 159

3	R1N	Open Iberian supramediterranean dry acid and neutral grassland	I-II	150, 156, 158	I	expert assessment, 159
3	R1P	Oceanic to subcontinental inland sand grassland on dry acid and neutral soils	I-II	150, 156, 158, 161	I	expert assessment, 159
3	R1Q	Inland sanddrift and dune with siliceous grassland	I	210	I	expert assessment
3	R1R	Mediterranean to Atlantic open, dry, acid and neutral grassland	I-II	150, 156, 158, 161	I	expert assessment, 159
3	R1S	Heavy-metal grassland in Western and Central Europe	I	expert assessment	I	expert assessment, 159
3	R1T	Azorean open, dry, acid to neutral grassland	II-III	161, 178, 185	I	expert assessment, 159
3	R21	Mesic permanent pasture of lowlands and mountains	II-III	161, 178, 185	I	expert assessment, 159
3	R22	Low and medium altitude hay meadow	II-III	161, 178, 185	I	expert assessment, 159
3	R23	Mountain hay meadow	II-III	161, 178, 185	I	expert assessment, 159
3	R24	Iberian summer pasture (vallicar)	II	expert assessment	I	expert assessment, 159
3	R31	Mediterranean tall humid inland grassland	II-III	expert assessment	I	expert assessment, 159
3	R32	Mediterranean short moist grassland of lowlands	II-III	expert assessment	I	expert assessment, 159
3	R33	Mediterranean short moist grassland of mountains	II-III	expert assessment	I	expert assessment, 159
3	R34	Submediterranean moist meadow	II-III		I	expert assessment, 159
3	R35	Moist or wet mesotrophic to eutrophic hay meadow	II-III		I	expert assessment, 159
3	R36	Moist or wet mesotrophic to eutrophic pasture	II-III		I	expert assessment, 159
3	R37	Temperate and boreal moist or	II-III	266, expert assessment	I	expert assessment, 159

		wet oligotrophic grassland					
3	R41	Snow-bed vegetation	I	expert assessment	I	expert assessment, 159	
3	R42	Boreal and arctic acidophilous alpine grassland	II	156-158, expert assessment	I	expert assessment, 159	
3	R43	Temperate acidophilous alpine grassland	II	156-158, expert assessment	I	expert assessment, 159	
3	R44	Arctic-alpine calcareous grassland	II	156-158, expert assessment	I	expert assessment, 159	
3	R45	Alpine and subalpine calcareous grassland of the Balkans and Apennines	II	151	I	expert assessment, 159	
3	R51	Thermophilous forest fringe of base-rich soils	I-II	expert assessment	I	expert assessment, 159	
3	R52	Forest fringe of acidic nutrient-poor soils	I-II	expert assessment	I	expert assessment, 159	
3	R53	Macaronesian thermophilous forest fringe	I-II	expert assessment	I	expert assessment, 159	
3	R54	*Pteridium aquilinum* vegetation	I-II	expert assessment	I	expert assessment, 159	
3	R55	Lowland moist or wet tall-herb and fern fringe	II-III	expert assessment	I-II	expert assessment	Based on reedbeds
3	R56	Montane to subalpine moist or wet tall-herb and fern fringe	II-III	expert assessment	I-II	expert assessment	Based on reedbeds
3	R57	Herbaceous forest clearing vegetation	?	no data	?	no data	Depends on forest types
3	R61	Mediterranean inland salt steppe	I-II	expert assessment	I	expert assessment, 159	Probably relatively high total biomass, but less than coastal salt marshes
3	R62	Continental inland salt steppe	I-II	expert assessment	I	expert assessment, 159	Probably relatively high total biomass, but less than coastal salt marshes
3	R63	Temperate inland salt marsh	II-III	expert assessment	I	expert assessment, 159	Probably relatively high total biomass, but less than coastal salt marshes
3	R64	Semi-desert salt pan	I-II	expert assessment	I	expert assessment, 159	Probably relatively high total biomass, but less than coastal salt marshes
3	R65	Continental subsaline alluvial pasture and meadow	II-III	expert assessment	I	expert assessment, 159	

3	R71	Temperate wooded pasture and meadow	II	20,21	I	expert assessment 20, 21
3	R72	Hemiboreal and boreal wooded pasture and meadow	II	20,21	I	expert assessment 20, 21
3	R73	Mediterranean wooded pasture and meadow	II	56	I	expert assessment 56
	HEATHLANDS AND SCRUB					
3	S11	Shrub tundra		215-217	I	expert assessment, 215-217
3	S12	Moss and lichen tundra		209, 211	I	expert assessment, 215-217
3	S21	Subarctic and alpine dwarf *Salix* scrub	II	215-216	I	expert assessment, 215-217
3	S22	Alpine and subalpine ericoid heath	II	202, 206-208	I	expert assessment, 215-217
3	S23	Alpine and subalpine *Juniperus* scrub	II	expert assessment	I	expert assessment, 215-217
3	S24	Subalpine genistoid scrub of the Amphi-Adriatic region	II	expert assessment	I	expert assessment, 215-217
3	S25	Subalpine and subarctic deciduous scrub	II	expert assessment	I	expert assessment, 215-217
3	S26	Subalpine *Pinus mugo* scrub	II	expert assessment	I	expert assessment, 215-217
3	S27	Krummholz with conifers other than *Pinus mugo*	II	expert assessment	I	expert assessment
3	S31	Lowland to montane temperate and submediterranean *Juniperus* scrub	II	expert assessment	I	expert assessment
3	S32	Temperate Rubus scrub	II	expert assessment	I	expert assessment
3	S33	Lowland to montane temperate and submediterranean genistoid scrub	II	expert assessment	I	expert assessment
3	S34	Balkan-Anatolian submontane genistoid scrub	II	expert assessment	I	expert assessment
3	S35	Temperate and submediterranean thorn scrub	II	expert assessment	I	expert assessment
3	S36	Low steppic scrub	I	170-15	I	expert assessment, 159
3	S37	*Corylus avellana* scrub	II	expert assessment	I	expert assessment
3	S38	Temperate forest clearing scrub	II	expert assessment	I	expert assessment
3	S41	Wet heath	II	expert assessment	I	expert assessment

3	S42	Dry heath	II	expert assessment	I	expert assessment 201, 408-410
3	S43	Macaronesian heath	II	expert assessment	I	expert assessment, 412
3	S51	Mediterranean maquis and arborescent matorral	II	56	I	expert assessment 412
3	S52	Submediterranean pseudomaquis	II	56	I	expert assessment 412
3	S53	*Spartium junceum* scrub	I-II	402-407, 412,411	I	expert assessment 412
3	S54	Thermomediterranean arid scrub	I-II	402-407, 412,412	I	expert assessment 412
3	S61	Western basiphilous garrigue	I-II	402-407, 412,413	I	expert assessment 412
3	S62	Western acidophilous garrigue	I-II	402-407, 412,414	I	expert assessment 412
3	S63	Eastern garrigue	I-II	402-407, 412,415	I	expert assessment 412
3	S64	Macaronesian garrigue	I-II	402-407, 412,416	I	expert assessment 412
3	S65	Mediterranean gypsum scrub	I-II	402-407, 412,417	I	expert assessment 412
3	S66	Mediterranean halo-nitrophilous scrub	I-II	402-407, 412,417	I	expert assessment 412
3	S67	Aralo-Caspian semi-desert	I	170-175	I	expert assessment
3	S68	Semi-desert sand dune with sparse scrub	I	210	I	expert assessment
3	S71	Western Mediterranean spiny heath	I-II	213, 214, 412,413	I	expert assessment 412
3	S72	Eastern Mediterranean spiny heath (Phrygana)	I-II	213, 214, 412,413	I	expert assessment 412
3	S73	Western Mediterranean mountain hedgehog-heath	I-II	213, 214, 412,413	I	expert assessment 412
3	S74	Central Mediterranean mountain hedgehog-heath	I-II	213, 214, 412,413	I	expert assessment 412
3	S75	Eastern Mediterranean mountain hedgehog-heath	I-II	213, 214, 412,413	I	expert assessment 412
3	S76	Canarian mountain hedgehog-heath	I-II	213, 214, 412,413	I	expert assessment 412
3	S81	Canarian xerophytic scrub	I	expert assessment	I	expert assessment

3	S82	Madeiran xerophytic scrub	I	expert assessment	I	expert assessment
3	S91	Temperate riparian scrub	II	expert assessment, 140-143	I	expert assessment
3	S92	*Salix* fen scrub	II	expert assessment	I	expert assessment
3	S93	Mediterranean riparian scrub	II	expert assessment	I	expert assessment
3	S94	Semi-desert riparian scrub	II	expert assessment	I	expert assessment
	FORESTS					
3	T11	Temperate *Salix* and *Populus* riparian forest	II	140-143	II-III	123, 124
3	T12	*Alnus glutinosa-Alnus incana* forest on riparian and mineral soils	II	140-143	I-II	expert assessment
3	T13	Temperate hardwood riparian forest	II	140-143	I-II	expert assessment
3	T14	Mediterranean and Macaronesian riparian forest	II	140-143	I	expert assessment
3	T15	Broadleaved swamp forest on non-acid peat	III-V	expert assessment, 146	I	expert assessment
3	T16	Broadleaved mire forest on acid peat	III-V	221,222,258 expert assessment	I-II	221, 222, 258
3	T17	*Fagus* forest on non-acid soils	II-IV	41-111	II-IV	expert assessment 63-75
3	T18	*Fagus* forest on acid soils	II-IV	41-111	II-IV	expert assessment 63-75
3	T19	Temperate and submediterranean thermophilous deciduous forest	II-III	56, 101, 102, 106	I-II	expert assessment 101, 102, 105, 106, 88, 89
3	T1A	Mediterranean thermophilous deciduous forest	II-III	56, 101, 102, 106	II-III	expert assessment 101, 102, 105, 106, 88, 89
3	T1B	Acidophilous *Quercus* forest	II-IV	expert assessment 41-111	II-III	expert assessment 41-111
3	T1C	Temperate and boreal mountain *Betula* and *Populus tremula* forest on mineral soils	II-III	expert assessment 41-111	II-III	expert assessment 41-111
3	T1D	Southern European mountain *Betula* and *Populus tremula* forest on mineral soils	II-III	expert assessment 41-111	II-III	expert assessment 41-111

3	T1E	*Carpinus* and *Quercus* mesic deciduous forest	II-III	expert assessment 41-111	II-IV	expert assessment 41-111	
3	T1F	Ravine forest	II-III	expert assessment 41-111	III	expert assessment 41-111	
3	T1G	*Alnus cordata* forest	II-III	expert assessment	I-II	expert assessment	
3	T1H	Broadleaved deciduous plantation of non site-native trees	II-IV	expert assessment 122-138	II-III	expert assessment 122-138	Sequestration rates depend strongly on nutrient content and moisture availability of soil and tree species
3	T1J	Deciduous self sown forest of non site-native trees	II-IV	expert assessment 122-138	II-III	expert assessment 122-138	
3	T1K	Broadleaved deciduous plantation of site-native trees	II-IV	expert assessment 122-138	II-III	expert assessment 122-138	Sequestration rates depend strongly on nutrient content and moisture availability of soil and tree species
3	T21	Mediterranean evergreen *Quercus* forest	III	56, 101, 106	II	expert assessment 101, 102, 105, 106, 88, 89	
3	T22	Mainland laurophyllous forest	II	56, 100, 101, 105, 106	I	expert assessment 101, 102, 105, 106, 88, 89	
3	T23	Macaronesian laurophyllous forest	II	56, 100, 101, 105, 107	I	expert assessment 101, 102, 105, 106, 88, 89	
3	T24	*Olea europea-Ceratonia siliqua* forest	II	56, 100, 101, 105, 108	I	expert assessment 101, 102, 105, 106, 88, 89	
3	T25	*Phoenix theophrasti* vegetation	I-II	expert assessment	I	expert assessment	
3	T26	*Phoenix canariensis* vegetation	I-II	expert assessment	I	expert assessment	
3	T27	*Ilex aquifolium* forest	II-III	expert assessment	II	expert assessment	
3	T28	Macaronesian heathy forest	II	56, 100, 101, 105, 108	I	expert assessment 101, 102, 105, 106, 88, 89	
3	T29	Broadleaved evergreen plantation of non site-native trees	II-IV	128-135	II-III	expert assessment 122-138	The model results (row 90-115) may over-estimate sequestration rates in litter; therefore we apply relatively lower rates
3	T2A	Broadleaved evergreen plantation of site-native trees	II-IV	57-59, 63-116, 128-135	II-III	expert assessment 122-138	Sequestration rates depend strongly on nutrient content and moisture availability of soil and tree species
3	T31	Temperate mountain *Picea* forest	III-IV	64, 67, 69, 70, 71-, 103, 107, 108, 111, 127	II-V	63, 64, 70, 71, 128, 129	
3	T32	Temperate mountain *Abies* forest	III-IV	64, 67, 69, 70, 71-, 103, 107, 108, 111, 127	II-V	63, 64, 70, 71, 128, 129	

3	T33	Mediterranean mountain Abies forest	III	expert assessment	I-III	expert assessment	
3	T34	Temperate subalpine *Larix, Pinus cembra* and *Pinus uncinata* forest	I-II	expert assessment	I-III	expert assessment	
3	T35	Temperate and continental *Pinus sylvestris* forest	I-II	expert assessment 82, 83	I-III	expert assessment	
3	T36	Temperate and submediterranean montane *Pinus sylvestris-Pinus nigra* forest	II	expert assessment 88, 89, 105, 106, 120, 121	I-III	expert assessment 88, 89, 105, 106, 120, 121	
3	T37	Mediterranean montane *Pinus sylvestris-Pinus nigra* forest	II	expert assessment 88, 89, 105, 106, 120, 121	I-III	expert assessment 88, 89, 105, 106, 120, 121	
3	T38	Mediterranean montane *Cedrus* forest	I-II	expert assessment	I	expert assessment	
3	T39	Mediterranean and Balkan subalpine *Pinus heldreichii-Pinus peuce* forest	II	expert assessment 88, 89, 105, 106, 120, 121	I	expert assessment	
3	T3A	Mediterranean lowland to submontane *Pinus* forest	I-II	expert assessment 88, 89, 105, 106, 120, 121	I	expert assessment	
3	T3B	*Pinus canariensis forest*	II	expert assessment 88, 89, 105, 106, 120, 121	I	expert assessment	
3	T3C	*Taxus baccata* forest	I-II	expert assessment 88, 89, 105, 106, 120, 121	I	expert assessment	
3	T3D	Mediterranean Cupressaceae forest	I-II	expert assessment 88, 89, 105, 106, 120, 121	I	expert assessment	
3	T3E	Macaronesian *Juniperus* forest	I-II	expert assessment 88, 89, 105, 106, 120, 121	I	expert assessment	
3	T3F	Dark taiga	II-III	expert assessment	?	no data	
3	T3G	*Pinus sylvestris* light taiga	II-III	expert assessment, 218, 219	?	no data	
3	T3H	*Larix* light taiga	II-III	expert assessment, 218, 219	?	no data	
3	T3J	*Pinus* and *Larix* mire forest	IV-V	221, 222, 367, 368	I-II	221, 222, 367, 368	

3	T3K	*Picea* mire forest	IV-V	221, 222, 367, 369	I-II	221, 222, 367, 368
3	T3L	Coniferous self sown forest of non site-native trees	III	126-139	II-V	expert assessment 117-149
3	T3M	Coniferous plantation of non site-native trees	III	126-139	II-V	expert assessment 117-149
3	T3N	Coniferous plantation of site-native trees	III	126-139	II-V	expert assessment 117-149
3	T42	Coppice and early stage plantations	I-II	expert assessment	I-III	expert assessment
3	T43	Recently felled areas	I-III	expert assessment	I	expert assessment	Carbon pools in litter and soil; depending on whether some trees remain
	SPARSELY VEGETATED HABITATS					
3	U11	Cave	I	expert assessment	I	expert assessment
3	U12	Disused underground mines and tunnels	I	expert assessment	I	expert assessment
3	U21	Boreal and arctic siliceous scree and block field	I	expert assessment	I	expert assessment
3	U22	Temperate high-mountain siliceous scree	I	expert assessment	I	expert assessment
3	U23	Temperate, lowland to montane siliceous scree	I	expert assessment	I	expert assessment
3	U24	Mediterranean siliceous scree		expert assessment	I	expert assessment
3	U25	Boreal and arctic base-rich scree and block field	I	expert assessment	I	expert assessment
3	U26	Temperate high-mountain base-rich scree and moraine	I	expert assessment	I	expert assessment
3	U27	Temperate, lowland to montane base-rich scree	I	expert assessment	I	expert assessment
3	U28	Western Mediterranean base-rich scree	I	expert assessment	I	expert assessment
3	U29	Eastern Mediterranean base-rich scree	I	expert assessment	I	expert assessment
3	U2A	Crimean base-rich screes	I	expert assessment	I	expert assessment
3	U31	Boreal and arctic siliceous inland cliff	I	expert assessment	I	expert assessment
3	U32	Temperate high-mountain	I	expert assessment	I	expert assessment

		siliceous inland cliff				
3	U33	Temperate, lowland to montane siliceous inland cliff	I	expert assessment	I	expert assessment
3	U34	Mediterranean siliceous inland cliff	I	expert assessment	I	expert assessment
3	U35	Boreal and arctic base-rich inland cliff	I	expert assessment	I	expert assessment
3	U36	Temperate high-mountain base-rich inland cliff	I	expert assessment	I	expert assessment
3	U37	Temperate, lowland to montane base-rich inland cliff	I	expert assessment	I	expert assessment
3	U38	Mediterranean base-rich inland cliff	I	expert assessment	I	expert assessment
3	U39	Boreal ultramafic inland cliff	I	expert assessment	I	expert assessment
3	U3A	Temperate ultramafic inland cliff	I	expert assessment	I	expert assessment
3	U3B	Mediterranean ultramafic inland cliff	I	expert assessment	I	expert assessment
3	U3C	Macaronesian inland cliff	I	expert assessment	I	expert assessment
3	U3D	Wet inland cliff	I	expert assessment	I	expert assessment
3	U3E	Limestone pavement	I	expert assessment	I	expert assessment
3	U3F	Weathered rock and outcrop habitats	I	expert assessment	I	expert assessment
3	U41	Snow pack	I	expert assessment	I	expert assessment
3	U42	Ice cap and glacier	I	expert assessment	I	expert assessment
3	U43	Rock glacier and unvegetated ice-dominated moraine	I	expert assessment	I	expert assessment
3	U51	Fjell field	I	expert assessment	I	expert assessment
3	U52	Polar desert	I	209	I	expert assessment
3	U53	Glacial moraines with very sparse or no vegetation	I	expert assessment	I	expert assessment
3	U61	Subarctic volcanic field	I	expert assessment	I	expert assessment
3	U62	Mediterranean, Macaronesian and temperate volcanic field	I	expert assessment	I	expert assessment

Annex 2 Classification of marine EUNIS habitat types according to classes of carbon stock and carbon sequestration rate

Table A2.1 *Applied classes for the carbon stocks of Marine habitats.*

CLASS number	Class range in carbon stocks (Mg C ha^{-1})
1	<10.00
2	10-50
3	50-100
4	100-150
5	>150

Table A2.2 *Applied classes for the carbon sequestration rate of Marine habitats.*

CLASS number	CLASS range in carbon sequestration rate (Mg C ha^{-1} yr^{-1})
1	negligible
2	<0.01
3	0.01-0.50
4	0.50-1.00
5	>1.00

EUNIS MARINE							
LEVEL	Code 2019	Habitat type	Carbon storage (Mg C ha^{-1})	Carbon sequestration rate (Mg C ha^{-1} yr^{-1})	Carbon stock class	Sequestration rate class	Notes
4	MA332, MB532, MB547, MB548, MB553, MB554, MB652, MA522, MA623, MB522, MA623, MB522	Seagrass beds	20-50	0.83	2	4	Majority in the underlying sediment although some storage in roots and rhizomes. Significant differences depending on the species with highest values in *P.oceanica*. Carbon storage ability can also increase with sediment depth
4	MA123, MA124, MA126, MB121	Kelp forest	5.0-9.0		1	1	Temporary storage in living material. Exported (offshore and beach cast) and can be sequestered in deep-sea surficial sediments.
4	MA123, MA124, MA126	Intertidal macroalgae	5		1	1	Temporary storage in living material, exported to shelf sediments
4	MB322, MB421, MB622	Maerl beds	620	>330,000	5	5	Longer-term store for organic and inorganic carbon. Rates vary between species. E.g. *P.calcareum* sequesters

							approx one fifth less than *L.glaciale*
4	ME112, MC222, MD221, ME123, ME221, ME322, ME151, MF151	Lophelia reefs	100	0.35	4	3	
4	MB222	Flame shell beds	0.6-0.7		1	1	
4	MC128	Horse mussel beds	40	0.4	2	3	Beds assumed to be 75cm deep
4	MA122, MA124, MA227, MB126, MC128, MB231, MC231, MD631, MB143, MB144, MB148, MB149, MB242, MC241, MA154	Blue mussel beds	0.15	0.01-0.4	1	3	Shellfish beds often considered to be a source of atmospheric CO_2 due to calcification process during shell formation. Source or stocks depends on relative balance between organic and inorganic carbon burial.
4	MB222, MB243	Subtidal oyster beds	1.3	0.01	1	3	shallow subtidal reefs dominated by organic-carbon-rich sediments and functioned as net carbon stocks
4	MB221, MC221	Tubeworm (Serpulid reefs)	7.81		1	1	reefs composed of masses of aggregated tubes very localised phenomenon. Calcareous tubes

							(occupied or relict) are a potential blue carbon stock.
4	MC421	Brittlestar beds	0.66	0.82	1	4	based on *O.fragilis* bed in Dover strait. After death brittlestar skeletons and calcareious plates incorporated into bottom sediments
		Faunal turfs	0.14		1	1	
2	MA3, MA4, MA5, MA6	Intertidal sediments	0.5 to 20	0.11-0.37	2	3	Higher levels in sediments with higher mud fractions. Based on accretion rate of 2mm yr^{-1}
2	MB3, MB4, MB5, MB6, MC3, MC4, MC5, MC6	Subtidal sediments	<10	0.003-0.009	1	2	Surficial sediments, and particularly deep-sea sediments, are the primary marine store of biologically-derived carbon.Higher levels in sediments with higher mud fractions. Based on 0.1mm accretion per year.

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