BLUE CARBON – THE ROLE OF OCEANS AS CARBON SINKS

Vegetated coastal habitats – mangrove forests, salt-marshes and seagrass meadows – have much in common with rain forests: they are hot spots for biodiversity, they provide important and valuable ecosystem functions, including a large carbon sink capacity, and they are experiencing a steep global decline (Duarte *et al.*, 2008, Duarte, 2009). Indeed, the world is losing its coastal habitats four times faster than its rain forests (Duarte *et al.*, 2008, Duarte, 2009) and the rate of loss is accelerating (Waycott *et al.*, 2009). However, whereas society is well informed of the benefits and threats associated with rainforests, there is a comparative lack of awareness on the status and benefits of vegetated coastal habitats. This is perhaps because of a "charisma" gap, where these often submerged, out of sight coastal habitats, are not as appealing to the public as their terrestrial counterparts (Duarte *et al.*, 2008). Yet, because of their similar functions and threats, coastal habitats can be considered as blue carbon sinks.

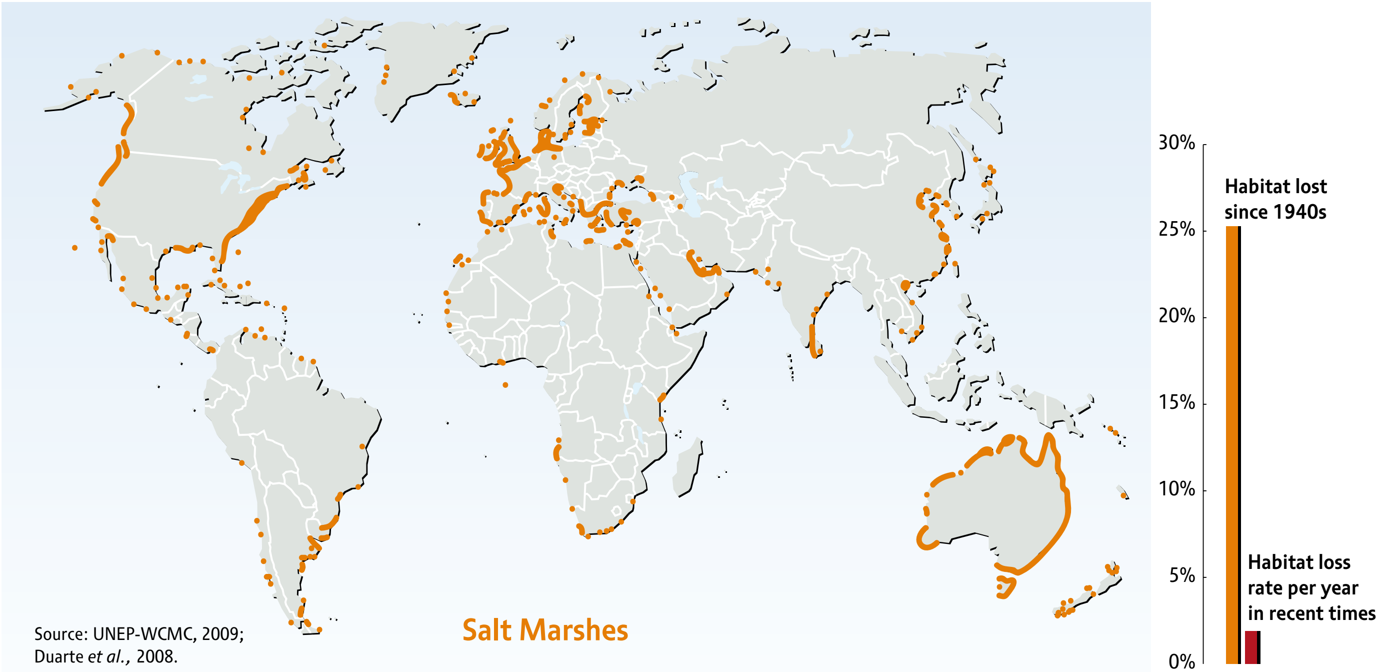
BLUE CARBON SINKS

One key function of vegetated coastal habitats is their role as carbon sinks. Benefiting from the excellent conditions available to support plant growth, vegetated coastal habitats rank amongst the most productive habitats in the world, comparable in production to the most productive agricultural crops (Table 1, Duarte and Chiscano, 1999). Much of their production is used to support ecosystem functions (Duarte and Cebrián, 1996). However, blue carbon sinks are strongly autotrophic, which means that these ecosystems fix CO_2 as organic matter photosyntheticaly in excess of the CO_2 respired back by biota (Duarte and Cebrián, 1996; Gattuso *et al.*, 1998; Duarte *et al.*, 2005a), thus removing CO_2 from the atmosphere. Some of this excess carbon is exported and subsidises adjacent ecosystems, including open ocean and beach ecosystems (Duarte and Cebrián, 1996; Heck *et al.*, 2008; Bouillon *et al.*, 2008). The remaining excess production of mangrove forests, salt-marshes and seagrass meadows is buried in the sediments, where it can remain stored over millenary time scales (Mateo *et al.*, 1997), thereby representing a strong natural carbon sink. This is most evident in the case of seagrass meadows, which accumulate enough materials as to significantly raise the seafloor, forming mats that can exceed 3 metres in depth.

In addition to burying a fraction of their own production, blue carbon sinks reduce flow, alter turbulence and attenuate wave action (Koch *et al.*, 2006), thereby promoting sedimentation and reducing sediment resuspension (e.g. Gacia and Duarte, 2001). Recent research has shown that the canopies of seagrass meadows trap particles entrained in the flow, which lose momentum upon impacting on the leaves, thereby promoting the sedimentation of suspended material to the seafloor (Hendriks

Mangroves

Source: UNEP-WCMC, 2009; Valiela *et al.*, 2001



Salt Marshes

Source: UNEP-WCMC, 2009; Duarte *et al.*, 2008.

Source: UNEP-WCMC, 2009; Waycott *et al.*, 2009.

Figure 16a–c: Distribution of the world's blue carbon sinks – seagrasses, mangroves, and salt marsh communities (Source: UNEP-WCMC).

et al., 2007). Isotopic analyses of the organic carbon accumulated in sediments of vegetated coastal habitats have shown that a significant fraction derives from plankton (Gacia *et al.*, 2002). On the continental shelf and in estuaries, terrestrial sources of carbon are also significant (Bouillon *et al.*, 2008), adding to the carbon sink capacity of these blue carbon sinks.

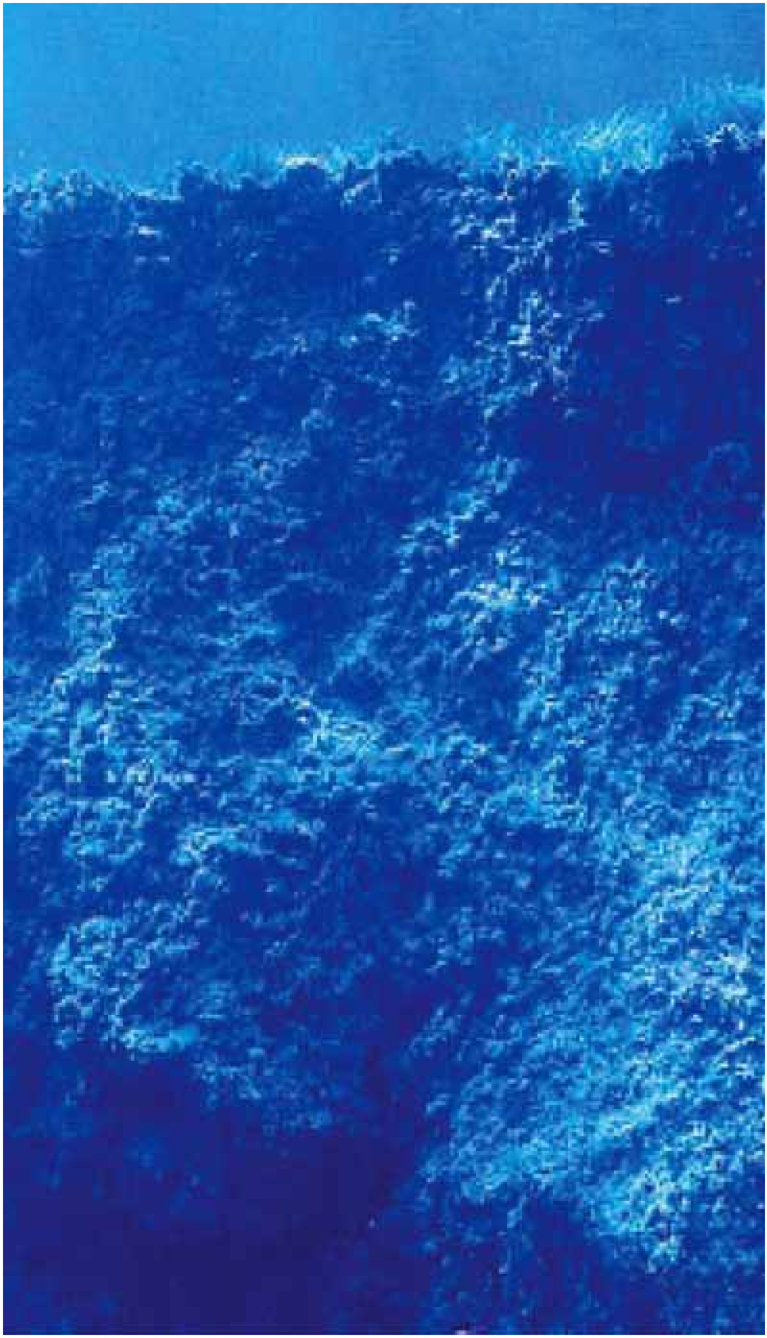
A consequence of the capacity of vegetated coastal habitats to accumulate materials in the seafloor is that they act as efficient carbon sinks, globally responsible for the burial of 120–329 Tg C yr^{-1}, which accounts for at least half of the lower estimate for global carbon burial in marine sediments (Table 1). Blue carbon sinks therefore play a major role in the oceanic carbon cycle (Duarte *et al.*, 2005a). The carbon burial capacity of marine vegetated habitats is phenomenal, 180 times greater than the average burial rate in the open ocean.

Carbon burial in the ocean represents slightly over 10% of the oceanic carbon sink capacity (up to 25% using maximum estimates, Table 1, see below), estimated, from observations and inverse models, to be about 2,000 Tg C year^{-1} (Sarmiento and Gruber, 2002). However, this 2,000 Tg C year^{-1} is the carbon annually transferred from the atmosphere to the oceans, where it is largely stored as dissolved inorganic carbon. The long-term residence of anthropogenic CO_2 in the oceans is uncertain, as this carbon does not penetrate deep enough to remain in the ocean over extended time scales. Indeed, half of the anthropogenic carbon stored in ocean waters is contained within the top 400 metres, where it may equilibrate back to the atmosphere within a few decades, and the amount present in the deep ocean – where it may remain over much longer time scales – is below the detection limit (Sabine *et al.*, 2004). Only a minute amount of the carbon taken up by the oceans is preserved in the deep-sea sediments, where it is effectively buried over long periods of time, representing 6 Tg C yr^{-1}, with a carbon burial per unit area of seafloor 180 times lower than the rate for blue carbon sink sediments (Table 1). In addition, there are concerns that the capacity of the water column of the oceans to act as a sink for atmospheric carbon will weaken in the future, and there is evidence that it may have started to do so (Doney *et al.*, 2009). Hence, only carbon sequestered in marine sediments, as in the case of blue carbon sinks, can be safely considered to represent a long-term marine carbon storage. Blue carbon sinks, which cover less than 0.2% of the seafloor, contribute about 50% (71% using maximum estimates, see Table 1) of the total burial of organic carbon in ocean sediments and therefore rank amongst the most intense carbon sinks in the biosphere (Duarte *et al.*, 2005a). Yet coastal vegetated habitats have been neglected from accounts of the global carbon cycle and global inventories of natural carbon sinks.

Blue carbon sinks are built by plants and trees (otherwise known as angiosperms such as mangroves, salt-marsh plants and seagrasses) but the coastal ocean also contains vast areas covered by algal beds. Most macroalgal beds (including kelp forests) do not bury carbon, as they grow on rocky substrates where burial is impossible.

UNCERTAINTY AND UPPER ESTIMATES OF CARBON SINK BY BLUE CARBON SINKS

There is uncertainty about these global rates, due to uncertainties in their areal extent as well as variability in carbon burial rates among individual ecosystems, although independent estimates for some ecosystems, such as mangrove forests, agree remarkably well (Bouillon *et al.*, 2008). For instance, estimates of the area covered by mangroves, probably the best constrained amongst vegetated coastal habitats, ranges from 0.11 to 0.24 million sq km (Bouillon *et al.*, 2008). Estimates of the area covered by seagrass meadows, the least constraint estimate, range from a documented area of 0.12 million sq km (Green and Short, 2003), to an upper estimate of 0.6 million sq km (Duarte and Chiscano, 1999) as the South East Asian archipelagos, such as Indonesia, are likely to hold vast, uncharted seagrass meadows (Duarte *et al.*, 2009). Indeed, the coastal area with sufficient submarine irradiance as to support seagrass meadows has been estimated at 5.2 million sq km (Gattuso *et al.*, 2006). Hence, a thorough inventory of blue carbon sinks may well yield a cover twice as large as the mean area considered in current, conservative global assessments (Table 1). Individual blue carbon sink ecosystems also vary greatly in their capacity to bury carbon, with the maximum reported rate corresponding to 17.2t C ha^{-1} yr^{-1} in a salt marsh (Table 1). The maximum carbon burial rates for any one habitat type are 3 to 10 times higher than the global mean value for these ecosystems (Table 1), providing evidence of the very



large carbon sink capacity of some specific vegetated coastal habitats. Indeed, the maximum reported carbon sink capacity of salt-marsh, mangrove and seagrass ecosystems (Table 1) exceeds by over 10, 6 and 2 fold that of undisturbed Amazonian forest, estimated at 1.02 t C ha^{-1} (Grace *et al.*, 1993). For instance, carbon burial by salt marshes, which cover a small area of the conterminous USA, has been estimated to account for 21% of the total carbon sink of all USA ecosystems (Bridgham *et al.*, 2006). Hence, an upper estimate of the carbon capture capacity of blue carbon sinks can be derived by combining maximum estimates of the area covered globally with upper estimates of the carbon buried per unit area (Table 1). These calculations yield an upper estimate for the carbon capture capacity of blue carbon sinks at 329 Tg C year^{-1}, accounting for 71% of the burial of organic carbon in the ocean (Table 1).

Table 1. Mean and maximum (in brackets) estimates of the area covered by blue carbon sinks and the annual organic carbon burial rates. Carbon burial rates are presented per hectare (mean,range and , the upper confidence limit of the mean of individual ecosystem estimates, in brackets) and globally (as reported ranges of mean rates of global carbon burial derived using different methods and, in brackets, an upper estimate derived using the maximum area and the upper confidence limit of the mean burial rate). The data is for vegetated coastal areas and their percentage contribution to carbon burial in the coastal and global ocean (in brackets the burial rate and percentage contribution of vegetated habitats calculated from the upper estimates). Total burial rates of organic carbon in estuarine and shelf sediments and deep-sea sediments are provided for comparison. Data derived from reviews by Cebrián and Duarte (1996), Duarte *et al.* (2005a), and Bouillon *et al.* (2008).

Component	**Area**	**Organic Carbon burial**	
	Million km^2	Ton C ha^{-1} y^{-1}	Tg C y^{-1}
Vegetated habitats			
Mangroves	0.17 (0.3)	1.39, 0.20 – 6.54 (1.89)	17 – 23.6 (57)
Salt Marsh	0.4 (0.8)	1.51, 0.18 – 17.3 (2.37)	60.4 – 70 (190)
Seagrass	0.33 (0.6)	0.83, 0.56 – 1.82 (1.37)	27.4 – 44 (82)
Total vegetated habitats	0.9 (1.7)	1.23, 0.18 – 17.3 (1.93)	114 – 131 (329)
Depositional areas			
Estuaries	1.8	0.5	81.0
Shelf	26.6	0.2	45.2
Total depositional areas			126.2
Total coastal burial			237.6 (454)
% vegetated habitats			46.89 (0.72)
Deep sea burial	330.0	0.00018	6.0
Total oceanic burial			243.62 (460)
% vegetated habitats			45.73 (0.71)

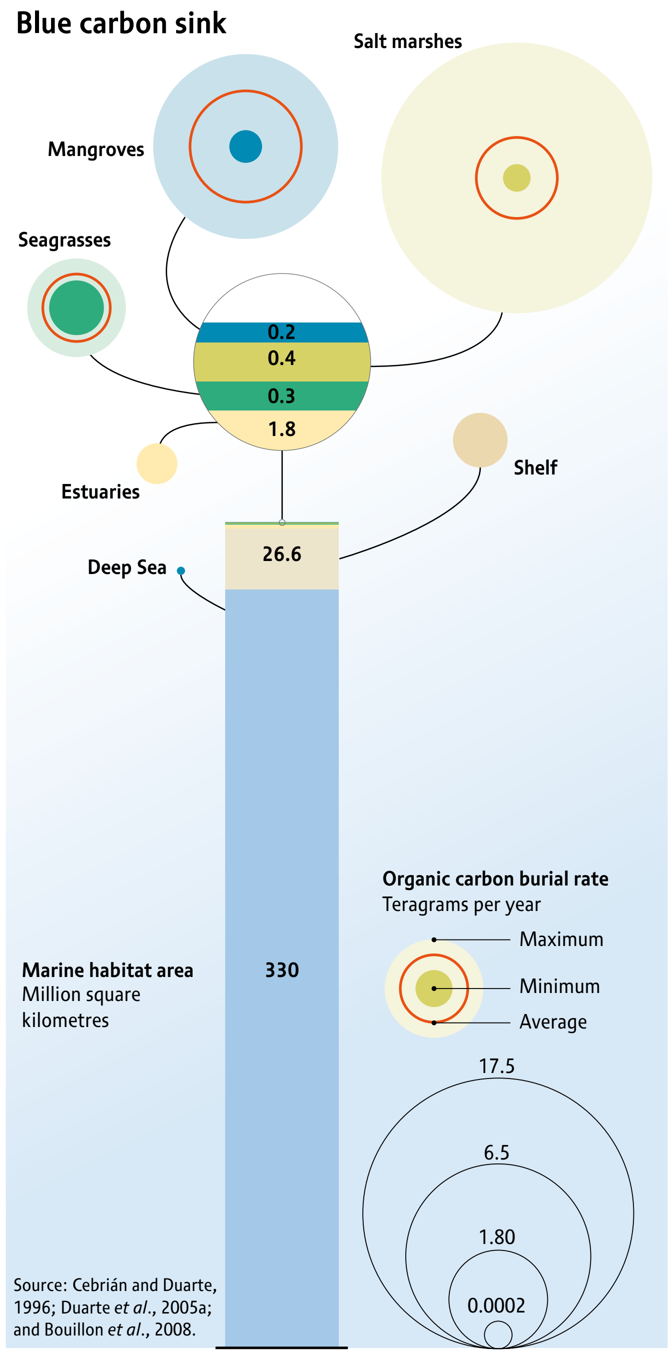
Fact box 4. Ocean carbon in the global cycle?

Several studies suggest that the oceans have taken up around 2,000–2,200 Tg C yr^{-1} over the past two decades (Gurney *et al.* 2002, Plattner *et al.* 2002, Sabine *et al.* 2004, Bender *et al.* 2005, Miller *et al.* 2005, Manning and Keeling 2006). The uptake increased slightly from around an estimated 1800 in the 1980s, to 2,200 Tg C yr^{-1} in the 1990s and the first half decade of the twenty-first century (McNeil *et al.* 2003, Canadell *et al.* 2007). However, only a portion of this carbon is actually stored permanently in the oceans, as much is recycled and released back within a few decades. Coastal ecosystems are currently storing an amount of carbon equivalent to around 25% of the estimated annual increase of approximately 2,000 Tg C yr^{-1} in the atmosphere.

Currently, fossil fuel emissions are estimated at 7,200 Tg C yr^{-1}, which results inapproximately 2,000 Tg C yr^{-1} increase in the atmosphere per year. Losses of seagrass communities, mangroves, and salt marshes have accelerated from around 0.9% per year in the first three quarters of a century to up to 7% per year in the more recent decades. Under current scenarios, most blue carbon sinks will be lost in the next two decades leading to a loss of annual carbon binding capacity equivalent to 4–8% of the total anthropogenic input. Hence, total emissions would therefore have to be reduced by an additional 4–8% by 2030 to retain the status quo, or 10% by 2050. In comparison, the total gain estimated from the UN REDD programme if fully implemented (including slowing deforestation and wide afforestation programmes), would by 2050 according to the IPCC amount to approximately 12–15% of the required emission reductions. Preventing the loss of the oceans blue carbon sinks would mean a significant contribution to reducing climate change, even compared to slowing deforestation of tropical rainforests. Afforestation programmes of mangroves could enhance this even further. The upper estimate of storage in oceans is approximately 450 Tg C yr^{-1} – equivalent near 10% of the required emission reductions. Hence, "Blue" and "Green" carbon combined could bind at least 25% of the projected required emission reductions.

	1980s (Tg C yr^{-1})	1990s (Tg C yr^{-1})	2000–2005 (Tg C yr^{-1})
Fossil fuel emissions	5200 ± 300	6400 ± 300	7200 ± 300
Atmospheric increase	–2900 ± 100	–3200 ± 200	–4200 ± 100
Oceanic uptake	–1900 ± 600	–2200 ± 700	–2200 ± 400
Net terrestrial flux	–400 ± 700	–100 ± 800	–800 ± 800
Land-use change	1500 ± 800	1600 ± 800	1500 ± 800
Residual terrestrial flux	–1900 ± 1100	–2600 ± 1100	–2300 ± 1100

Table 2. The Global carbon budget Tg C yr^{-1} – around 2,200 Tg C are captured per year in oceans, but only a portion of it is stored, mainly in sediments in oceans blue carbon sinks, such as mangroves, marshes and seagrass communities (Canadell *et al.*, 2007; Houghton, 2007).



Source: Cebrián and Duarte, 1996; Duarte *et al*., 2005a; and Bouillon *et al*., 2008.

Figure 17: Blue carbon sinks.

Fact box 5. Geo-engineering proposals for mitigating CO_2

Interest has been growing in the use of geo-engineering to provide a technically and potentially commercially viable mitigating solution to combat increasing atmospheric CO_2 concentrations (see IPCC, 2005 for an overview). Several of these proposals intend to enhance the function of the ocean as a carbon sink, or to store CO_2 in subsea geological formations. Some of these suggestions might sound dramatic and farfetched, but if the concepts are scientifically sound and technically feasible, they should not be disregarded. However, evaluating these new innovations is in most cases not a simple story, as they pose significant ecological, economic, political and ethical challenges (Nature News, 2009) giving cause for concern. With too many unknown variables and current modeling limitations, assessment of the risks and consequences of these proposals will be a challenge.

There are two main approaches. The first is to reduce energy entering the earth's system by blocking radiation so it cannot be absorbed in the first instance (e.g. spraying aerosols to increase cloud cover, use of solar shades, increasing reflective capacity of urban areas); the second is to reduce the concentration of CO_2 in the atmosphere by transferring it into long term storage reservoirs, thereby facilitating the escape of energy from the earth (Lenton and Vaughn, 2009; IEA, 2004). These approaches are at varying degrees of development; while some have been through in-situ experimentation, others are still just theoretical. Current research shows that most ocean geo-engineering concepts are high risk for undesirable side-effects (e.g. increase in ocean acidification), have limited application, uncertain outcome and potentially non-reversible impacts on the marine environment. This highlights the need to apply a precautionary approach when investigating ocean geo-engineering interventions.

Table 3. An overview of the main ocean carbon cycle geo-engineering proposals, the concept behind these ideas and current status of investigation.

Proposal	Concept	Status of research
Ocean fertilization	Primary production in some areas of the ocean is limited by macro or micro nutrients (such as iron, silica, phosphorus or nitrogen). By increasing the availability of these nutrients, primary productivity could be increased resulting in an acceleration of the natural rate of CO_2 uptake by the oceans from 2 Gt C yr^{-1} (Huesemann, 2008) and increase CO_2 storage in the deep sea. Any CO_2 stored in this way would be removed from the global carbon cycle for up to 1,000 years. Promoted by commercial groups and enterprises (e.g. Climos) and with potential for trading credits on the voluntary carbon market.	• Approximately 13 small scale in situ experiments have been conducted since 1993, but have proven inconclusive about the CO_2 sequestration effectiveness of ocean fertilization; • To make a viable contribution to reducing atmospheric CO_2 concentrations, ocean fertilization would have to be carried out over large areas, and potentially would need to be sustained on a millennial timescale (Lenton and Vaughan, 2009); • International concern has been expressed, inter alia, about the high ecological risks. International bodies and experts have called for restrictions and caution (e.g. IMO, 2007; CBD 2008; Gilbert *et al.*, 2008; Seibel and Walsh 2001); • Parties to the London Convention agreed that, given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed. An assessment framework for future scientific research and in-situ experiments is under development (IMO, 2008).
Altering ocean mixing	Use of 200m long ocean pipes to enhance the mixing and upwelling of nutrient rich waters (e.g. Lovelock and Rapley, 2007); Enhance downwelling by using floating pumps to cool waters and form and thicken sea ice (Zhou and Flynn, 2005)	• Never reached field trial stage; • Calculations indicate sequestration flux that would be achieved is trivial on any meaningful timescale; and costly (Lenton and Vaughan, 2009).
Increasing ocean alkalinity	Increasing the alkalinity of the oceans by: • Adding carbonate, thereby increasing the capacity of the water to absorb CO_2 (Kheshgi, 1995). Harvey (2008) suggested the use of finely ground limestone, other proposals foresee the use of thermally decomposed limestone (Cquestrate, 2009); • Enhancing the solubility of CO_2 in the oceans by a process equivalent to the natural silicate weathering reaction. HCl is electrochemically removed from the ocean and neutralized through reaction with silicate rocks.	• This is as yet highly theoretical, but under active research, e.g. by Cquestrate, which is an opensource project to explore the idea, encouraging evidence based debate and investigation (Cquestrate, 2009); • It is possible that the CO_2 emissions generated from preparing the carbonate material would match the CO_2 sequestered (Lenton and Vaughan, 2009).

Proposal	Concept	Status of research
	The increase in ocean alkalinity resulting from the removal of HCl causes atmospheric CO_2 to dissolve into the ocean where it will be stored primarily as HCO^{3-}. (House *et al.*, 2007); • These are the only marine geo-engineering proposals that would remove CO_2 from the atmosphere without causing an increase of ocean acidification.	
Geological carbon storage	Injection of CO_2 into deep geological formations such as saline aquifers or depleted oil and gas reservoirs below the sea floor	• In operation since 1996. Measures and guidance (e.g. to reduce the risk from leakages) were adopted by international bodies (IMO/London Convention, OSPAR). Studies have being conducted to research and model long term consequences and how secure such storage would be (e.g. Gilfillan *et al.*, 2009, Statoil Sleipner Project)
Dissolution injection of CO_2 into the water column CO_2 injection onto the sea floor	CO_2 is transported by ship or pipeline offshore and then injected into the water column at great depth (>1000m or deeper) where the CO_2 dissolves and remains isolated from the atmosphere for centuries. (UNESCO-IOC/SCOR, 2007); CO_2 is placed directly onto the sea floor at depths greater than 3000m, where the CO_2 would form long-lasting 'lakes' with low dissolution rates.	• Both concepts been subject to years of theoretical research/modeling and some small scale field experiments, but have yet been deployed or fully tested (UNESCO-IOC/SCOR, 2007). Research indicates that there would be a gradual release of injected CO_2 back to the atmosphere over a timescale of hundreds of years to millennia (depending on depth and local site conditions); • There is no known mechanism for preventing catastrophic acute release of injected CO_2 (UNESCO-IOC/SCOR, 2007), there are significant environmental risks and impacts associated with these proposed methods of storage (IPCC, 2005; Sedlacek *et al.*, 2009). Injection of CO_2 into the water column or on the sea bed affects marine organisms nearby and ocean chemistry (e.g. by increasing acidity). In the light of the potential for severe environmental impact, the placement of carbon dioxide streams in the water column or on the sea bed has been prohibited in 2007 via the amendment of the London Convention Protocol and in a legally binding decision agreed under OSPAR (OSPAR, 2007).