

Carbon Capture and Sequestration: Potential Environmental Impacts

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Abstract

Over the last few years, understanding of the profound implications of anthropogenically driven climate change has grown. In turn, this has fuelled research into options to mitigate likely impacts. Approaches involving the capture of carbon dioxide and its storage in geological formations, or in marine waters, have generated a raft of proposed solutions. The scale of some of these proposals is such that they will exert impacts of global significance in their own right.

Proposals fall into two broad categories:

- storage of liquid CO₂ or products of reacted CO₂ into intermediate/deep oceanic waters.
- storage of liquid CO₂ into sub-seabed or terrestrial geological formations.

For the most part, while the technical feasibility of these schemata has been widely explored, the same is not true of their ecological implications. In the case of deep/intermediate oceanic waters, poor baseline understanding of the associated ecosystems is a considerable impediment to any reliable predictive assessment of likely impacts of carbon dioxide storage in these systems. Disruption of marine microbiological processes and degradation of benthic ecosystems, including those with high levels of endemism, have been identified as potentially serious impacts. Similarly, the physiology, ecology and likely responses of micro-organisms present in targeted geological formations require evaluation prior to any consideration of the use of such formations for storage of CO₂. In addition, the impacts of any leakage to surface need also to be considered.

Accordingly this paper explores current uncertainties and detailed informational needs related to ocean and geological storage of fossil fuel-derived CO₂. Particular emphasis is placed upon the ecological impacts of these proposals in relation to existing and emergent understanding of deep water/soil ecosystems and the indeterminacies attached to this understanding.

Introduction

The capture of carbon dioxide generated by fossil fuel combustion, coupled with its subsequent storage into free circulating oceanic waters or sub-seabed/terrestrial geological formations, has been proposed on a number of occasions and is currently the subject of discussion at government level in a number of countries (see e.g.: DTI 2000). As such these schemata are part of a raft of planetary engineering approaches to climate change mitigation. Some of these are illustrated in Figure 1 below:

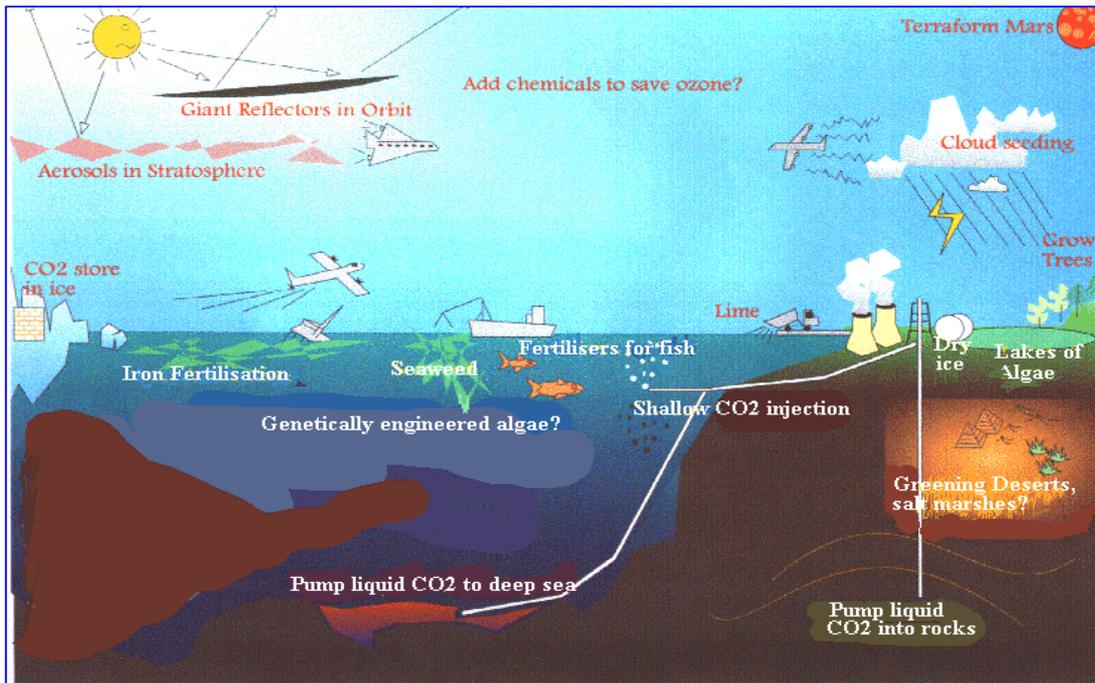


Figure 1 Schematic representation of various proposals which have been made to mitigate anthropogenic climate change through planetary engineering projects. Source: Matthews (1996), reproduced by permission.

As a component of this raft of potential solutions, the idea is to develop ocean/geological storage systems as a means of mitigating the impacts of anthropogenically driven climate change. Effective mitigation by these means implies the need for effective isolation of the captured CO₂ over long time frames. The potential quantities which may be stored by any given ocean or geological scheme have been estimated and are reproduced in Table 1 below:

Table 1 estimates of carbon reservoirs of different biosphere compartments and order of magnitude estimates of potential capacities for carbon sequestration (adapted from Herzog 2001)

Reservoir size	Gt (billion tonnes) carbon
Oceans	44 000
Atmosphere	750
Terrestrial	2 200
Sequestration potential	Gt (billion tonnes) carbon
Oceans	1000s
Deep saline formations	100s-1000s
Depleted oil and gas reservoirs	100s
Coal seams	10s-100s
Terrestrial	10s

On the basis of these data, it appears that the oceans and saline aquifers present the greatest opportunities for storage of anthropogenically derived CO₂. The rationale behind the major proposals is outlined below.

The proponents of these large scale planetary engineering projects assert that such approaches are consistent with the United Nations Framework Convention on Climate Change (UNFCCC) which 'explicitly mentions the need for using sinks and reservoirs as one component of a more comprehensive portfolio of strategies for reducing greenhouse gas emissions' (Adams *et al.* 2002). It should be noted, however, that the UNFCCC also explicitly enjoins parties to manage such sinks in a sustainable manner.

Moreover, in addition, there are legal instruments which specifically impinge upon the use of the deep ocean to store fossil fuel-derived CO₂. On an international basis the London Convention (1972) prohibits the dumping of industrial waste at sea or in sub-sea bed formations. More re-

gionally, the OSPAR Convention (1992) reinforces and extends the provisions of the London Convention within the North East Atlantic area. The question of whether ocean carbon storage constitutes a regulated activity under these Conventions, and in particular whether fossil fuel-derived CO₂ constitutes an industrial waste, needs to be urgently resolved.

Schemata to capture and store carbon dioxide either in ocean systems or geological formations have in common the capture phase of operations followed by liquefaction and transport. The environmental risks associated with this phase are not considered in detail in this current paper. These risks can largely be described in terms of probabilistic likelihood of process engineering failure, or failure of the CO₂ transport infrastructure. There is considerable operational experience of both the process engineering involved in capture and in the transport of CO₂ by pipeline. The most serious impacts are likely to result from failure of transport pipelines and a large release of carbon dioxide in gaseous form. It is possible that such releases could endanger human life and those of livestock. A natural (though extreme) analogue is that of Lake Nyos, a volcanic crater lake in Cameroon which outgassed large quantities (estimated at 80 million cubic metres) of carbon dioxide causing 1700 deaths and loss of livestock up to 25km from the crater (Kling *et al.* 1994, Clarke 2001).

Ocean Storage Options and Potential Impacts

i) The Oceans and the Global Carbon cycle

The rationale behind ocean storage of carbon injected as liquid CO₂ is described by GESAMP (1997) as essentially:

'a short-circuit mechanism that disposes of fossil-fuel combustion CO₂ directly into the deep ocean, thereby reducing direct injections to the atmosphere and accelerating the process of attaining of atmosphere-ocean equilibrium. It can be viewed as an acceleration of the natural, but slow, process of transferring CO₂ from the atmosphere to the deep ocean which is currently estimated to be occurring at a rate of 2 Gt C per year'.

Accordingly, wide-scale adoption of ocean storage is viewed as a means potentially of avoiding the 'transient' high peak of atmospheric CO₂ predicted for the next few centuries arising from projected future emissions (IPCC, 1996). Ultimately, the equilibrium reached with the atmosphere (over many centuries), it is argued, would be about the same as that which would have occurred without intervention. Such proposals are specifically predicated upon the basis that it will be possible to capture the carbon dioxide emitted from the majority of the world's power stations and transport it for injection into deep water (GESAMP 1997). Given continued development of fossil fuel power generation, a yearly commitment to store around 7Gt of CO₂ is not an unrealistic projection.

The global carbon cycle can be visualised schematically as in Figure 2 above while the various anthropogenic emission sources quantified by the IPCC (1996) is summarised in Table 2.

Atmospheric carbon dioxide is transferred rapidly into seawater at the air-sea interface, particularly when strong winds cause breaking waves and entrainment of bubbles. As a result of the chemical equilibrium between molecular carbon dioxide and the bicarbonate and carbonate ion present in seawater, only around 1% of the CO₂ remains in dissolved molecular form with the rest being converted to bicarbonate ion. Once the carbon dioxide has become dissolved into the surface waters it enters the marine carbon cycle and may ultimately be transported into deep waters by two major processes, the solubility and the biological pumps.

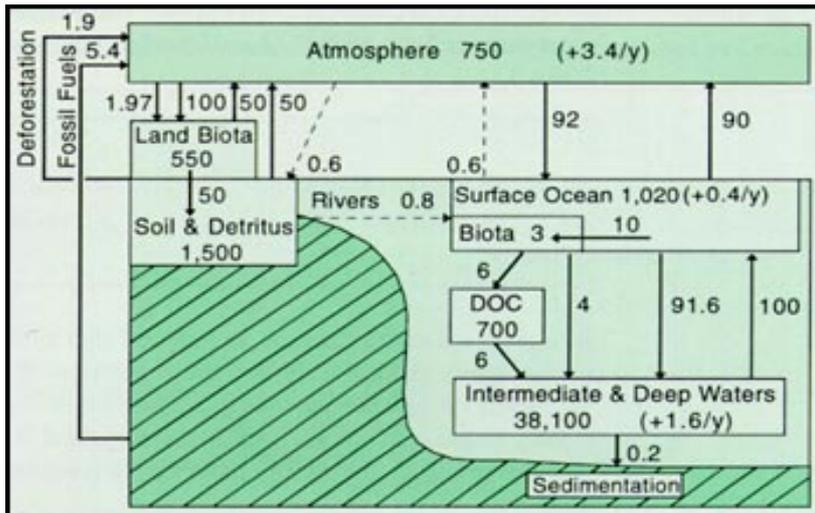
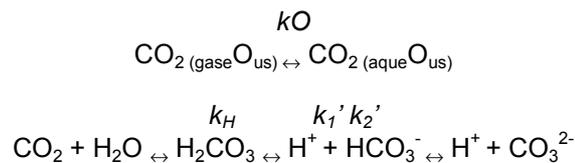


Figure 1 Schematic representation of the global carbon cycle for the 1980's. Fluxes are given in $GT\ y^{-1}$, reservoirs in Gt. The figures in parentheses indicate the increase in given compartments of carbon on an annual basis due to anthropogenic carbon dioxide emissions. See also legend to Table 1 and body of text. Source: IEA (1998a) Reprinted from Siegenthaler and Sarmiento (1993)

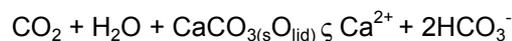
The basic chemical reactions determining CO_2 assimilation in seawater and ocean systems are as follows:



where kO = the solubility coefficient of CO_2 in seawater, k_H is the hydration constant and k_1' and k_2' are the apparent first and second dissociation constants of carbonic acid. The carbonate ion is an important measure of buffering capacity, and therefore capacity to neutralize CO_2 entering seawater through the reaction:



CO_2 can also be neutralized by calcium carbonate in suspended particulate form or incorporated into sediment through the reaction:



This reaction can take place with biogenic calcium carbonate present in both living and dead calcified organisms.

Under deep ocean conditions, CO_2 hydrate (clathrate) may form as $CO_2 \cdot 6H_2O$ or $CO_2 \cdot 8H_2O$. This is thought to form around droplets at depths greater than 500m. This is regarded as an interfacial stage, whereas the formation of a clathrate boundary around CO_2 present as a lake on the bottom of the ocean is likely to be more stable and inhibit CO_2 dissolution over longer time-scales.

Table 2: Global carbon budget for post industrial times showing major emission sources and uptakes in PgCy⁻¹ (Gt). Discrepancies between the figures cited in this table and those cited in Figure 2 and in the text arise from the considerable uncertainties attached to estimates of carbon fluxes and reservoirs Source: IPCC (1996)

Emissions	PgC/yr
Fossil Fuels	5.5±.5
Tropical Deforestation	1.6 ± 1.0
Uptake	PgC/yr
Atmospheric Buildup	3.3
Ocean Uptake	2.0 ± 0.8
Forest Regrowth (NH)	0.5 ± 0.5
Land Sink (by difference)	1.3 ± 1.5

Even with the current uncertainties which exist in relation to the size of carbon reservoirs and fluxes, simple calculations based upon the actual concentration of CO₂ and the theoretical saturation achievable in deep ocean waters indicate a notional capacity for several million Gt of CO₂. In practical terms, this is constrained by the amount of carbonate ion available to neutralise the carbonic acid formed by dissolved carbon dioxide if large excursions in overall oceanic pH values are to be avoided (see below). Estimates for carbonate available in deep ocean sediments range between only 1,600 Gt and 4,920 Gt. Dissolved carbonate ion in ocean waters deeper than 500m have been estimated at 1,320 Gt. It must be stressed that these values are highly speculative due to the paucity of empirical data (see: Wong & Hirai, 1997). Nevertheless they have spurred much research into how CO₂ might be injected into deep ocean waters and stored there.

The carbon cycle in the ocean is based upon interactions between physical, chemical and biological processes. These processes are understood in individual terms to varying extents, but the interactive aspects are subject to extremely large uncertainties (Falkowski *et al.* 2000). In large part this is due to poor spatial and temporal resolution of understanding of these processes in the ocean despite the data generated by large ocean research programmes on this topic and to the resultant inadequacies of the mathematical models applied to such studies (Follows *et al.*, 1996; Ormerod, 1996). CO₂ uptake from the oceans has largely been inferred from calculations based upon sparse total inorganic carbon measurements. Improving the precision of these estimates by suitably intense sampling programmes is likely to be some decades into the future (Goyet *et al.*, 1997). Hence, current published notional annual uptake estimates for CO₂ range between 1.5 and 3.1 Gt. The question of how and where anthropogenic CO₂ penetrates into the ocean will remain unanswered until additional field measurements are available covering all areas of ocean within the depth of the winter mixed layer at an appropriate spatial resolution. In many respects this question is allied to the questions concerning the likely retention time of carbon dioxide injected into the ocean.

Considerable indeterminacies attach to the interrelationships of other biogeochemical cycles with the carbon cycle. Accordingly there is a great need to continue to gather baseline data on the global carbon cycle, to disentangle the inter-relationships and to quantify the carbon fluxes, sinks and reservoirs involved. Reliable quantification of these may prove somewhat challenging given that in some cases possible changes cannot yet even be ascribed a positive or negative dimension, much less a magnitude. It is quite possible too (Falkowski *et al.* 2000) that the existing natural sinks involving the ocean will be diminished under a climate change scenario..

ii) Injection of CO₂ into ocean waters

Essentially, the proposals for storage of CO₂ in the oceans hinge around two basic methods of introduction of the gas as a liquid, illustrated in Figure 3. Both systems essentially introduced CO₂ into the oceans in an uncontained form so that CO₂ dissolves and ultimately re-enters the carbon cycle. Plans to store quantities of solid carbon dioxide either in cold terrestrial regions, or by discharging blocks of 'dry ice' from ships seem largely to have disappeared from active consideration. A further scheme proposed for marine storage involves the reaction of CO₂ with limestone and water to produce bicarbonate which can then be discharged to the ocean, thereby mitigating against limitations in carbonate neutralisation capacity (Rau and Caldeira 1999; Caldeira and Rau 2000). This scheme does not appear to be as evolved as those involving direct introduction of CO₂ to the oceans. Accordingly, this paper considers only the scenar-

ios outlined in Figure 3. The injection scenarios have been described in a number of documents (see: Johnston *et al.* 1999; Herzog, 2001).

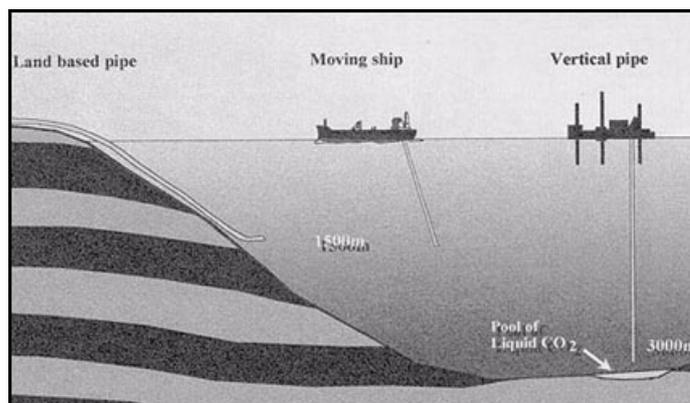


Figure 3: The proposed introduction of liquid carbon dioxide from a fixed or towed pipeline into mid ocean waters and the discharge of liquid carbon dioxide onto the seabed from a fixed platform. In practice ships could be used in place of the platform to create a seabed lake of CO₂ also. Source IEA (1998a).

Mostly, research effort has focused on the introduction of CO₂ by pipeline. At depths of less than 500m, introduction of CO₂ will create bubble plumes since, at ambient pressures and temperatures, carbon dioxide exists as a gas. These bubbles will dissolve in the seawater and, it is suggested, become trapped below the ocean thermocline. Although in engineering terms this is a relatively simple option, the retention time of the gas would be relatively short, of the order of 50 years (see: GESAMP 1997). At temperatures and pressures between 500m and 3000m, carbon dioxide exists as a positively buoyant liquid. Hence, it will form a droplet plume, perhaps with the droplets covered in film of hydrate, which could slow dissolution (Drange *et al.* 2001). Injection into intermediate depth waters is assumed to result in a CO₂ enriched plume where diminished pH values are likely to persist for many tens of kilometers down current, depending upon the degree of constraint imposed by, for example, density discontinuities. It is possible that in this case hydrate formation could inhibit the uptake of CO₂ in seawater if it results in a plume of droplets, which rise to the hydrate phase boundary (Brewer *et al.* 2000).

The injection of CO₂ into deep oceanic waters is likely to have qualitatively different impacts as compared to introduction into intermediate depth waters. Below 3000m, it is anticipated that CO₂ will form a dense liquid plume which could ultimately form a lake of liquid CO₂ on the sea bottom (Adams *et al.*, 1995; Brewer, 2000) bounded by a clathrate surface. This surface will inhibit (though not prevent) its dissolution into the overlying waters. Retention times in these cases should be much greater than those achieved by injection into shallower water since deep water exchanges with surface water at a much lower rate than surface water interacts with the atmosphere in the upper mixed layer of the sea. Calculations have suggested that a lake of CO₂ on the deep ocean floor derived from 1GW of coal fired power plant over ten years of operation could cover 654,500m² of sea floor to a depth of 80.9m and contain 58 million tonnes of the liquefied gas (Wong & Hirai, 1997). The assumption that the pool would remain 80.9m in depth is merely a hypothetical construct to operate the mathematical model. Unless constrained by local topography or the formation of a clathrate boundary it seems reasonable to assume that, in practice, the liquid CO₂ might spread out to form a thinner layer over a much wider area, with the consequence of more widespread impacts. This would depend upon the degree to which any hydrate formation (see below) constrained the CO₂. Eventually, however, ocean processes will dissolve all forms of dumped CO₂ and transport it ultimately towards the surface. It has been estimated that, at a depth of >3000m, a pool of CO₂ containing 58.4 Mt would dissolve into the deep water over approximately 240 years.

iii) Resultant physico-chemical modification

Normal pH values in seawater are 8.0-8.2 at the surface, decreasing to 7.7-7.8 in deep water (Train 1979). In some productive tropical environments, pH values may embrace a daily range of 7.3-9.5 as a result of biological sequestration.

Irrespective of the considerable pH buffering provided by seawater *via* the carbonate system (and to a lesser extent other weak acid salts such as borate), the introduction of large quantities of CO₂ directly into the deep ocean will modify the water pH locally to a significant degree. In addition, an elevation of free carbon dioxide can be anticipated. Moreover, if the CO₂ contains impurities (as would seem likely for many industrial waste streams) such as sulphur oxides, nitrogen oxides, trace metals or organic chemicals then the behaviour and impact of these will need to be considered in addition to the impact of pH change alone.

Models suggest the pH excursions likely to result from introduction of CO₂ are substantial (IEA 1996, partially reproduced by GESAMP 1997). These figures suggest that a pH of below 7.5 would exist through some 1500 cubic kilometres of water if the CO₂ from ten power plants was introduced at a single point as a droplet plume and that this would rise to 5900 cubic kilometres if introduced as a dense plume in shallower water. The centre-line distances from the point of release to reach a pH value of 7.5 are 530 and 2200 kilometres respectively.

v) Potential Impacts

On the basis of the above, potential impacts upon marine biological systems which need to be considered are those due to:

- pH reduction
- carbonate dissolution
- co-recovered materials such as sulphur oxides, nitrogen oxides and metals
- changes in speciation of e.g. metals and ammonia.
- 'smothering' effects

In predicting the extent of likely impacts it is necessary to establish baseline datasets relating both to the scale and extent of the physico-chemical perturbation and the character of the biological systems involved. As noted above, current prediction of pH excursion is based upon mathematical modeling. It is unlikely that the technological means will exist to generate precise *in situ* data sets over a relevant (*i.e.* extensive) spatial scale for pH changes in the deep ocean resultant from CO₂ storage. With respect to availability of baseline data sets required to evaluate biological impacts, much depends upon the level of biological organization involved. This is illustrated in Figure 4:

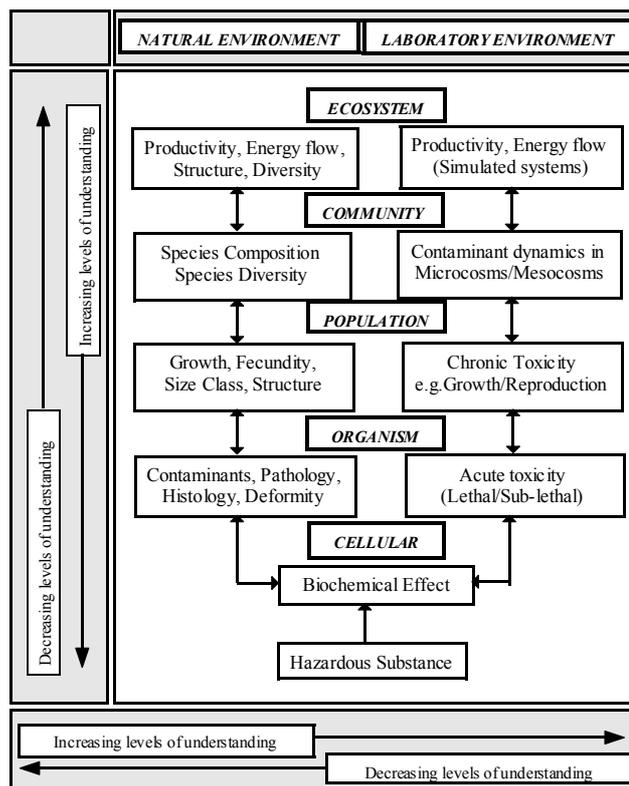


Figure 4: Schematic diagram showing levels of biological organization and associated biomarkers of toxicological impact at each level. Levels of scientific understanding tend to decrease in relation to natural as opposed to laboratory systems and with increasing levels of biological organization. Source: Santillo et al. (1998)

In general, impacts of physico-chemical changes upon living systems tend to be assessed using single species toxicity tests, the results of which are then extrapolated to predict whole ecosystem impact (see: Santillo *et al.* 1998). The biological markers of effect employed (biomarkers or endpoints) are predominantly cellular, organismal, and less commonly, population (e.g. sentinel species). Few reliable markers have been identified at the community and whole ecosystem level. This is an acknowledged problem that pervades the whole field of environmental toxicology. While regulatory endpoints have been defined for many situations, their relevance as significant systemic biological endpoints is often highly questionable.

In the case of deep sea environments, even relevant species data are very sparse. It is widely acknowledged that, in ecological terms, the deep oceans are poorly understood. In recent years the paradigm under which deep sea environments have been characterized as homogenous, sparsely populated and lacking in diversity has been challenged by the discovery of hydrothermal vent ecosystems, cold seep systems, seamount ecosystems, coldwater coral reefs and gas hydrates (Roberts 2002). Seamounts, for example, have been found to be hotspots of diversity, with a high proportion of unique species (Koslow *et al.* 2000; 2001). These topographical features are numerous. To our knowledge, no toxicological endpoints/biomarkers exist for any of the species present in these various ecosystems. Even if they did, extrapolation of findings to predict impacts on the wider ecosystems would not be possible since the community structure and dynamics of these systems are so poorly characterized. It is only recently, for example, that knowledge of species distribution in the oceans has advanced to the point where basic hypotheses concerning the existence of latitudinal biodiversity gradients have been able to be tested (Gray 2001).

Some work on disturbance of faunal communities has been carried out in the deep ocean, specifically the analysis of pre-and post disturbance characteristics of the meiobenthic fauna impacted by potential deep-sea mining activities (Ahnert & Schriever 2001; Vopel & Thiel 2001). These studies are analogous to meiofaunal studies carried out in shallower waters (Warwick 1988) to identify pollution impacts. This fauna, comprised of extremely small species, generally lends itself to detailed statistical analysis. Even so, in the deep-water studies, the lack of repli-

cates prevented even some fundamental components of analysis (e.g. depth distributions of organisms) being carried out.

The use of very small organisms allows resolution of physical impacts over relatively small areas. It is not clear how these techniques would translate to the much bigger areas likely to be impacted by deep ocean storage of CO₂. Overall the lack of general baseline information on deep-sea ecosystems and their likely responses to perturbation, along with the difficulties inherent in working with such systems, present a highly important suite of uncertainty and indeterminacy.

a) pH reduction

Existing data suggest that the reduction of marine pH values over a wide area is likely to have appreciable impacts on organisms in deep ocean habitats. CO₂ causes acidification not only in the water to which it is introduced, but also in organismal tissues and body fluids. Intra- and extracellular acid-base parameters will reach new steady state values which, if they do not cause acute effects, could result in chronic metabolic and reproductive impacts. It is generally considered that deep ocean organisms have evolved for life in a physico-chemically stable environment and may be poorly equipped to accommodate and/or avoid changes. While the majority of information on impacts of reduced pH on aquatic organisms relates to freshwater species (see: Train 1979; Wolff *et al.* 1988), some data do exist on marine organisms. A common problem with many of the studies carried out on marine fish is a failure to distinguish properly between the effects of low pH and of the CO₂ released by addition of the acid used. Similarly, for other marine organisms, the body of data is hard to interpret since data are scant and other variables were often not adequately controlled. Existing data on pH responses have, however, been synthesized into a predictive model described by Auerbach *et al.* (1997) and Caulfield *et al.* (1997). Most of the biological impact analyses of ocean carbon storage schemata are based upon this predictive model notwithstanding the inherent limitations in the body of biological response data.

The US EPA water quality criterion for pH in marine waters (Train 1979, EPA 2002) was set to maintain it within the range 6.5-8.5 but with the proviso that it should not rise or fall more than 0.2 units outside the normally occurring range. Studies suggest that plankton and benthic invertebrates are more sensitive than fish to changes in pH. Reported experimental work on reduced pH impacts on deep sea organisms appears to be even more limited, restricted to (qualitative) observations made of fish and motile invertebrates exposed to extremely small quantities of introduced CO₂ (Tamburri *et al.* 2000). Some limited work has also been carried out on marine bacterial communities exposed to elevated CO₂, but these were not carried out under deep ocean conditions (Sugimori *et al.* 2001).

In relation to intermediate depth CO₂ injection, one study has been published which investigated the impact of reduced pH upon bacterial processes (Huesemann *et al.* 2002). Specifically, nitrification reactions were suppressed by 50% when pH was reduced from 8 to 7 and by 90% at pH 6.5. This led the authors to postulate wide-ranging impacts upon the cycling of nitrogen in waters influenced by carbon storage activities.

Overall, however, the general paucity of data on pH impacts at the organismal and higher levels of biological organisation must be seen as a further important barrier to current assessment of likely impact of deep ocean carbon storage schemata.

b) Carbonate dissolution

A number of groups of marine animals have shells or skeletal structures based around calcium carbonate. This can be dissolved by reaction with CO₂ in water. Accordingly, some deep-water corals and bivalve molluscs, among other organisms, could be particularly vulnerable to this process. In addition, the neutralization of CO₂ by reaction with calcareous sediments could provoke changes in the sedimentary infauna. No detailed information appears to have been published on this and its biological significance is therefore unknown. If realised, however, widespread dissolution of exoskeletal structures could have profound secondary impacts.

c) Co-recovered materials

While the potential significance of co-recovered materials present with captured CO₂ is acknowledged by GESAMP (1997), it appears that no information is available concerning the sig-

nificance of this. Impact studies need to take account of the fact that nitrogen oxides, sulphur dioxides, metals and possibly a variety of organic chemicals could be present in the CO₂.

Speciation of other compounds

The speciation and, therefore, biological availability/ activity of various metals and ammonia may be affected by reduced pH. The significance of this in deep marine waters impacted by CO₂ storage is unknown.

d) 'Smothering' effects

As noted above, introduction of liquid CO₂ into the deep ocean to form 'lake' on the seafloor could cover substantial areas of sea floor. It is reasonable to assume that living systems at the seafloor at such points would be obliterated.

iv) Research needs

Research needs attach to many aspects of the likely impacts of carbon dioxide storage in the deep oceans. Requirements appear to be largely to address generic concerns, but site specific considerations will also apply as potential storage sites are identified. Significant uncertainties, knowledge gaps and indeterminacies include:

- Structure and function of deep sea ecosystems
- Effects of reduced pH on deep ocean organisms at all levels of biological organization
- Potential impacts upon biodiversity hotspots (seamounts, hydrothermal vents, seeps etc.)
- Temporal and spatial extent of changed pH regimes and of associated biological impacts
- Identification of relevant and applicable biomarkers of effect of changed pH
- Possible interactions of CO₂ storage with other biogeochemical cycles and onward effects
- Ecological impacts of carbonate dissolution on fauna with calcareous structures
- Ecological impacts of carbonate dissolution on microflora of calcareous sediments
- Extent of ' smothering 'impacts at scale of likely storage operations
- Additive/synergistic impacts of materials co-recovered with captured CO₂ upon biological systems
- Development and validation of models used
- Site specific considerations

2. Storage of CO₂ in geological formations

i) Geological Options

A number of schemata have been proposed involving the use of various kinds of geological formations. These have been summarized by the UK's Department of Trade and Industry (DTI 2000). The use of depleted oil and gas formations to store CO₂ extends from the concept of reservoir flooding for EOR or the re-injection of CO₂ separated from natural gas. The arguments supporting this concept are based around the containment historically afforded by such formations over geological timeframes. Similarly, deep saline aquifers have been identified as natural formations where injection of CO₂ followed by its reaction with minerals to form carbonates would essentially lock up the gas permanently. A similar rationale attaches to the recovery of methane from deep unmineable coals beds where CO₂ would be used to displace the methane and in doing so become 'locked up' in the coal.

Figure 5 schematically represents a system involving the injection of carbon dioxide into a sub-seabed geological formation. Such an operation is currently taking place in the North Sea Sleipner field and was initiated in late 1996 by Statoil the Norwegian State Oil Company. Around 1 million tonnes of carbon dioxide are being pumped annually into a porous salt water aquifer some 32,000 km² in extent (IEA, 1998b). This Utsira sandstone formation lies around 1 km below the sea floor above the gas producing Heimdal formation and below an impermeable shale. Seismic monitoring activities have been employed to allow the movement of the gas through the aquifer to be followed. The carbon dioxide in this case is derived from the gas field where the natural gas brought to the surface contains around 9% CO₂. This is reduced to about 2.5% by treatment and the stripped CO₂ is injected into the sandstone formation. This is the first time that injection of carbon dioxide has been practised on such a large scale and the first time that carbon dioxide has been compressed and injected from an offshore platform (Bakliid *et al.*, 1996). It is planned to initiate a second project bases on similar technology at an Arctic: the Snohvit field (Statoil 2003).

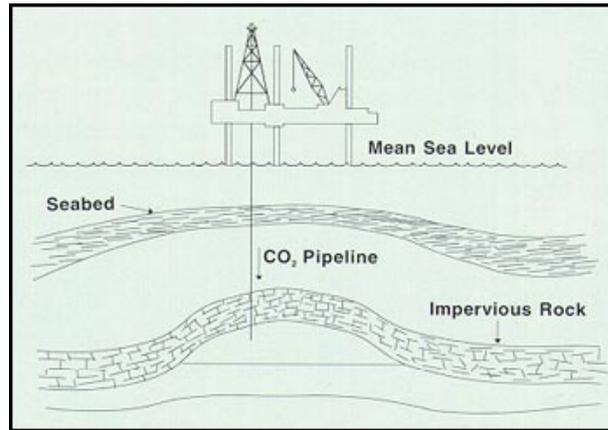


Figure 5: Schematic representation of injection of carbon dioxide into a subseabed formation. This is currently underway in Norwegian waters in the Sleipner field From IEA (1998a)

A similar project is under consideration by a consortium involving Exxon and the Indonesian State Oil Company in the Natuna offshore gas field in the South China Sea. This field is one of the largest in the world and, if the project goes ahead, up to 100 million tonnes of CO₂ would be injected annually into a sub-sea bed aquifer (Hanisch, 1998). In this case also, the CO₂ is removed from the natural gas recovered in which it is present at concentrations of around 70% by volume (Herzog *et al.*, 1997).

Despite concerns about the legality of the current Norwegian marine operations under international law (see: Johnston *et al* 1999) the use of saline aquifers for carbon dioxide storage is conceptually and practically well advanced. It is intended that the CO₂ be isolated permanently from the carbon cycle. While saline aquifers comprise the greatest potential geological CO₂ storage option with a capacity of between 100-10,000Gt CO₂, depleted oil and gas reservoirs also represent a significant potential storage volume. The use of carbon dioxide for enhanced oil recovery purposes is a standard oil industry procedure. In general it appears that schemata for the geological storage of carbon dioxide are at a far more advanced stage than those proposed for storage of carbon dioxide by injection into deep ocean waters. It seems that geological storage options are underpinned by a far more extensive information and database than exists for unconstrained ocean options and this has been consolidated by research projects specifically aimed at identifying and characterising potential geological resources of this kind. (see *e.g.* Holloway 1996).

The research required in relation to the use of geological formations identified as targets for this purpose is likely to be formation specific but, given the extent of some targeted formations, evaluation could require a regional or even continental overview of a variety of aspects. Similar considerations apply to deep coal beds. The historical containment of oil and gas reserves is no guarantee of containment in the long-term since the integrity of such formations is generally compromise by large numbers of wells drilled into them, and by structural changes resultant from extraction of the hydrocarbon resources. All these considerations imply that such schemata will carry a long-term, trans-generational commitment to monitoring activities.

ii) Potential for leakage

The potential impacts associated with carbon dioxide in geological formations are largely associated with the possibility of leakage. It is possible that large scale release of gaseous carbon dioxide from formations used for CO₂ storage could take place with associated mortality of humans and their livestock (see: information on Lake Nyos above). The potential for such leakage will depend upon caprock integrity and the security of well capping methods in the longer term together with the degree to which the CO₂ is eventually 'trapped' through solubility in *e.g.* residual oil, formation waters or by reaction with formation minerals to form carbonates. As noted by Bruant *et al.* (2002) even in formations with adequate nominal capacity some of the injected CO₂ is expected to leak as a result of the buoyancy of the separate phase carbon dioxide, the induced pressure gradients from the injection and the variable nature of strata acting as barriers to upward migration. In addition it is possible that the reaction of CO₂ with reservoir minerals

could affect permeability and porosity. Accordingly, CO₂ leaking from storage formations could intercept aquifers, surface waters and the land surface.

iii) Potential impacts

Leaks from natural CO₂ reservoirs and their impacts have been documented. Bruant *et al.* describe the surface impacts of leakage of magmatic CO₂ at Mammoth Mountain in the U.S. In addition to early stage human asphyxia, large areas of trees have died off as a result of high soil CO₂ concentrations. No additional lethal agents have been detected in this natural analogue. In the case of anthropogenically stored CO₂ the possibility of co-stored materials such as nitrogen and sulphur oxides leaking also needs to be taken into account.

One aspect of potential environmental impact that has received little attention is that likely upon sub-soil ecosystems. Although surficial terrestrial systems have been extensively researched in terms of their microbial ecology and the way in which this relates to other soil organisms, far less work has been carried out to investigate deep, sub-soil microbial communities and the wider ecological interactions which they may have. Given the possible biomass of these communities (based simply upon the sheer volume of habitat which they have available to occupy), this seems a substantial indeterminacy. Recent work (Cowen *et al.* 2003) has shown that a diverse (though relatively low biomass) microflora exists in the ocean basin crust consisting of organisms related to known nitrate and sulphate reducers together with heterotrophic organisms. Other work suggests that deep subsurface microbial systems are defined by heterogeneous physico-chemical conditions in subsurface environments (see: Brockman and Murray 1997) and that microbial life is widespread within the whole depth of the earth's crust including extreme temperature systems (see: Vorobyova *et al.* 1997). The overall functions of these deep microbial communities are unknown and the subject of considerable debate (Kerr 2002). Impacts upon these ecosystems due to CO₂ storage could be substantial but the consequences largely unknown.

iv) Research Needs

Research needs related to terrestrial geological formations are largely site specific in nature although designed to address concerns which are generic in nature. Broadly, these research needs attach to the issue of long-term containment and the consequences of containment failure. These include:

- Identification and characterization of natural analogues
- Site specific assessments of storage formation integrity
- Assessment of potential leakage pathways through fractures/porous media
- Potential impact on water resources, surface ecosystems
- Potential for solubility/mineral trapping and impacts on formation porosity
- Potential for catastrophic release
- Monitoring and remediation methods
- Development of geophysical monitoring techniques
- Characterisation of soil micro-organisms and potential ecological impacts
- Evaluation of impacts due to co-recovered acids gases and other contaminants

Conclusion

The portfolio of research needs associated with all forms of carbon storage is extensive. The potential impacts of carbon dioxide storage differ both qualitatively and quantitatively depending upon whether the storage is unconfined in deep ocean systems or in the constrained environment of sub-seabed or terrestrial geological formations. In addition, the impacts of ocean storage are likely to depend on whether the CO₂ is injected into intermediate depth waters, or introduced to form a lake bounded by clathrate. In the case of geological formations, the storage of CO₂ will differ according to the relative importance of solubility and mineral trapping as opposed to simple containment of unchanged liquid CO₂.

The differing research agendas implied by the different storage schemata reflect different states of knowledge. Fundamental questions as to the character of deep ocean systems and likely impacts of CO₂ storage on them need to be resolved, whereas the research needs attached to geological options tend to be more targeted at site specific issues.

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