Shellfish Sequestration: The Augmented Cultivation of Molluscs, and the Preservation of their Shells, as a Means of Sequestering Carbon Dioxide[1]

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Abstract

This article describes the concept of shellfish sequestration and how it may remove substantial quantities of carbon dioxide from the atmosphere. In this proposal, the cultivation of mussels and other bivalve molluscs would be expanded around the world and the shells of those molluscs would be disposed of in a manner that would ensure long-term sequestration of the CO_2 *that is embodied in them. Given that there is rapid equilibration of* CO_2 *concentrations between the atmosphere and surface layers of the sea, shellfish sequestration should have the effect of reducing concentrations of* CO_2 *in the atmosphere. Calculations suggest that it may be possible, within one human lifetime, to take as much of* CO_2 *out of circulation as has been released into the atmosphere since the beginning of the industrial revolution by the burning of fossil fuels and the production of cement. Costs would be substantial but affordable. There would be several spin-off benefits including a reduction in the acidification of the oceans or its rate of increase, employment for large numbers of people, the production of large amounts of protein-rich food, the creation of incentives to avoid*

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[1] It appears that the main proposition in this article—that the augmented cultivation of bivalve molluscs and the proper disposal of their shells would provide a means of removing large amounts of CO_2 from the atmosphere—is not valid! When $CaCO_3$ is removed from seawater, its pH shifts toward the acidic, and the CO_2 concentration and pCO_2 of the water increases, leading to increased concentrations of CO_2 in the atmosphere. A diagram showing the effects of various ocean biogeochemistry processes on CO_2 and pH can be found in Figure 1.1.3 of *CO_2 in Seawater: Equilibrium, Kinetics, Isotopes*, Richard E. Zeebe and Dieter Wolf-Gladrow, Amsterdam: Elsevier, 2001. We did have some doubts that the mechanism would work as we anticipated, and we did seek advice from someone with specialist knowledge of marine chemistry. But it turned out that the advice we were given was wrong!

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pollution of coastal seas, and the creation of marine reserves where large-scale fishing would be proscribed.

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1 Introduction

This article, based on a submission by the first author to the Virgin Earth Challenge,[4] describes how *shellfish sequestration*, to be explained, may help to remove “anthropogenic, atmospheric greenhouse gases so as to contribute materially to the stability of Earth‘s climate.”[5] The scheme aims to reduce levels of CO_2 in the atmosphere. It does not address the problem of bringing down the concentrations of other greenhouse gases.

This proposal is an extension or development of well-known schemes that aim to sequester atmospheric CO_2 via the stimulated growth of biological agents, but it promises to circumvent the main worries associated with some current proposals of that type. Of course, there are uncertainties and possible snags with what we are proposing—and these will be discussed. But we believe that none of these possible problems are showstoppers that would rule out further investigation and development.

Calculations shown later in this document suggest that, by means of shellfish sequestration, it may be possible, within one human lifetime, to take as much CO_2 out of circulation as has been released into the atmosphere since the beginning of the industrial revolution by the burning of fossil fuels and the production of cement. Even at less ambitious levels, it could make a useful contribution to the stabilisation of the world’s climate.

In what follows, we shall first outline existing proposals to sequester carbon via the stimulated growth of algal blooms, and we will summarise their apparent drawbacks. In Section 3, we shall describe the concept of shellfish sequestration, and then in sections that follow we shall describe how the proposed scheme may avoid the main problems associated with ‘algal bloom’ schemes, we shall examine some potential problems, and we shall assess the potential of shellfish sequestration to bring down concentrations of CO_2 in the atmosphere.

2 Sequestration of carbon via the stimulated growth of algal blooms

It is now widely recognised that, in about one third of the world’s oceans, a shortage of iron in the water imposes a limit on the growth of planktonic microalgae. In several experiments, it has been shown that, in those areas of ocean, the addition of iron to the water, in a suitable form, can trigger the growth of algal blooms (See, for example, Watson *et al*., 2008; Boyd *et al*., 2007; Bakker *et al*., 2006; Coale *et al*., 1996).

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[4] The proposal was submitted to the Virgin Earth Challenge in February 2008.

[5] Virgin Earth Challenge: the Competition, 2007-12-22, www.virgin.com/subsites/virginearth/.

These observations have led to the idea that, since many algae (e.g., coccolithophores) incorporate carbon in their skeletal structures as they grow, and since some of that carbon will be more-or-less permanently trapped in ocean sediments when algae die and sink to the ocean floor, the artificial stimulation of algal blooms could be a useful way to remove excess carbon from the oceans and thus indirectly reduce levels of CO_2 in the atmosphere (see, for example, Schrope, 2007).[6]

A variation on this idea is that, since algae are the key base element of marine food chains, the artificial stimulation of algal blooms could produce a bonanza for the fishing industry and, at the same time, it could help to sequester carbon—since a proportion of the algae in each bloom would not be eaten but would die and fall to the ocean floor and be incorporated in ocean sediments, as before (Kraufvelin *et al*., 2006; Bokn *et al*., 2003).

A possible bonus from schemes of this sort is that plankton produces dimethyl sulphide (DMS) and that is thought to help cool the world by increasing the numbers of cloud condensation nuclei in the atmosphere (Watson, 1998).

2.1 Possible problems

This subsection briefly reviews some of the concerns that have been expressed about proposals to sequester atmospheric CO_2 by stimulating the growth of algal blooms.

2.1.1 Sequestration of carbon

One of the problems with artificially-stimulated blooms of algae as a means of sequestering carbon is that it is actually rather difficult to establish exactly how much sequestration has been achieved (Boyd *et al*., 2000, 2007). Available evidence suggests that the amount of sequestration may be rather small and unlikely to have much impact on global carbon budgets (Buesseler *et al*., 2004).

One apparent snag is that iron-fertilised water may spread into areas where iron is plentiful and where shortages of other nutrients (such as nitrates) are limiting factors. In that case, any initial bloom of algae will be short-lived and will not succeed in locking away much carbon. In a similar way, an iron-stimulated bloom may have the effect of mopping up other nutrients which are critical for algal growth, so that the initial bloom is snuffed out fairly quickly.

Another apparent problem is that many algae will be eaten and the carbon that they contain will pass up a food chain and eventually be released back into the ocean and the atmosphere when creatures in that food chain die and decay. Algae that do die and sink towards the ocean floor may decay and release their carbon at any stage before they are covered by sediments.

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[6] When planktonic micro-algae die and sink from the surface layers of the sea into deeper waters, the carbon in their bodies may remain in those deeper layers in organic or inorganic form for decades or even hundreds of years (Falkowski, 2000; Marinov and Sarmiento, 2004). Although this may be regarded as a kind of partial carbon sequestration, it is probably best to reserve that term for ways of locking up carbon that are more secure and more long lasting.

2.1.2 Possible release of CO_2

More worryingly, it has been suggested that algal blooms may not only be ineffective in removing CO_2 from the atmosphere, they may actually release CO_2 into the environment:

> *... the immediate effect of calcification is a relative increase of* pCO_2*, in part controlled by the buffering capacity of seawater in surface waters due to the assimilation of bicarbonate according to the equation:*
>
> $$2HCO_{3-} + Ca^{2+} = CaCO_2 + CO_2 + H_2O$$
>
> *and a parallel drop in alkalinity which, in turn, shifts the dissolved inorganic carbon (DIC) equilibrium in the direction of CO2 ...* (Fernandez *et al*., 1993, p. 272).

Although similar effects have been observed by Robertson *et al*. (1994), they suggest that “... coccolithophore blooms still represent a net sink for carbon into the sediments with respect to the atmosphere.” (p. 298).

More recent experiments, that took samples through the full life cycle of the *Emiliania huxleyi* coccolithophore organism, found a distinctly decreasing trend in the observed levels of dissolved CO_2, suggesting that the overall effect of the blooms was to create a sink for atmospheric CO_2 (Delille, 2005). But these experiments lasted only 4 weeks and the conclusions drawn cannot be readily extrapolated to field conditions where recurrent and successive blooms of coccolithophores occur.

2.1.3 Eutrophication and the release of methane

Another possible problem with schemes to fertilise the oceans is that they may produce ‘eutrophication’: excessive growth of algae and other plants, shortages of oxygen when those plants die and decay, and the consequent death of fish and other creatures (Anderson *et al*., 2002). Bacteria that are active in this anaerobic brew may release methane into the atmosphere, a gas that is about 23 times more potent in its greenhouse effect than CO_2.

3 Shellfish sequestration

The scheme proposed here is broadly similar to algal bloom schemes in that it relies on the growth of living organisms to remove CO_2 from the atmosphere, and it proposes ways of increasing the growth of those organisms beyond their current levels. But it appears to provide a much more robust means of ensuring long-term sequestration of CO_2 and to offer much more certainty than algal bloom schemes about how much CO_2 would be sequestered, and it has some other advantages too.

In this section, we shall first describe shellfish sequestration in outline and then we will describe aspects of the proposal in more detail. In sections that follow, we will discuss possible snags with the proposal and we will try to assess the potential of the scheme to sequester CO_2.

3.1 Outline

The central idea in shellfish sequestration is easily stated:

A *Since the shells of marine molluscs contain calcium carbonate that is derived, directly or indirectly, from CO_2 in the sea, the proper disposal of the shells of those molluscs may take that CO_2 out of circulation for long periods of time.*

B *Reducing the concentration of CO_2 in the surface layers of the sea will help to reduce the concentration of CO_2 in the atmosphere.*

As can be seen from these brief statements of principle, the main focus in this proposal will be on molluscs rather than shellfish in general (a category that includes lobsters, crabs and other crustaceans).[7] As we shall see, the main focus of this proposal will actually be on filter-feeding marine bivalve molluscs such as mussels, scallops, oysters and clams.

It seems likely that molluscs that are growing now in the world's seas are part of the so-called 'biological pump' that removes CO_2 from circulation. Those that die in the sea will leave their shells at the bottom where, normally, they will become covered with silt, more shells and other debris so that the CO_2 that they contain will be locked up in more-or-less permanent form, in much the same way that CO_2 has been sequestered in the past by the build-up of calcareous sediments on the ocean floor that later became chalk and limestone.

Many of the shells of molluscs that are harvested for human consumption (either wild or farmed) are likely to find their way into landfill dumps where the CO_2 that they contain may remain for long periods of time. Although these kinds of processes are probably having the effect of sequestering CO_2 without the need for any new initiative, it seems likely that, even if all anthropogenic emissions of CO_2 were to cease tomorrow, the rate at which CO_2 is being sequestered now via the shells of marine molluscs is too slow to have much impact, within reasonable timescales, on CO_2 levels in the atmosphere.

This brings us to a third statement of principle:

C *If the proper disposal of shells of marine molluscs is to have a significant impact on concentrations of CO_2 within a reasonable time, it will be necessary to increase the quantities of those molluscs by farming them on a much larger scale.*

If we can expand the cultivation of marine molluscs around the world and ensure that their shells are disposed of in an appropriate manner, we should be able to remove useful amounts of CO_2 from the seas and the air. That is the essence of this proposal.

To our knowledge, there has been only one other proposal of this kind, that by Hickey (2008). There is no mention of anything similar in recent reviews of geoengineering proposals for removing CO_2 from the atmosphere (The Royal

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[7] The alliterative ring of "shellfish sequestration" made it a more appealing name than "mollusc sequestration" or something like that.

Society, 2009; Matthews, 2010). We believe that the present proposal advances the concept beyond Hickey's pioneering proposal.

Aspects of this idea will be developed in subsections that follow.

3.2 Factors that influence the growth of marine bivalve molluscs

As described in Spencer (2002), the main factors that influence the culture and growth of marine bivalve molluscs are these:

- The availability of suitable *substrates* for the attachment or support of bivalves:
    - Mussels generally need somewhere that provides good support, where they will not sink in or become covered with silt. By means of their byssus threads, they can attach themselves securely to rocks, or artificial structures such as wrecks, piers, or sub-surface ropes (as we shall see). However, by attachment to one another, they form clumps that can exploit less stable muddy substrates.
    - Although some scallop species can form byssal attachments as adults, most commercial scallops are free-living on the sea bed. Existing scallop culture mainly employs net bags or 'ear-hanging' on sub-surface long-lines.
    - Oysters have requirements that are similar to mussels but they cement themselves to the substrate instead of using byssus threads. Traditional oyster culture in Europe, for example, deployed millions of limed roof tiles as substrate for settling oyster larvae. Nowadays, most oysters are grown in bags on inter-tidal trestles.
    - Clams generally live just below the sea bed burrowed into soft sediments using their siphons to gain nutrition.
- *Sea temperature*. Within limits, marine bivalves grow faster when the sea is warmer, and they can be killed by freezing.
- *Movement of water*. Although currents are critical for the supply of food-rich water to cultivation areas, extreme wave action or very strong currents can strip newly settled bivalves from their support and may also damage the structures to which they are attached.
- *Exposure to air, siltation, salinity, oxygen and pollution*. Bivalves that are out of the water at low tide cannot feed at those times and they grow more slowly than those that remain constantly submerged. High siltation events can smother young bivalves and even when they are older they cannot cope with high silt loading. Apart from oysters, bivalves generally prefer the relatively high salinity of open coastal areas. Oxygen supplies are normally sufficient but can occasionally drop to levels that are harmful. Of course, pollutants of various kinds can cause a lot of damage.
- *Biological factors*. Successful cultivation of marine bivalves depends on several biological factors including the availability of good supplies of young molluscs ('seed'), adequate food supplies (algae and other microscopic marine

> organisms), toxic algal blooms, predators such as crabs and starfish, diseases, competitors, and the effects of fouling by seaweed and other organisms that can reduce flows of water around growing molluscs.

Of these several factors, the one that appears to be most significant in limiting the worldwide growth of bivalve molluscs is the availability of suitable substrates. In nature, mussels, oysters, scallops and clams must rest on something or be attached to something and this normally means the bed of the sea, including shoreline rocks that are covered by the sea when the tide rises.

Although there are abyssal species of bivalve molluscs (such as the long-neck clams (*Cuspidaria*) that burrow in the mud and suck in small crustaceans through their siphons), most bivalve molluscs are filter feeders that need to be close enough to the surface to take advantage of algae and other microscopic organisms that depend directly or indirectly on photosynthesis, powered by the light of the sun.

In general, filter-feeding bivalves must live on the sea bed where it is shallow enough to be lit by the sun, where it is not too soft, not too silty, not overrun with crabs, starfish or competing species, not too turbulent, not too hot or cold, and not polluted by sewage or industrial waste. Collectively, these things impose a limit on the growth of filter-feeding bivalves but the key appears to be the amount of sea bed available that is congenial to these organisms.

As we saw in Section 2, shortages of iron in sea water can limit the growth of algae in some parts of the world's oceans and the addition of iron to the water in those regions can remove that limiting factor and cause a dramatic increase in the growth of algae. The basis of the present proposal is that, in a similar way, the growth of marine bivalve molluscs around the world is limited by the availability of suitable sites for them to grow and that, if more suitable sites are provided, there can be a corresponding expansion in the abundance of those molluscs.

In the next section, we shall see how that may be achieved.

3.3 How bivalve molluscs may be farmed on a large scale

Today, bivalve molluscs are farmed in a variety of ways, as described in Spencer (2002). Sometimes, molluscs are grown on the sea bed as they would do naturally but with care taken to give them what they need and protect them from predation and other harmful influences. More commonly, molluscs are grown on structures above the sea bed: frameworks that are mounted on the sea bed, floating rafts, or 'longline' structures that are made of natural or synthetic ropes. Because scallops are motile, their controlled culture requires them to be contained in wooden or metal cages or bags made of netting. Oysters can be encouraged to cement themselves to suitable structures and mussels can fix themselves securely on the substrate by means of their byssus threads. Clams can be grown in trays suspended in the water but they do best on the sea bed where it is relatively soft.

If bivalve molluscs are to be farmed on a much larger scale, methods of cultivation will need to be developed that allow shellfish farms to be extended into areas of the sea that are less sheltered and further from the shore than existing cultivation sites. No doubt there is a variety of methods that would allow shellfish farms to be expanded in this way. One possible candidate is suggested here.

The method of cultivation that we are proposing is a version of the ‘subsurface longline’ method described in Spencer (2002, Chapter 7), first developed on a large scale for scallop culture in Japan and which has been adopted and modified worldwide in the latter years of the 20th century. It is best suited for the cultivation of mussels but can be readily adapted for the growth of scallops or oysters.

The main elements of the proposed method are shown in Figure 1. As can be seen in the plan view, the main framework for each module is a horizontal square or rectangular grid of ropes supported by buoys. In the diagram, the buoys are shown at the corners but others could of course be added wherever they are needed. The ropes may be made of a natural fibre such as hemp or a synthetic fibre such as polypropylene.

The elevation view shows that the horizontal grid of ropes would be anchored to the bed of the sea so that it would be held in the sea at a level below the wave zone when the tide is at its lowest. This is to protect the structure from possible damage by waves.

Suspended from the main grid are large numbers of weighted thinner lines. These provide the substrate for the growth of mussels, fixed directly to the lines. Natural mussel settlement can be encouraged on the lines by deploying them at appropriate times in suitable sites. Alternatively, mechanical ‘socking’ methods are already well developed in the industry whereby juvenile or seed mussels (dredged from the wild) are placed in a long ‘sock’ around a central line. The mussels attach byssally to the line and the sock soon decays. Scallops can be grown in ‘pocket’ nets or other type of holding structures fixed to the lines, as described in Spencer (2002, p. 91). Oysters are not normally grown commercially on long line systems, but on shore-based trestle systems. Nevertheless, in addition to the potential for expansion of shore-based oyster culture, long line systems can be modified to accommodate oyster culture.

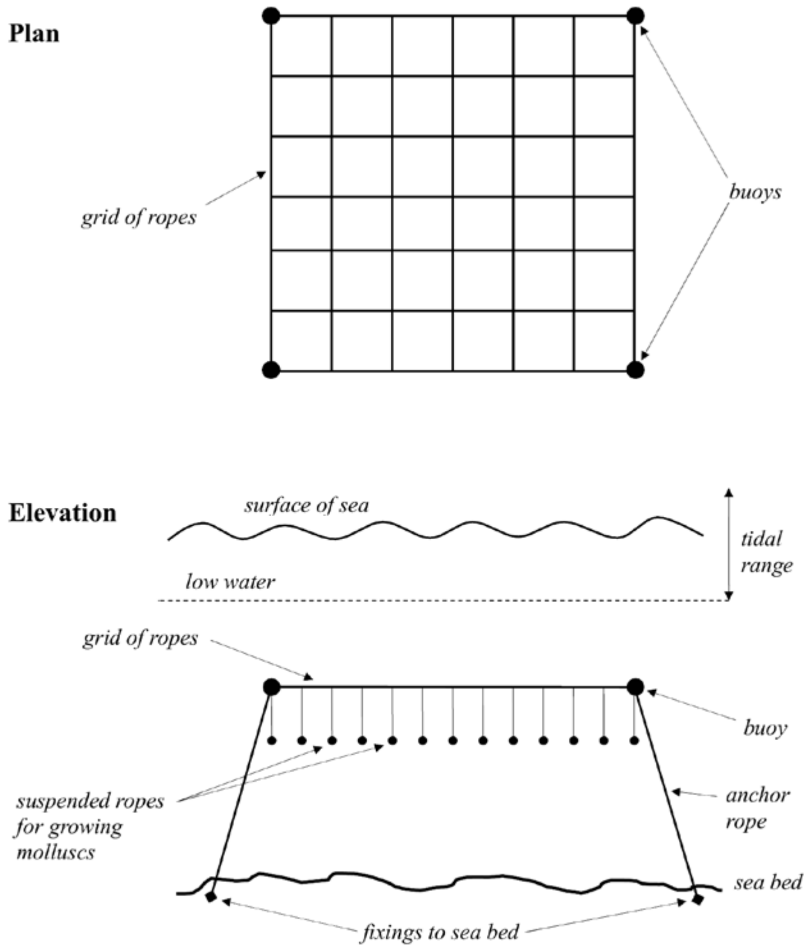

Figure 1: Plan and elevation views of a long line structure to support the growth of bivalve molluscs. No dimensions have been given because the structure can be scaled to whatever size is best for local conditions. Of course, the structure could be rectangular instead of square and it can be multiplied as many times as desired.

3.3.1 Collection or cultivation of spat

An important part of the cultivation of marine bivalves is ensuring a good supply of young molluscs, known as ‘spat’. Mussel spat are very rarely produced in dedicated hatcheries because this is normally considered to be rather expensive for a low value species like the mussel. More often, mussel spat are collected from natural ‘spatfall’ in the open sea using ‘spat collectors’ such as poles or ropes, or simply dredged up in huge quantities from settlement regions that do not support adult beds. After the spat have grown to about 10 mm in diameter they can be transferred to other substrates (long lines etc) at a suitable spacing to allow them to grow to full size.

Traditionally, spat of the European oyster (*Ostrea edulis*) were collected on the low shore on a suitable substrate such as limed roof tiles or mussel shells. However, this species has been ravaged by disease (*Bonamiosis*) and is no longer produced in significant quantities. Nowadays most commercial oysters (*Crassostrea gigas*, the Pacific oyster) originate from hatcheries and hatchery seed is supplied to farmers who on-grow the oysters to commercial size on trestles on the low shore. The Pacific oyster is an invasive species and, because it has become naturalized in many parts of the world, collection of natural spatfall is now feasible.

The spat of scallops are normally collected on monofilament nylon line within ‘onion bags’ which are suspended from subsurface longlines below the wave zone. As with mussels and oysters, scallops are allowed to grow a little and are then transferred to where they will be grown to full size—often net bags suspended on ropes. The kind of structure shown in Figure 1 was developed in Japan to be suitable both for the collection of spat and the on-growing of scallops to harvestable size.

3.3.2 Variations

No doubt, there is plenty of scope for fine-tuning of the scheme that has been described and plenty of scope for variations adapted to local conditions.

No dimensions have been given in Figure 1 because support structures are likely to vary, depending on local conditions. In sheltered waters close to the shore, these structures are likely to be relatively small but further out to sea they can be made larger.

There may be a case for using poles in some parts of the structure instead of ropes to help maintain the desired configuration.

One possible refinement where shellfish are being cultivated at some distance from the shore is to make use of old ships that would otherwise go for scrap. These may be anchored at suitable spots in and around the cultivation area and used in at least two ways:

- They may provide refuge for shellfish farmers if they get caught out in bad weather or they may provide facilities for rest, recreation and electronic communication that may not be available on smaller boats.
- They may be used as fixing points for the horizontal grids of ropes, thus reducing the need for vertical anchor ropes.

Another possibility is to use the under-water parts of offshore wind turbines as anchor points for subsurface longlines. There could be a useful synergy between offshore wind farms and shellfish farms.

Yet another possibility is to establish shellfish farms in areas between offshore wave farms[8] and the shore so that the wave farms, by extracting energy from waves, would provide some protection from turbulence in the open sea.

To reduce the amount of labour needed to run shellfish farms, it will be necessary to invest in further development of existing techniques for automation of all aspects of long-line culture.

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[8] See, for example, the Pelamis Wave Energy Converter, www.pelamiswave.com/.

3.3.3 Advantages and shortcomings

Given the overall aim of increasing the scale of shellfish farming around the world, the kind of structure that we have proposed appears to have some advantages compared with other systems of cultivation:

- A structure of ropes, as shown in Figure 1, is likely to be relatively cheap compared with the kinds of trays, cages or rafts that are used in some shellfish farms.
- Because the structures would be below the wave zone:
    - They should be relatively safe from damage by rough seas. This means there would be much less need to restrict shellfish farming to sheltered areas near the coast and there would be much greater scope to expand shellfish farming into the open sea.[9]
    - Boats with a shallow draft would be able to move freely around the area of any shellfish farm without undue disturbance of the farm. This would be a particular convenience for shellfish farmers themselves who would be able to attend to necessary tasks on the farm from any point on the surface.
- Because the molluscs would be growing above the sea bed, they should be relatively safe from attack by bottom-living predators such as crabs or starfish.

Possible problems with the proposed scheme include:

- In very deep water, the long anchor ropes that would be needed might become rather expensive.
- The system would probably not work very well in areas where there were strong currents.

Regarding the first of these possible problems, it might be possible to devise a variant of the system where the rope structures were attached to large buoys[10] instead of the sea bed and those buoys could conceivably be kept in position by the application of small amounts of renewable energy (solar or wind), using positioning information from the Global Positioning System.

3.4 Collection and disposal of shells

For the purpose of CO_2 sequestration, it will be necessary for the shells of cultivated molluscs to be collected up for disposal. One possibility is for the edible contents of shellfish, either cooked or raw, to be removed soon after harvesting so that the shells can be sent directly to where they will be disposed of. If fresh molluscs, including their shells, are sold on the open market, then a system will be needed to collect up the shells—something like bottle banks for empty bottles or collection points for old clothing or paper.

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[9] The avoidance of wave damage appears to have been the main reason that subsurface longline methods were developed originally, and in that respect they appear to be successful off the coasts of Asia and elsewhere in the world.

[10] Or even superannuated ships, as mentioned earlier.

For the purpose of CO_2 sequestration, we believe that the best place to dispose of the shells of molluscs would be on land or in very shallow water, perhaps in projects to reclaim land from the sea. Bearing in mind that rising temperatures are causing sea levels to rise, there may be a ready market for the shells as materials to build new dikes or enlarge existing dikes in places like the Netherlands or Bangladesh.

In any such project, at least two precautions would probably be necessary:

- Banks of shells would need to be protected from wave action using tougher materials such as granite.
- There may also be a need to protect the shells from solution by carbonic acid in rainwater, perhaps by capping each deposit with a layer of clay.

With precautions like these, we believe that banks of shells could provide an effective means of sequestering CO_2 for long periods of time.

3.5 CO_2 in the atmosphere and in the sea

When marine molluscs lay down calcium carbonate in their shells, the carbon and oxygen atoms come from the sea where they exist in solution as CO_2 (some of which combines with water to form carbonic acid, H_2CO_3 (Murray, 2004, p. 3)), bicarbonate ions (HCO_3) or carbonate ions (CO_3). But of course, the aim of shellfish sequestration is to remove CO_2 from the atmosphere (where it has a greenhouse effect) and not from the sea, except insofar as this helps to remove CO_2 from the atmosphere.

The assumption behind shellfish sequestration and schemes for stimulating the growth of marine algae is that if CO_2 (or HCO_3 or CO_3) can be removed from the sea, this will increase the capacity of the sea to absorb CO_2 from the atmosphere and will thus help to bring down atmospheric concentrations of CO_2.[11]

In broad-brush terms, this is clearly true but the details are complex and still not fully understood (see Falkowski, 2000; Marinov and Sarmiento, 2004). That said, “Atmospheric CO_2 continuously exchanges with oceanic CO_2 at the surface. This exchange, which amounts to 90 gigatons (Gt) of carbon per year in each direction, leads to rapid equilibration of the atmosphere with the surface water.” (Falkowski, 2000, p. 292). So removing dissolved CO_2 (or HCO_3 or CO_3) from the surface layers of the sea—as shellfish sequestration would do—should have a fairly direct and rapid effect on concentrations of CO_2 in the atmosphere.

Since there are relatively enormous amounts of dissolved inorganic carbon in the deeper parts of the sea (Marinov and Sarmiento, 2004), there is a risk that this might find its way into the surface layers and nullify the effects of shellfish sequestration. Fortunately, it appears that, for now, there is a net flow of dissolved inorganic carbon from the surface layers into the depths of the sea (Falkowski, 2000; Marinov and Sarmiento, 2004).

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[11] As is noted in Section 5.4, there is an equilibrium between CO_2, HCO_3 and CO_3 in the sea so that the removal of any one of them will tend to reduce the concentrations of the others (Murray, 2004).

3.6 Incentives

In order to expand shellfish farming around the world, it will be necessary to provide incentives. Shellfish farmers may derive some of their income from the sale of shellfish or their soft contents as food for human consumption, or, more importantly, as a replacement for fishmeal. If the world's population is allowed to continue expanding as it is now, there should be a market for that food, although it is possible that people will become tired of eating mussels, oysters or scallops and this may bring down prices. For a large shellfish industry to be viable, it is likely that a system will be needed to pay farmers for their role in sequestering CO_2. The details of how this may be done, and who would pay, would need to be worked out. There is some brief further discussion of costs in Section 6.8.5, below.

4 Overcoming the shortcomings of algal bloom schemes

This section considers how shellfish sequestration may overcome the apparent shortcomings of algal bloom schemes that were described in Section 2.

4.1 Sequestration of carbon

Compared with schemes for the stimulated growth of algal blooms, shellfish sequestration appears to offer a much more robust method of ensuring that CO_2 is removed from circulation for long periods of time and there appears to be much less uncertainty about how much CO_2 is actually locked up.

There is no doubt that, when shellfish grow, they remove the elements of CO_2 from the sea and there is little doubt that, to the extent that that is successful, it will increase the capacity of the sea to absorb CO_2 from the atmosphere.

There appears to be little doubt that if the shells of molluscs are disposed of in an appropriate way, then their embodied CO_2 may be taken out of circulation for long periods of time, in much the same way that CO_2 has been sequestered via the formation of chalk and limestone.

4.2 Possible release of CO_2

As was described in Section 2.1.2, an apparent problem with algal bloom schemes is that when algae take carbon from inorganic forms dissolved in the sea, they appear to take it from bicarbonate in the water and not from dissolved CO_2—and the corresponding chemical reactions has the effect of releasing CO_2 into the water. Since bivalve molluscs may build their shells in a similar way, shellfish sequestration might produce the same effect. For this reason, the issue is discussed as a possible problem for the present proposals, in Section 5.4, below.

4.3 Eutrophication and the release of methane

Unlike algal bloom schemes, there appears to be little risk that shellfish sequestration would lead to eutrophication and the release of methane. This is because shellfish would normally be grown without the need for any artificial fertilisation and, if it proved necessary to use some fertiliser, relatively small amounts would be needed, as described in Section 5.5.

5 Possible problems

This section briefly reviews some things that might cause the shellfish sequestration to fail or to be less successful than we might hope. As mentioned in the introduction, it does appear that none of these possible problems are sufficient to rule out further investigation and development of these proposals.

5.1 Calcium as a limiting factor?

As was mentioned in Section 5.5, it seems likely that any local shortages of nutrients such as iron or nitrates may be overcome by the judicious application of relatively small amounts of fertiliser.

But the process of locking away large amounts of CO_2 in the form of calcium carbonate in the shells of bivalve molluscs would also have the effect of locking up large amounts of calcium. Is it possible that shortages of calcium in the sea might cause the shellfish sequestration project to founder?

Sea water contains about 0.04% calcium by mass (Castro and Huber, 2005), the mass of all the water on the planet is estimated to be 1.4×10^{21} kg and about 97% of this is sea water.[12] From these figures, we can calculate that the total mass of calcium in the world's seas is about 5.432×10^{14} tonnes or 543.2 teratonnes (Tt). This is very much larger than the 1236 Gt of CO_2 that has been released by human activities since the beginning of the industrial revolution (see Section 6.2). So there is no reason to believe that shortages of calcium would be a problem for shellfish sequestration.[13]

5.2 Acidification of the oceans

> *The oceans are absorbing carbon dioxide (CO_2) from the atmosphere and this is causing chemical changes by making them more acidic (that is, decreasing the pH of the oceans). In the past 200 years the oceans have absorbed approximately half of the CO_2 produced by fossil fuel burning and cement production. Calculations based on measurements of the surface oceans and our knowledge of ocean chemistry indicate that this uptake of CO_2 has led to a reduction of the pH of surface seawater of 0.1 units, equivalent to a 30% increase in the concentration of hydrogen ions. ... there is convincing evidence to suggest that acidification will affect the process of calcification, by which animals such as corals and molluscs make shells and plates from calcium carbonate.*
> (The Royal Society, 2005, p. vi)

This and other evidence (e.g., Comeau et al., 2009; Gazeau et al., 2007; Orr, 2005) suggests that the shellfish sequestration project may be stalled by increasing

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[12] Wikipedia, "Ocean", http://en.wikipedia.org/wiki/Ocean#Physical_properties, 2010-03-29.

[13] In calcium carbonate, $CaCO_3$, there is less calcium by weight than CO_2 (see Section 6.3). Hence, the weight of calcium needed for shellfish sequestration is less than the weight of CO_2 that would be sequestered.

acidity of the seas leading to the failure of shell production in bivalve molluscs or a decrease in their rates of growth. However, there are too many uncertainties in this area to be able to say that acidification of the oceans will necessarily cause the shellfish sequestration project to founder. Even if it did, there should be a window of opportunity between now and then when useful amounts of CO_2 could be removed from the seas and the air. We believe the project is worth developing for that reason and because acidification of the oceans may turn out to be less of a problem for the growth of bivalve molluscs than we might now fear.

One possible reason for optimism is that shellfish have a relatively short generation time (from 1 to 5 years) which means they can potentially respond relatively quickly to environmental changes. Although “it is not certain whether marine species, communities and ecosystems will be able to acclimate or evolve in response to changes in ocean chemistry” (The Royal Society, 2005, p. vi), there is a chance that they will:

- When the shells of molluscs are growing, calcium carbonate is laid down within an organic matrix composed of β-chitin, silk-like proteins, and glycoproteins (Kalisman et al., 2001). It is possible that this organic matrix may serve to protect the calcium carbonate from attack by acidic sea water and that any such protective function may be enhanced by natural selection.

- Since fresh-water mussels can survive and thrive in water that has a relatively low pH (about 7) compared with the pH of sea water (about 8), it is clear that there is no fundamental physical barrier to the evolution of marine molluscs that can tolerate levels of pH down to 7, and perhaps even less.

5.3 Impact on the environment

Although shellfish farming is a relatively benign activity, it is clear that it does have an impact on the environment and that would be magnified if the industry were to be scaled up as envisaged in this proposal.

One possible worry is that shellfish do not merely feed, they produce faeces and pseudofaeces[14] as well. It can happen that deposits of faeces and pseudofaeces from shellfish farms are large enough to be harmful to species living on the sea bed below those farms, although it appears that the impact is normally less than with ordinary fish farming (Spencer, 2002, pp. 243–244; Beadman *et al*., 2004). On the positive side, there is the possibility that, if faeces and pseudofaeces from shellfish farms were to become buried in silt on the sea bed, the carbon that they contain may be sequestered for long periods of time, adding to the sequestration potential of shellfish farming. However, in this article we have made no attempt to explore that possibility.

Another concern is the ‘carrying capacity’ of local environments subjected to enhanced utilization of algal foods through high aquaculture activity. If that carrying capacity is exceeded then the whole local ecosystem could be at risk. However, research into local carrying capacity over a commercial mussel bed (Saurel *et al*., 2007) demonstrates that mussels adjust their feeding behaviour to

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[14] Particles that molluscs have rejected as food and have not consumed.

levels of chlorophyll *a* (a proxy for algal food) in the surrounding seawater and will simply grow slower when conditions are not ideal. This would imply that significant mollusc aquaculture activities that approached the local carrying capacity may not have dramatically wider ecological effects. However, supplementary feeding of shellfish (as described in Section 5.6, below) might alter that conclusion.

Environmental impacts would need to be assessed and steps taken to minimise them. If negative impacts remain, one may ask whether they are justified. Pending a full assessment of these things, we are inclined to believe that the potential benefits of shellfish sequestration, especially the potential which it has to stabilise the earth’s climate, are likely to outweigh any local impacts.

5.4 Possible release of CO_2

As was mentioned in Sections 2.1.2 and 4.2, shell-forming organisms may derive the calcium carbonate in their shells from bicarbonate ions in the sea and this will have the effect of releasing CO_2. The reaction goes like this:

$$2HCO_3 + Ca \Leftrightarrow CaCO_3 + CO_2 + H_2O.$$

This process, which is sometimes called the ‘carbonate counter pump’, has been noted by a number of authors (Robertson et al., 1994; Elderfield, 2002; Takahashi, 2004; Cameron, 2005).

Clearly, the CO_2 that is released by this reaction may find its way into the atmosphere and would in any case tend to reduce the capacity of the surface layers of the sea to absorb CO_2 from the atmosphere. Either way, it looks like bad news for shellfish sequestration and suggests that it might fail to achieve the objective of reducing the concentrations of CO_2 in the atmosphere. However, before we rush to that conclusion, we need to look at things in a bit more detail.

Since most of the dissolved inorganic carbon in the oceans is in the form of bicarbonate ions, it does seem likely that shell-forming organisms create calcium bicarbonate in accordance with the equation shown above. However, we have not yet found any direct evidence for this. It is at least theoretically possible that at least some of the calcium carbonate in the shells of marine organisms is derived from dissolved CO_2 or from carbonate ions.[15] To the extent that this is true, it would reduce or eliminate the effect of the carbonate counter pump.

Another consideration, which is probably more important, is the buffering effect of carbonate ions in the sea. Although there is less carbonate in the sea than bicarbonate,[16] it is still very abundant. Any release of CO_2 by the formation of calcareous shells is likely to be modulated by the buffering capacity of the carbonate system (Murray, 2004; Marinov and Sarmiento, 2004; Frankignoulle, 1994). The reaction goes like this:

$$CO_2 + CO_3 + H_2O \Leftrightarrow 2HCO_3.$$

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[15] And it seems likely that this would vary from one organism to another.

[16] In the surface waters of the sea, the proportions of the three species of dissolved inorganic carbon are CO_2: 0.5%, HCO_3: 88.9%, and CO_3: 10.9% (Marinov and Sarmiento, 2004).

In general, the three forms of dissolved inorganic carbon are in dynamic equilibrium and the system is likely to adjust quite quickly to any disturbance of that equilibrium (Murray, 2004).

A third consideration is the effect of removing the elements of CO_2 from the surface layers of the sea in the form of calcium carbonate. While it is clear that, on geological timescales, this can be a major sink for CO_2 (as evidenced by the enormous masses of chalk and limestone around the world), people writing about the carbonate counter pump seem generally to assume that the process is not significant on human timescales. Thus Elderfield (2002) writes that "We imagine that the carbonate accumulations that drape the deep-sea floor or form the White Cliffs of Dover provide a sink for CO_2, which they do—but only on long time scales."

One possible reason for believing that the process is very slow is that the shells of coccolithophores and foraminifera are so small that a large proportion of them dissolve as they sink towards the ocean floor. This means that much of the carbonate in them may be returned to the surface by upwelling and only a little may actually settle and be sequestered in calcareous sediments. With shellfish sequestration, the situation is different:

- The shells which are to serve as a store of CO_2 are very much larger and more robust than the shells of coccolithophores and foraminifera. Provided they are stored as described in Section 3.4, it seems likely that most of the calcium carbonate contained in them would be safely locked away.
- It is envisaged that relatively large amounts of carbon would be removed from the surface layers of the sea on relatively short timescales (see Section 6.6). The process would certainly be significant on human timescales.

Given that the three forms of dissolved inorganic carbon (CO_2, HCO_3 and CO_3) tend always to be in equilibrium, then removing the elements of CO_2 from the surface layers of the sea must necessarily reduce the concentrations of all three forms of dissolved inorganic carbon in those surface layers.[17] This will increase the capacity of the surface layers to absorb CO_2 from the atmosphere.

In summary, the formation of biogenic calcium carbonate may indeed release CO_2 into the surface layers of the sea but it seems likely that most of this would be mopped up quite quickly by the buffering effect of carbonate in the sea. At the same time, the proper disposal of the shells of marine molluscs would have the effect of removing the elements of CO_2 from the surface layers of the sea, with a consequent reduction in the concentrations of all three forms of dissolved inorganic carbon and a corresponding increase in the capacity of the sea to absorb CO_2 from the atmosphere.

As was mentioned in Section 2.1.2, there is experimental evidence (Delille, 2005) suggesting that the growth of shell-forming marine organisms may indeed result in a net reduction in the concentration of CO_2 in the surface layers of the sea,

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[17] Providing there is no net influx of carbon from the air or from deeper parts of the sea.

although it is not clear how much of the carbon is removed in organic form and how much is removed in the form of calcium carbonate.

5.5 Shortages of nutrients

Normally, marine filter-feeding molluscs grow successfully in the sea and obtain sufficient food from algae and other microscopic organisms that occur naturally. However, it is possible that, in some parts of the world's seas, there may be shortages of iron, nitrates or other nutrients that may be sufficiently severe to limit the growth of molluscs. In situations like that, there may be a case for making good shortages of nutrients by adding fertilisers to the sea where shellfish farms are located in order to encourage the growth of sufficient algae to provide food for the growing molluscs.

It is important to emphasise that any such use of fertilisers would be quite different from the use of iron to stimulate the growth of algal blooms. In the latter case, the aim is to create a large growth of algae and there is a risk of causing eutrophication. But in the case of shellfish farming, the aim would be bring the growth of algae up to the rather low levels needed by filter-feeding molluscs and to avoid any kind of excessive bloom that might lead to eutrophication.

5.6 Shortages of algae and other microorganisms

Although we do not have documentary evidence for this [XXX], it appears to be the case that, in the relatively small shellfish farms of today, mussels or other molluscs in the farm get their food partly from algae and other microorganisms growing within the area of the farm and partly from food organisms brought into the farm by currents. It has been suggested to us that, if shellfish farms were to become very much larger, molluscs growing in the central areas of each farm might suffer from shortages of food because molluscs in the outer areas would filter out the food brought in by currents and would also physically block the movement of currents.[18]

Possible solutions to problems of that kind include:

- Limiting the size of each farm and ensuring that there is adequate spacing between farms. This seems to be a practical solution for the time being but might become problematic if shellfish cultivation were to be greatly expanded, as envisaged in Sections 3.3 and 6.5.
- *Artificial feeding*. In areas where there is a shortage of naturally-occurring food organisms, a concentrated 'paste' of live algae may be mixed into the water to boost food supplies. Possible sources for such supplementary supplies of algae include:
    - *Algal farms*. Microalgae may be grown in ponds on land, or in 'photobioreactors' (transparent plastic bags or tubes) on land or floating in the sea. This is already an established practice in the industry [XXX].

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[18] We are grateful to John Holmyard of Offshore Shellfish Ltd (Argyll, UK) for these points.

    - Another possibility is collecting algae from the open sea, something that might be done by cargo ships as they travel around the world.[19] A potential benefit is reducing high concentrations of algae in areas of the sea where food chains have become unbalanced as a result of over-fishing of large predator species.[20]

- It may also be possible to boost the growth of algae in the central areas of shellfish farms by the judicious application of fertilisers, as described in Section 5.5.

5.7 Farming problems

All kinds of farming are subject to problems of various kinds and shellfish farming is no different. Actual or potential problems include:

- Shellfish vary in their feeding requirements and the varied species composition of natural algal blooms means that the total amount of algae in the seawater may not relate directly to shellfish growth (Spencer, 2002, pp 40-41).

- Shellfish can be affected by diseases such as Bonamiasis which has virtually wiped out flat oyster production in Europe (Laing *et al*., 2004).

- Starfish, crabs, birds and other predators may take a toll.

- Where shellfish are being farmed for food, care needs to be taken that they do not become a source of viral or bacterial infection for people and that contamination with heavy metals, industrial chemicals or algal toxins stays well within safe levels (Laing *et al*., 2004).

However, the industry has long experience of dealing with problems of this kind. Solutions can normally be found, depending on local conditions.

6 The potential of shellfish sequestration

Given that the aim of the present proposal is to remove CO_2 from the atmosphere, an obvious question is the rate at which this might be done and how that compares with the amount of CO_2 that needs to be removed or, indeed, the quantity of fossil CO_2 that is currently being dumped into the atmosphere each year. In what follows, we shall consider those last two questions first.

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[19] Naturally, there would be a need to filter out larger organisms and return them to the sea. Then it would be necessary to concentrate the algae using a centrifuge, flocculation, froth flotation, or other established method.

[20] See “Eat more anchovies, herring and sardines to save the ocean's fish stocks” (The Guardian, 2011-02-18, http://www.guardian.co.uk/environment/2011/feb/18/fishing-food).

6.1 The rates at which CO_2 has been and is being added to the atmosphere

One way of assessing the rate at which CO_2 needs to be sequestered in order to have a significant impact is to look at the rates at which anthropogenic CO_2 has been added to the atmosphere in the industrial era up to the present day.

In 1970, annual global CO_2 emissions from fossil fuel burning and cement manufacture were about 4.1 GtC/yr but by 2005 emissions had risen at a more-or-less steady rate to about 7.8 GtC/yr (Forster, 2007, Figure 2.3 (b)). These figures equate to 15.2 $GtCO_2$/yr and 28.9 $GtCO_2$/yr, respectively.[21] As can be seen from the graph shown in Figure 2,[22] annual emissions of fossil carbon in 1900—about the time when annual emissions began to rise steeply—were about 0.5 GtC/yr, which equates to 1.8 $GtCO_2$/yr.

If we make the simplifying assumption that there has been a linear increase in annual CO_2 emissions between 1900 and 2005, the average annual emissions over the period has been about $((28.9 - 1.8)/2) + 1.8 = 15.4$ $GtCO_2$/yr. This is a rough indication of the rate at which CO_2 should be removed from the air and the sea if we are to bring CO_2 levels back towards what they were before the industrial revolution.

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[21] These figures for gigatonnes (metric) of carbon dioxide are derived by multiplying the corresponding figures for GtC by 3.7 (see Appendix to Intergovernmental Panel on Climate Change Fourth Assessment Report, Climate Change 2007: Synthesis Report, www.ipcc.ch/ipccreports/ar4-syr.htm, Section 3.2, Scientific units).

[22] This chart shows global annual fossil carbon dioxide emissions, in million metric tons of carbon. The original data came from Marland et al. (2003). The data were originally presented in terms of solid (e.g. coal), liquid (e.g. petroleum), gas (i.e. natural gas) fuels, and separate terms for cement production and gas flaring (i.e. natural gas lost during oil and gas mining). In the plotted figure, the gas flaring (the smallest of all categories) has been added to the total for natural gas. The original version of this figure was prepared by Robert A. Rohde from publicly available data, and is incorporated into the Global Warming Art project. The figure shown is an updated version produced by Mak Thorpe.

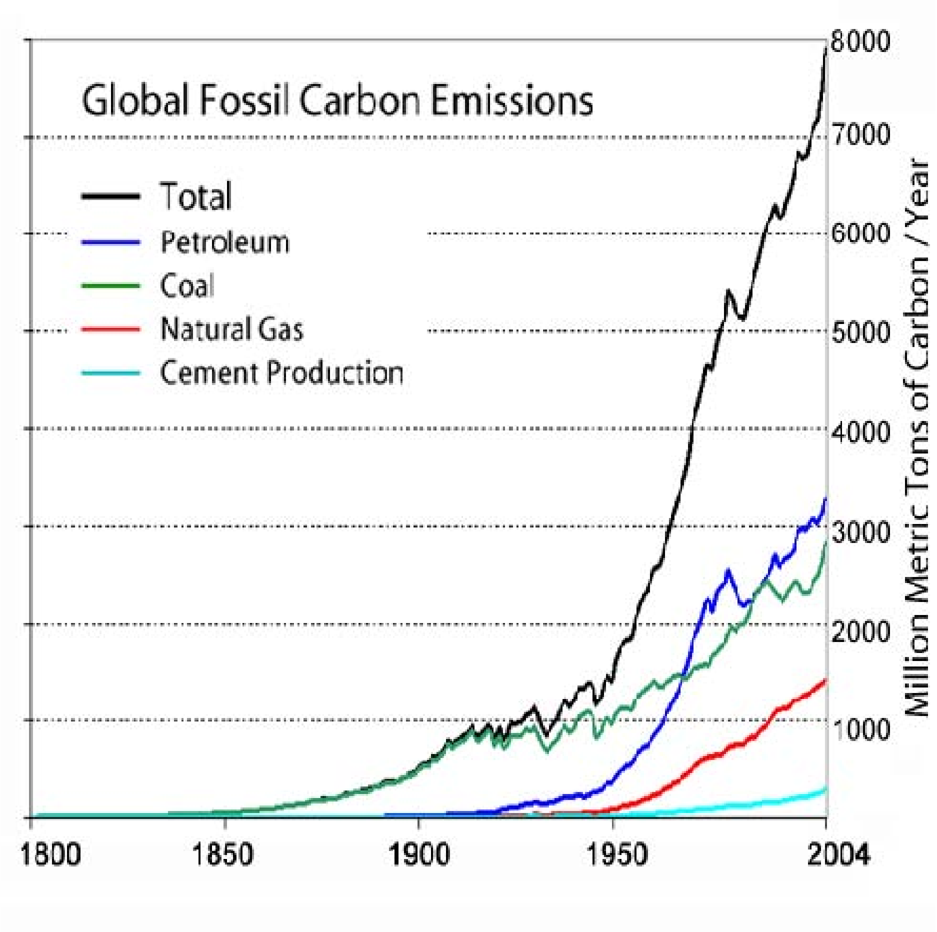

Figure 2: How global emissions of fossil carbon have risen over the years since industrialisation began. Image created by Mak Thorpe (reproduced under the Creative Commons Licence). It is based on an earlier image created by Robert A. Rohde (Global Warming Art).

6.2 Excess CO_2 in the air and the sea

Another indication of how much CO_2 needs to be sequestered is the total quantity of CO_2 that has been released into the atmosphere by human activities since the beginning of the industrial revolution. The worldwide cumulative emissions of fossil carbon between 1751 and 2010, from the burning of fossil fuels and the production of cement, are estimated to be 337 gigatonnes (Boden, *et al.*, 2010). This equates to 1236 $GtCO_2$.

6.3 How much CO_2 could be sequestered in the shells of bivalve molluscs that are being farmed today?

In order to answer the question “How fast could CO_2 be sequestered by shellfish sequestration?” we may start by trying to establish the sequestration potential of shellfish production around the world, as it is practiced now. In principle, the shells of mussels, scallops, oysters etc that are currently harvested all over the world could all be disposed of as described in Section 3.4 and, if the reasoning in that section is correct, this would have the effect of sequestering the carbon that is contained in those shells. Although this could be done with the shells of molluscs that have grown naturally and been gathered or ‘captured,’ we will assume that there is relatively little scope for expanding the quantity of carbon that may be sequestered in this way so we will be ignoring this aspect of shellfish production and we will instead focus on molluscs that are the product of farming or aquaculture, as described in Section 3.

Table 1, which is an extract from figures given in FAO (2008, p. 50), shows the quantities of marine molluscs that were produced by shellfish farms around the world in 2008. More than 90% of this production was from Asia with China making by far the greatest contribution. If we exclude ‘miscellaneous marine molluscs’ and assume that the rising trend of recent years, particularly in China, has continued in the years up to 2011, then it seems reasonable to say that, in round figures, the worldwide production of bivalve marine molluscs is now about 12 million tonnes.

Species group	Tonnes (2008)
Oysters	4,164,000
Clams, cockles, arkshells	4,397,000
Mussels	1,625,000
Scallops, pectens	1,411,000
Miscellaneous marine molluscs	983,000
Total	12,580,000

Table 1: Worldwide aquaculture production of molluscs in 2008 (from FAO, 2008, p. 50).

Of course, that weight of shellfish is not all CO_2. To find out how much CO_2 may be sequestered by the proper disposal of the shells of 12 million tonnes of molluscs, we need take account of the proportion of that weight which is shell and the proportion of the shells that corresponds to CO_2 in a form that can be sequestered for very long periods, as described in Section 3.4. Relevant figures are shown in Table 2.

Component	Proportion	Weight (tonnes)
Molluscs	-	12,000,000
Shells	0.5	6,000,000
Calcium carbonate	0.95	5,700,000
CO_2	0.44	2,508,000

Table 2: A spreadsheet for the calculation of the sequesterable CO_2 in a given weight of bivalve molluscs. Each figure for ‘proportion’ applies to the tonnage in the previous row.

In mussels, the proportion of each animal, by weight, that is shell is about 0.5.[23] If we take this as representative of bivalve molluscs in general and apply this

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[23] The maximum meat yield from mussels is about 50% of the total weight but mussels are marketed down to meat yields of 35 to 40% (Bayne, 1976, p. 407). Since the byssus threads are

proportion to the original tonnage, the corresponding weight of shells is 6,000,000 tonnes.

Of the shells, at least 95% is calcium carbonate, a small amount may be magnesium carbonate, and the rest is proteins or other organic compounds (Wheeler, 1992, p. 195; Poulicek *et al.*,1983). If we focus on the calcium carbonate as being that part of the shells that can be sequestered effectively and if we apply the (rather conservative) proportion just mentioned, then the weight of calcium carbonate in the original tonnage would be about 5,700,000 tonnes.

Given the standard atomic weights of calcium, carbon and oxygen as 40.08, 12.01 and 16, respectively, the molecular weight of $CaCO_3$ is 100.09 and the molecular weight of CO_2 is 44.01. So the CO_2 that is, in effect, contained in each molecule of $CaCO_3$ represents 44.01 / 100.09 = 0.44 of each molecule by weight. If we apply this proportion to the tonnage of calcium carbonate just calculated, we find that the weight of sequesterable CO_2 contained in 12 million tonnes of molluscs is about 2,508,000 tonnes.

If the shells of bivalve molluscs that are currently farmed around the world were all to be collected up and disposed of as described in Section 3.4, then, each year, about 2.5 million tonnes of CO_2 could be removed from the air and the sea and locked away in a more-or-less permanent store.

6.4 Shellfish cultivation would need to expand

On the strength of the estimate just given and the figures presented in Sections 6.1 and 6.2, shellfish sequestration does not look terribly promising. An annual reduction in CO_2 levels of 2.5 million tonnes is much less than the 15 gigatonnes of CO_2 that have been dumped into the atmosphere each year on average during the 20^{th} century and it is a rather tiny proportion of the 'fossil' CO_2 that has been released since the beginning of the industrial revolution (Section 6.2).

Clearly, if the cultivation of bivalve molluscs and the proper disposal of their shells is to have any significant impact on CO_2 levels in the atmosphere, there would need to be a dramatic expansion of the industry.

6.5 How big could shellfish cultivation become?

In order to assess how big the global shellfish farming industry might become, let us suppose that each shellfish farmer would normally wish to live on land and return home at the end of each working day, rather than servicing his or her farm from some kind of hypothetical floating residence, far out to sea. In short, shellfish farms would normally be located as close to the shore as possible and not scattered anywhere across the oceans.

With shellfish farms as they exist today, this is not a problem. They are invariably close to shore and small enough so that any part of any farm can be reached easily during the day.

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very light and everything else is shell, it is clear that at least 50% of the weight is shell. We shall assume that the same is true for other bivalve molluscs.

In order to simplify the calculations that follow, we shall suppose that, contrary to fact, shellfish farms occupy a strip of water of a constant width around half the coastlines of the world. To get a handle on how far the global shellfish farming industry might be expanded, we may calculate how wide that notional strip of water currently is. A spreadsheet with some relevant figures is shown in Table 3.

Item	Quantity
Production rate (tonnes/hectare/year)[24]	18
Production rate (tonnes/km^2/year) [25]	1,800
World mollusc production (tonnes/year)[26]	12,000,000
Area required for world production (km^2)[27]	6,666
Length of world's coastlines (km)[28]	1,634,701
Usable length of coastline (km)[29]	817,350
Width of coastal strip (m)[30]	8.16

Table 3: A spreadsheet to calculate the notional width of a strip of sea around half of the world's coasts to accommodate shellfish farms of today. The origin or derivation of each figure is given in the footnote for each item.

Of course, some coastal areas would be unsuitable because they are too cold or too hot, because they are polluted or because the sea is being used for some other purpose. And there would be gaps in the coastal strip for shipping lanes and the like. Making allowance for these kinds of things, we may guess that only half of the world's coastal areas might be used for shellfish cultivation.

From Table 3, we can see that the width of the notional strip of water around half of the world's coastlines that would accommodate present-day shellfish farms is 8.16 metres.

Let us now suppose that the world's shellfish farming industry was expanded by a factor of 10,000. This is, of course, an arbitrary figure but it will provide a reference point for discussion of the potential contribution that shellfish sequestration might make to reducing the amount of CO_2 that is in circulation.

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[24] In the 1980s, France produced 30,000 tonnes of mussels by the subsurface longline method each year. Production rates reached 18-20 tonnes per hectare per year on its Atlantic and Mediterranean coasts (Gosling, 1992, p. 478). In these calculations, it is assumed that this is representative of what might be achieved worldwide. To err on the side of caution, the lower end of the range has been assumed. However a Swedish multi-longline system reports a production of 400 tonnes per hectare per year (Gosling, 1992, p. 479) so we are actually being very conservative in our calculations.

[25] 1 km^2 = 100 hectares.

[26] See Section 6.3.

[27] Calculated from figures in the previous two rows.

[28] This figure comes from World Resources Institute, EarthTrends, http://earthtrends.wri.org/, 2011-03-03. Actually, any figure for the length of any coastline is somewhat arbitrary because it depends on how closely the measured line follows the detailed twists and turns of the coast. We probably need to assume that the main bays and headlands are followed but the details of rocks and smaller features are ignored.

[29] Making allowance for the fact that some coastal areas are not suitable for shellfish cultivation, as discussed in the text, we may guess that half the world's coastal areas may be used.

[30] Calculated as $W = (A/L) \times 1000$, where W = width of strip in metres, A = area of shellfish farms in km^2, and L = length of world's coastlines in km.

If shellfish farming around the world were to be expanded by a factor of 10,000, then we may infer that, on average, it may be accommodated within a coastal strip of sea that would be $8.16 \times 10^4 / 10^3 = 81.6$ km or 50.7 miles from side to side.[31]

Is this realistic? Although it may take an effort of imagination to conceive of shellfish farming on this scale, we believe there is no insuperable reason why the industry could not grow to that size or even bigger. It is a very modest expansion compared, for example, with the explosion in the rabbit population in Australia in the 19th century[32] or the growth in the numbers of road vehicles since cars were invented.

It is true that, with a shellfish farming industry of that size, it would take some time for shellfish farmers to reach the most distant parts of their farms and there may be a case for them sometimes staying out to sea for periods longer than a day, just as ordinary fishermen do. But in general there seems to be no reason in principle why marine bivalve molluscs should not be grown in quantities that are far larger than today and, as we shall see in the next subsection, this could make a substantial contribution to the stabilisation of the world's climate.

6.6 What is the potential impact of shellfish cultivation on this scale?

If the cultivation of marine bivalve molluscs were to be expanded by a factor of 10,000, then the quantities of CO_2 that could be sequestered each year by the proper disposal of the shells would increase from the 2.5 million tonne potential of present-day shellfish farms to a much more realistic 25 $GtCO_2$/yr. This rate of sequestration compares favourably with the average rate at which anthropogenic CO_2 has been added to the atmosphere between 1900 and 2005: roughly 15.4 $GtCO_2$/yr (Section 6.1). If that rate were to be maintained from year to year, then the time that would be needed to remove as much CO_2 as has been released by human activities since the beginning of the industrial revolution would be $1236 / 25 \approx 50$ years.

It appears that shellfish sequestration has the potential to take significant quantities of CO_2 out of circulation within a tolerably short time. If all anthropogenic emissions of CO_2 can be stopped, it is conceivable that, within one human lifetime, concentrations of CO_2 in the atmosphere might be returned to pre-industrial levels. If emissions of other greenhouse gases can be controlled, the world's climate might then stabilise.

Even if the expansion of mollusc cultivation were to be less ambitious—increasing the size of the industry by a factor of, say, 2000 instead of 10,000—the rate of sequestration—5 $GtCO_2$/yr or 1.36 GtC/yr—would comfortably exceed the 'Removal Target' of the Virgin Earth Challenge: "1 billion tonnes of carbon-

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[31] In this calculation, we have assumed that there is no limit on the sizes of shellfish farms and no requirement to space them out as suggested in Section 5.6 as a possible solution to the possible problem of food shortages in the central areas of shellfish farms.

[32] According to Wikipedia, 2010-10-21, "... within ten years of their introduction in 1859, rabbits had become so prevalent that two million could be shot or trapped annually without having any noticeable effect on the population. It was the fastest spread ever recorded of any mammal anywhere in the world." (see http://en.wikipedia.org/wiki/Rabbits_in_Australia).

equivalent per year for 10 years."[33] In conjunction with other methods for extracting CO_2 from the atmosphere, shellfish sequestration could make a useful contribution to the stabilisation of the earth's climate.

6.7 Emissions from the shellfish industry?

Although the figures given in the previous subsection look promising, we need to take account of emissions that may arise from the processes of cultivating shellfish and disposing of their shells.

At first sight, we need to take account of emissions arising from the ordinary activities of the people involved in the new industry—from their houses, from food production and processing, from transport, and so on. But those emissions would be much the same even if shellfish sequestration was not developed. So it seems reasonable to exclude those emissions from our calculations and concentrate on emissions arising directly from the industry. Those may include:

- Emissions from the manufacture of boats, ropes and other equipment required for shellfish sequestration.
- Emissions from the boats of shellfish farmers.
- Emissions arising from the transportation of shells from where they are produced to where they are disposed of, and from the process of disposal.
- Sundry emissions from other sources.

Taking an optimistic view, we may suppose that the world's industries, transport systems, and so on, move rapidly towards zero emissions and that there would be few emissions or none at all from the shellfish sequestration industry.

Although, taking a pessimistic view, we may imagine large emissions from manufacturing, transportation, and other elements of shellfish sequestration, it is difficult to quantify what those emissions might be. However, it seems reasonable to suppose that they would not be more than if each person involved in the new industry was to emit CO_2 at the same rate as the average person in the USA, estimated to be 18.9 tonnes per capita per year in 2007.[34] Given that shellfish sequestration could employ as many as 160 million people (see Section 6.8.2), emissions might be as high as $160 \times 10^6 \times 18.9 = 3.0$ $GtCO_2/yr$. But even at this high level, net sequestration under our ambitious scenario would still be a very welcome $25 - 3.0 = 22$ $GtCO_2/yr$ (a reduction of 12%).

Even at the reduced rate, it would, under our ambitious scenario, take only $1236 / 22 \approx 56$ years to remove as much CO_2 from circulation as has been released by human activities since the beginning of the industrial revolution. Under the less ambitious scenario, the rate of sequestration—4.4 $GtCO_2/yr$ or 1.12 GtC/yr—would still exceed the 'Removal Target' of the Virgin Earth Challenge.

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[33] See Virgin Earth Challenge Terms and Conditions, 2010-10-21: www.virgin.com/subsites/virginearth/.

[34] See 'United Nations Millennium Development Goals Indicators,' http://unstats.un.org/unsd/default.htm.

On balance, we believe that it should be possible to develop shellfish sequestration in such a way that emissions from the industry are much closer to the optimistic view than to the pessimistic view just described.

6.8 Employment, food supplies, other benefits, and costs

This subsection briefly discusses five other aspects of shellfish sequestration: its potential to combat acidification of the oceans, and to provide employment, additional food supplies, and other benefits, and its likely cost.

6.8.1 Combating acidification of the oceans

One of the worries about geoengineering proposals to reduce solar radiation reaching the surface of the earth is that, while they may help to keep the planet cool, they do nothing to combat acidification of the oceans caused by increasing concentrations of CO_2 (as outlined in Section 5.2) and its potential impacts on marine ecology, including the growth and survival of corals, shellfish and other organisms that incorporate calcium and other carbonates in their skeletons or shells.

An attraction of shellfish sequestration and other schemes for removing CO_2 from the oceans and the atmosphere is that—to the extent that they are successful[35]—they would have a direct impact in reducing acidification or, at least, its rate of increase.

6.8.2 Employment

As we saw in Section 6.5, the area of sea required for shellfish cultivation today is about 6,666 km^2. If the industry were to be expanded by a factor of 10,000, the area of sea that would be needed would expand to 66.66 million km^2. If we suppose that each square kilometre of shellfish farm requires about 2 people to look after it, then about $66.66 \times 2 \times 10^6 = 133.32$ million people would be involved in farming. We may guess that perhaps another 20% would be needed for associated industries such as the manufacture of ropes, the building and maintenance of boats, installing the infrastructure for fish farms, and disposing of the shells. So the total number of people involved in shellfish sequestration and its ancillary industries might be about 160 million people.

Given that the world's population is still increasing, we may suppose that there would not be a shortage of people to run the shellfish sequestration industry. It seems likely that many people would welcome the employment opportunities that it would offer.

6.8.3 Food supplies

A potentially valuable bonus from shellfish sequestration is that mussels, scallops and oysters are a source of food. If the 12 million tonnes of bivalve molluscs that are now produced each year were to be expanded by a factor of 10,000, worldwide annual output of molluscs would be about 120 gigatonnes. Since, as we noted

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[35] It is possible, of course, that acidification of the oceans would undermine the shellfish sequestration project itself. But, as discussed in Section 5.2, there are reasons for cautious optimism on that front.

previously, about half of that weight is the edible contents of the molluscs, shellfish sequestration could provide about 60 gigatonnes of protein-rich food to help feed the world. This is very much larger than the 142 million tonnes of fish produced by capture and aquaculture in the world in 2008 (FAO 2008) and the 260 million tonnes of meat produced in the world in 2004 (FAO 2006).

Fishmeal—produced from the capture of small fish not appropriate for direct human consumption and from trimmings from fish processing—is a critical resource. Annually about 20 million tonnes of raw materials are used to produce 5 million tonnes of fishmeal.[36] There is concern that this level of ocean harvest is not sustainable. Fishmeal is used worldwide as a source of protein for animal (and fish-farm) feedstuffs and is seen as a major part of worldwide food production. Shellfish meat could act as a supplement, or as a complete alternative to fishmeal and therefore reduce human dependency on this source of protein.

6.8.4 Other benefits

A potentially useful side-effect of shellfish sequestration is that, since shellfish are quite sensitive to pollution and since, as a source of food, they should be kept clean, the whole enterprise would provide a very powerful incentive to control pollution. Since the coastal waters where shellfish would be farmed may be contaminated by pollutants from the land and from the main bodies of the oceans, there would be strong incentives to control pollution coming from both directions.

Shellfish sequestration could have a big impact in helping us to clean up the planet. Since large-scale fishing would not be possible in the areas where shellfish were being farmed, those areas might serve as useful refuges for fish. Although not true Marine Protected Areas (MPAs) because of the aquaculture activities and the associated environmental disturbance (increased extraction of seston,[37] and increased deposition of faeces and pseudofaeces) they would be partial reserves.

6.8.5 Costs

It is hard to know how much one would need to pay people to work in shellfish sequestration but, bearing in mind that the sale of the edible contents of farmed molluscs would be a source of income, and since large numbers of people are now having to live on less than US$1.25 per day,[38] one may guess that there would be enough people who would be willing to do the work for an annual payment of US$3000.[39] At that rate, given that about 160 million people would be needed to run the industry (Section 6.8.2), and ignoring other costs,[40] the annual worldwide cost of sequestering 25 $GtCO_2$ would be $3000 \times 160 \times 10^6$ = US$480 billion—

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[36] www.seafish.org.

[37] Minute living organisms and particles of nonliving matter which float in water and contribute to turbidity.

[38] "List of countries by percentage of population living in poverty", Wikipedia, 2011-01-30, http://en.wikipedia.org/wiki/List_of_countries_by_percentage_of_population_living_in_poverty.

[39] As a point of detail, it would probably be best to pay people for the shells that they deliver for sequestration, rather than an up-front annual payment.

[40] Such as the cost of transporting shells to disposal sites and managing their disposal.

which equates to US$19.2 per tonne of CO_2 or US$70.4 per tonne of carbon. This is considered to be within the 'medium' range for the sequestration of carbon.[41]

However, since the cultivation of shellfish is already a viable industry in many parts of the world without any payments for carbon sequestration, these estimates may be on the high side. A payment of, say, US$5 per tonne of shells (equivalent to US$11.97 per tonne of CO_2 or US$43.86 per tonne of carbon[42]), may provide sufficient incentive for shellfish farmers to deliver what would otherwise be a waste product. At that rate, the cost of sequestering 25 $GtCO_2$ each year would be just over US$299 billion.

Of course, US$480 billion and US$299 billion are large sums of money but the costs would be shared amongst all countries in the world.[43] To put those costs in perspective, they are substantially less than the US$2,157 billion that the world was spending on defence in 2007.[44] They are also much less than the US$741 billion that the USA spent on defence in the same year.[45] Since it is now clear, as Ban Ki-Moon has said, that climate change is as big a threat as war,[46] and since the Stern report concluded that, amongst other things, the economic benefits of strong, early action to combat climate change considerably outweigh the costs,[47] we need to be prepared to spend this kind of money to make good the damage that has been caused by unrestrained emissions of CO_2.[48]

7 Conclusion

Shellfish sequestration has the potential to lock up large quantities of CO_2 relatively quickly. Within one human lifetime, it could potentially take as much CO_2 out of circulation as has been released into the atmosphere since the beginning of the industrial revolution by the burning of fossil fuels and the production of cement.

But if, as some scientists fear, climate change were to cause sinks for CO_2 to become sources of CO_2, if other positive feedback loops were to kick in, or if the

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[41] "Costs are assessed as 'low' if generally less than $20 per tonne of carbon sequestered, 'medium' if between $20 and $80, otherwise 'high'." (The Royal Society, 2009, p. 19).

[42] These equivalences have been calculated assuming that 0.95 of mollusc shells is calcium carbonate, as described in Section 6.3, and using the figures for molecular and atomic weights given in that section.

[43] No doubt, those countries that have, over the years, emitted the largest amounts of CO_2, should pay the lion's share.

[44] Worldwide military expenditures, GlobalSecurity.org, http://www.globalsecurity.org/military/world/spending.htm.

[45] *ibid*.

[46] "The danger posed by war to all of humanity and our planet is at least matched by the climate crisis and global warming." Ban Ki-Moon, Secretary General of the UN, March 2007, http://news.bbc.co.uk/2/hi/in_depth/6410305.stm.

[47] See http://politics.guardian.co.uk/economics/story/0,,1935208,00.html.

[48] One of the most effective ways of raising the necessary money would be the auctioning of permits to extract coal, oil or gas from the ground. In the 'Kyoto2' proposals (Tickell, 2008), it is estimated that the auctioning of such permits would raise about US$1 trillion every year.

‘clathrate gun’ were to fire,[49] then stabilisation of the world’s climate might become much more difficult or, indeed, impossible to achieve.

If we stop adding more fossil carbon to the atmosphere and bring other greenhouse gases under control, then providing the world has not passed or is not too close to some tipping point where climate change would become unstoppable, shellfish sequestration has the potential to contribute materially to the stability of the Earth’s climate.

Shellfish sequestration has the additional attraction that it should help to combat acidification of the oceans, it would provide jobs and earnings for many people around the world, it would provide a substantial, protein-rich addition to world food supplies, it would provide incentives to control pollution and, by excluding industrial-scale fishing from large areas of the sea, it may, in effect, create new relatively protected marine reserves.

Shellfish sequestration will not come cheap but it is affordable. Unless or until some better solution presents itself, there does appear to be a case for further investigation and development.

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[49] See, for example, de Garidel-Thoron et al. (2004).

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