Governance and equity in the development and deployment of negative emissions technologies

Stream: Toward just, fair and equitable Earth System Governance

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Abstract

This paper draws on a recent global assessment of carbon dioxide removal (or negative emissions) technologies (NETs) undertaken by the author for Friends of the Earth in the UK. Alongside criteria such as cost and technical readiness, the review applied criteria regarding controllability, accountability and side effects (including distributional impacts) to around 30 prospective NETs found in the literature.

This paper presents a summary of results of the assessment, and in particular, focuses on the environmental justice and governance issues identified as arising from the development of NETs. NETs could have major implications for intergenerational equity if their development (or potential) permits mitigation to be postponed, and their deployment could have significant distributional impacts between countries or groups.

Three major concerns are discussed. First, the potential moral hazard arising from the development of NETs, and possible mechanisms to limit the implications of moral hazard both within and beyond carbon markets. Second, the challenges arising from the distribution (and potential limits to the overall availability) of geological storage for carbon dioxide. And third, the implications of competition for biological productivity for negative emissions through biotic technologies (eg tree burial) or through the application of carbon capture and storage techniques to bioenergy.

The paper also reflects on the selection, definition and application of the assessment criteria to derive potential lessons for the governance of current and future geoengineeering research, development and deployment.

1. Introduction

Past reviews of negative emissions options have focused on relatively few technologies (Socolow *et al* 2011; McGlashan *et al* 2010), or taken a broad approach to different options in a wider geoengineering context (Shepherd *et al* 2009). The present study is based on a deep and broad assessment of around thirty proposed techniques. It develops a novel and more functional categorisation, and identifies a series of generic governance and justice issues common to some or all negative emissions techniques. With major opposition to solar radiation management approaches to geoengineering on various grounds, negative emissions or carbon dioxide removal approaches may well be seen as preferable as a complement to carbon mitigation. While broadly endorsing that conclusion, this study suggests that there are significant challenges in governance of negative emissions technologies which have not yet been adequately considered.

1.1 Defining Negative Emissions Techniques

Negative emissions techniques (or technologies) (NETs) are means of withdrawing greenhouse gases from the environment such that atmospheric concentrations are reduced below the level that would have resulted without the NET. In the literature on geo-engineering (eg Shepherd *et al* 2009), they are often described as carbon dioxide removal (CDR).

NETs encompass a wide variety of techniques. Most either make use of a chemical reaction to extract CO_2 from the air (or to bind CO_2 dissolved in sea water); or else exploit the ability of plants to extract CO_2 from the air to form biomass (and then capturing that carbon in some form). Here these two main routes are described as 'direct' and 'indirect' capture routes.

Figure 1 shows how direct and indirect routes could be applied to all the major carbon sinks in the natural carbon cycle[1]. Researchers have considered ways to increase carbon flows or retention in most of these areas.

In addition to the direct/indirect categorisation, Figure 1 also categorises NETs according to the storage

1 The only exception is the biotic sink itself, where NETs constitute techniques which increase the rate of flow of carbon into, and/or the proportion retained in, biomass.

mechanism (partly following McGlashan *et al* 2010). Mineral storage binds CO_2 in a mineral form into rocks or soil; pressurised storage compresses captured CO_2 and injects it into a geological storage reservoir; oceanic storage binds the carbon with chemicals naturally occuring in the ocean, and biotic storage holds the carbon in a stable organic form such as soil organic matter, construction timber, or buried biomass.

Figure 1: Carbon cycle schematic showing different categories of NET

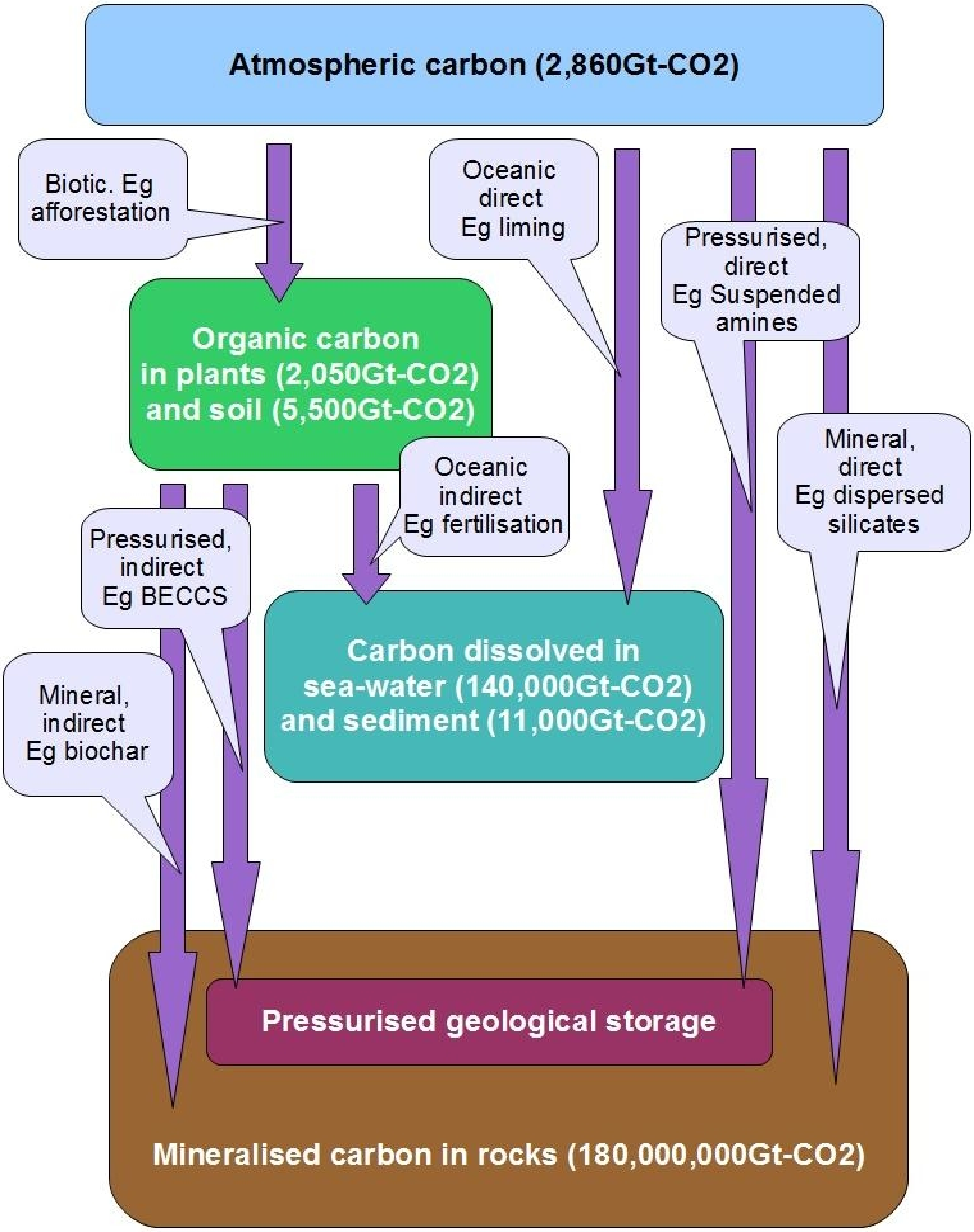

Table 1 describes each of the fourteen techniques that were subjected to more detailed assessment so as to ensure a basic common understanding and vocabulary of the processes involved.

Table 1: The Negative Emissions Techniques subjected to detailed assessment		
Category	*Technique*	*Description*
Mineral	Soil mineralisation	The addition of silicate minerals to soils (or surface water) to accelerate the natural process of carbonation of such minerals through dissolution both in the soil and in runoff (Shuiling & Krijgsman, 2006; Köhler *et al*. 2010).
	Magnesium cement	The replacement of carbonate in cement with a magnesium oxide from magnesium silicate, which combines with atmospheric CO_2 while setting (Vlasopolous, 2010).
	Biochar	Storing partially combusted organic matter (char) in soil by burial, preventing the return of biotic carbon to the atmosphere via decomposition. The char can be created from organic matter by pyrolysis or gasification, either of which provides some bioenergy (Shackley & Sohi, 2011).
Pressurised	Direct Air Capture (supported amines)	Adsorption of CO_2 directly from the atmosphere using amines in a solid form, suspended on a branched framework, through which air is pumped, or circulated by wind. The CO_2 is recovered by washing in vacuum, pressurised and injected into geological storage (Lackner 2009, Eisenberger *et al* 2009).
	Direct Air Capture (Wet Calcination)	Capture of CO_2 directly from the atmosphere using wet scrubbing systems based on calcium or sodium cycling technology. The CO_2 is recovered by calcining, pressurised and injected into geological storage (Keith et al, 2006, Baiocchi et al 2006, Socolow et al 2011).
	BECCS (Combustion)	Carbon dioxide is captured from the emissions from combustion of bioenergy sources. Because bioenergy is nominally carbon neutral, capture of the majority of combustion emissions creates a net negative emission across the bioenergy cycle (from plant growth to energy utilisation) (Karlsson *et al* 2010).
	BECCS (Ethanol/BLG)	As for BECCS (Combustion), but the CO2 is captured at an earlier, fuel conversion stage such as ethanol fermentation or black liquor (wood pulp effluent) gasification (Karlsson *et al* 2010).
Oceanic	Ocean Liming	The addition of calcium hydroxide (Kheshgi, 1995) or calcium bicarbonate solution (Rau & Caldeira, 1999 and Rau, 2011) to ocean surface waters, accelerating uptake of CO_2 from the atmosphere, and enabling the ocean to hold a higher total CO_2 store (Jenkins *et al* 2010).
	Ocean Fertilisation	Increasing ocean productivity through addition of limiting nutrients such as iron, phosphate or nitrogen, with the expectation that dead biological matter will sink into the deep ocean and add to stored carbon there. There is great uncertainty over the effectiveness of these proposed techniques (Shepherd *et al* 2009).
Biotic	Forest management	Increasing forest area by planting new forest or extending agro-forestry on suitable land, and /or enhancing management of existing natural and plantation forests to maximise the carbon sink.
	Wetland restoration	Rewetting and restoration of peatlands, tidal salt marshes and mangrove swamps to enhance anaerobic storage of dead organic matter (Parish *et al* 2008; Chmura *et al* 2003).
	Soil management	'No-till' agriculture to reduce the loss of carbon through oxidation when ploughing, thus enhancing the natural soil sink (Lal et al 2004; or organic soil management, using manures and composts to increase the levels of soil organic content (Azeez, 2009).
	Timber use in construction	Increased use of harvested timber in long-life construction applications, thus increasing the store of carbon in the built environment.
	Biomass burial	Burial of harvested biomass in anaerobic conditions (on land) or in the deep ocean (Zeng et al, 2011; Strand and Benford, 2009).

The techniques listed in table 1 are also included in table 2 and Figure 3 below[2]. In the present paper it is unecessary to consider the techniques in further detail as the governance and justice challenges considered

2 Other techniques were also reviewed but are not included here because for various reasons their potential appears more limited, or very limited information was is available on them. These included: mineral carbonation in autoclaves (Shuiling & Krijgsman, 2006), sea-water injection into basalts (Keleman and Matter, 2008), accelerated carbonation of mineral slag (Eloneva et al, 2007), direct air capture by use of fluidised beds (Nikulshina et al, 2009), electrodialysis (Eisaman et al 2009) or metal organic frameworks (Banerjee et al 2008; Wang et al. 2008), BECCS on biogas upgrading (Karlsson et al 2010) or biohydrogen production, ocean liming via electrochemical splitting (Rau 2008) or removal of HCl (House et al 2007), ocean fertilisation with iron (Shepherd et al 2010), use of GM crops for soil carbon management (Jansson et al 2010), cellulose aggregate concrete (Hemcrete, undated), and regenerative grazing (Lovell and Ward, undated).

here emerge either at the system level (moral hazard) or at category levels (Direct Air Capture (DAC) and Bioenergy with Carbon Capture and Storage (BECCS) raise storage issues, and biotic techniques raise issues of competition for biomass).

1.2 The purposes and need for NETs

Because of past failures to mitigate emissions effectively there is little prospect of safely balancing carbon budgets in the future without NETs. NETs may also offer effective offsets for 'recalcitrant' emissions (ones that are difficult or highly expensive to remove by current decarbonisation strategies). Other negative impacts of decarbonisation technologies such as biofuels might also lead us to prefer NETs in some circumstances. Finally, NETs might reduce the overall costs of meeting specific carbon budgets by replacing the most expensive elements of a given strategy or increasing flexibility in the timing of emissions cuts.

To estimate the demand for NETs two simple representative global scenarios for cumulative emissions are used, based on the difference between two IPCC SRES scenarios (A1B: atmospheric CO_2 approx 700ppm in 2100 and B1: atmospheric CO_2 approx 550ppm in 2100)(IPCC, 2000) and James Hansen's indicative safe level (350ppm CO_2) (Hansen *et al* 2008). These two reductions, divided over 75 years, imply an average rate of negative emission, globally, of 21-37 Gt pa. If NETs are introduced only after 2050 the average rate rises to 32-52 Gt-CO_2 pa[3] and the peak atmospheric concentration of CO2 is also higher, even for the same final concentration.

The extent and timing of the need for NETs will depend on the speed and depth of mitigation action (which will largely determine both cumulative emissions and the timing of peak emissions). If mitigation rates follow a scenario of delivery of the Copenhagen pledges followed by 80-95% reductions in Annex 1 countries and around 55% reductions elsewhere by 2050 (Lowe *et al* 2010) concentrations might be restricted to around 500 ppm by 2100, requiring a total negative emission of 1200Gt-CO_2 (24Gt pa over 50 years) to achieve 350 ppm. Even with very aggressive mitigation including a phase out of unabated coal use by 2030 (Hansen *et al* 2008) there is still a residual negative emission required in the order of 400Gt-CO_2 (50 ppm, or 8 Gt pa over 50 years).

2. Methodology and criteria for assessment

A review of approximately 30 different NETs found in the literature, which could contribute to meeting these requirements, was undertaken[4]. Data was gathered from iterated web searches, mainly using Google Scholar, providing a large literature list, primarily from peer-reviewed or official sources. An initial scoping search was analysed to establish a categorisation of NETs, which was then populated with data from subsequent searches.

A few semi-structured telephone or face-to-face interviews were conducted with researchers and policy experts in the field to explore emerging conclusions about particular technologies, rankings and policy approaches.

Seven broad criteria – identified in the process of the scoping search - were used to evaluate the techniques (see Box 1). These were applied consistently to fourteen techniques with selected according to apparent capacity and information availability.

3 To calculate annual reductions we use the rough approximation that each ppm reduction requires a negative emission of 8 Gt (Socolow *et al* 2011), and thus gaps of respectively 1600Gt and 2600Gt.

4 The full report and detailed spreadsheet of the assessment can be found at https://sites.google.com/site/mclarenerc/research/negative-emissions-technologies

Box 1: Assessment Criteria

Technical capacity and scalability: The technique can make a significant contribution to the overall level needed, and does not run into technical limits or become increasingly difficult or expensive at large scale. Ideally the technique should show economies of scale.

Controllability: Use of the technique can be controlled, in particular such that it can be halted if unforeseen negative impacts arise. Moreover, choices about deployment should be under the control of democratic institutions rather than being proprietary or corporate controlled.

Accountability: The impacts of the technique should be capable of being adequately measured and accounted for.

Side effects: The technique should not have unacceptable or unsustainable negative impacts. Ideally it will offer social, environmental or economic co-benefits.

Energy requirement: The technique should be relatively energy efficient, and have the potential to be run using renewable energy sources or low grade (waste) heat.

Status: The technique should be at least theoretically proven, and ideally well advanced into laboratory or field trials to give a reasonable degree of confidence regarding its performance on the other criteria identified.

Cost: High cost is not necessarily a reason to exclude a technique from consideration, but lower costs would mean earlier and more widespread use may be practical, and impose less burden on taxpayers for the same level of abatement.

3. Summary of findings of assessment

The overall assessment of the main options considered is summarised in Table 2 below. The NETs assessed are at various stages of development (mostly confined to the laboratory, or indeed in many cases, theory). Those close to deployment are typically very limited in scale (with an estimated capacity well below 3Gt pa) and face greater challenges in measuring and accounting for carbon stored than the less well developed direct capture techniques. All the techniques with high potential capacity are expected to remain high cost (at least $250 per ton CO_2) and require access to either or both geological storage, and a significant supply of renewable energy. A practical strategy towards NETs will therefore involve construction of a mixed package if abatement rates in the 10-30Gt pa range are to be achieved.

The energy demand of NETs is likely to remain a major obstacle in several cases, and means that NETs are unlikely to be deployed in preference to point-source mitigation measures. An effective net carbon balance for several options, particularly for direct air capture, depends on the widespread availability of low-carbon heat or electricity.

Few NETs involve side effects so severe as to rule out their use. Ocean fertilisation with iron might fall into this category, but is also ruled out by the serious uncertainties over its effectiveness and measurability. But many have side effects that should constrain their use: particularly biotic techniques that would divert biological productivity from other vital ecosystem services. It should be noted that these constraints have been considered in estimating the potential capacity shown in Figure 3, and in table 2 the traffic light system then assesses whether that level of capacity could be achived.

Almost all the options involved face issues of governance in terms of who controls them: either as a result of land ownership (for the biotic techniques) or the control of patents (for most of the rest).

Figure 2 below sets out schematically, a possible scenario and package of NETs. It is based on IPCC SRES A1B adapted broadly in line with the analysis of Lowe *et al* (2010) as described earlier, combined with a roughly 1200Gt CO_2 cumulative package of NETs (averaging 24Gt CO_2 pa for 50 years), estimated as necessary to achieve 350 ppm.

The package includes most terrestrial biotic techniques, air capture, BECCS, ocean liming but not fertilisation, soil mineralisation and magnesium cement. NETs are assumed to be introduced in 2030, with a 40 year roll out to rates in 2070 which match the levels shown in Figure 3 below. The package would require more than 540Gt of storage by 2100, exceeding our conservative estimates, but well within the IPCC's 'likely' estimate. It can be seen from this that a challenging package of NETs which stretches potential storage limits still only contributes less than half of the total reduction in the cumulative budget (accounting for 150 ppm reduction in a total reduction of around 350 ppm).

Table 2 : A high level assessment of obstacles to deployment of NETs

NET	Capacity / scalability	Accountability	Side effects	Energy requirement	Status	Cost
Soil mineralisation with olivine	amber	red	amber	amber	amber	green
Magnesium Silicate Cement	amber	amber	green	green	green	green
Biochar – pyrolysis	amber	amber	amber	green	green	amber
Biochar – gasification	amber	amber	amber	green	amber	amber
Supported amines for direct air capture	green	green	green	amber	red	red
Wet calcination for direct air capture	green	green	green	red	red	red
BECCS – combustion / co-firing	green	green	amber	amber	amber	amber
BECCS – ethanol fermentation	amber	green	amber	amber	green	green
BECCS - black liquor (BLG) / pulp	amber	green	amber	amber	amber	green
Ocean liming (calcination)	green	amber	amber	amber	red	green
Ocean fertilisation (macro-nutrients)	amber	red	amber	green	red	amber
Forest restoration / management	amber	amber	green	green	green	green
Habitat restoration: peatlands and other wetlands	amber	amber	green	green	green	green
Soil management (eg No-till practices)	amber	red	green	green	green	green
Timber use in construction	red	green	green	green	green	green
Tree burial in anaerobic conditions	amber	amber	amber	green	amber	amber

Key: red = serious obstacle or problem, may not be overcome
amber = significant obstacle, or unknown
green = challenges are relatively small, and probably surmountable

Figure 3 illustrates the estimated global capacity, costs and readiness of NETs. The bubbles are equivalent in size to the estimated annual global capacity, and they are located against axes of technical readiness (where higher = more ready), and cost. The costs – which are represented here as single figures rather than ranges - should be treated as at best indicative[5].

This discussion of the potential role and capacity of NETs raises many issues and questions. Below we focus on three major ones. First, the risk of moral hazard: that the potential or actual availability of NETs might reduce mitigation. Second the the implications of limits to storage capacity for captured CO_2. And finally the implications of competition for biological productivity by biotic NETs or the deployment of BECCS.

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5 To allow some degree of comparison of scale a 'global indicative' need bubble of 30Gt CO2 has been included.The placing of this is not representative of a 'need' for any specific cost or readiness.

Figure 2: Schematic contrasting mitigation and NETs in a 350 ppm scenario

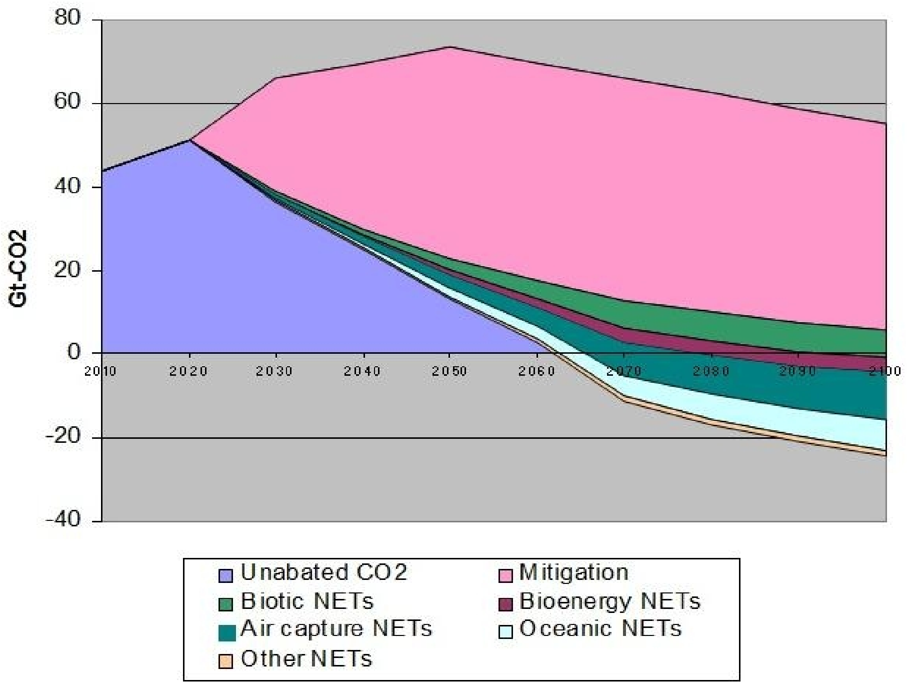
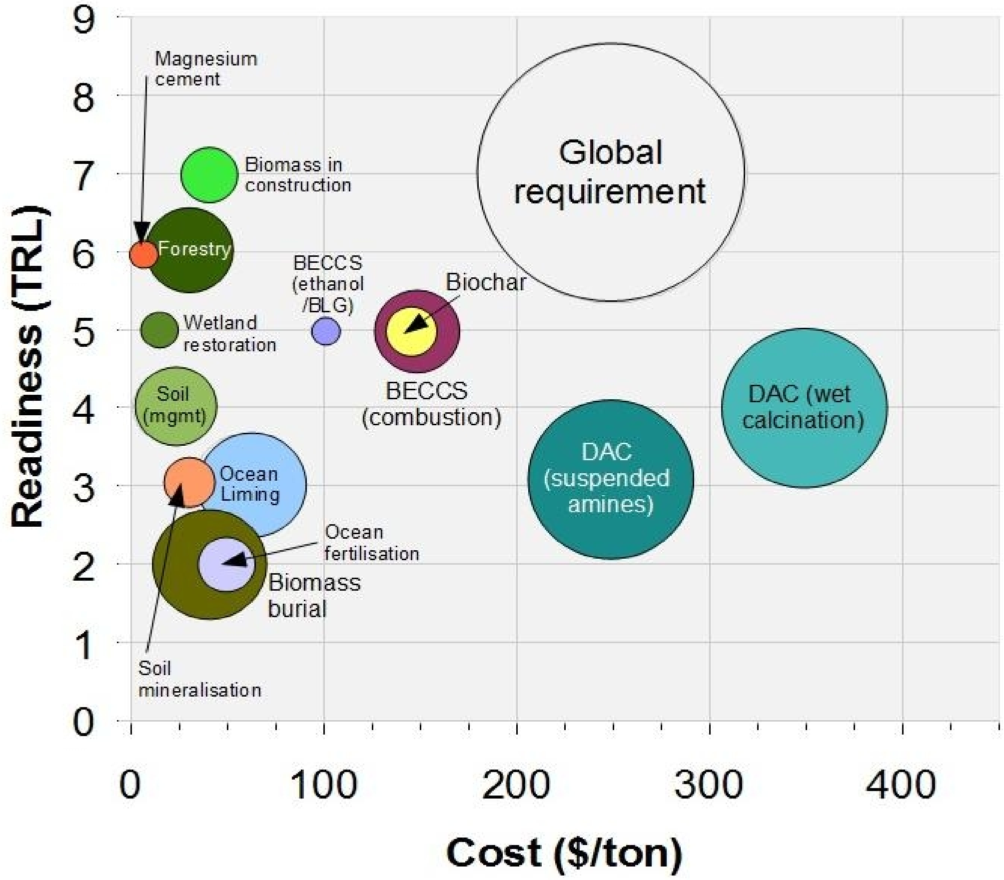


Figure 3: Provisional global assessment of NETs: scale, cost and readiness



4. Discussion

4.1 Moral hazard

Moral hazard arises when a decision maker is (or believes him- or herself to be) in some way insured against the consequences of their decision. The potential moral hazards involved with NETs fall into two broad categories:

1. The expected availability of NETs could lead to reduced or delayed mitigation activity, increasing the risks of dangerous climate change (and/or requiring the elevated deployment of (relatively high cost) NETs in the future).
2. The actual availability of NETs is used to offset continuing emissions (merely slowing the increase in atmospheric concentrations) rather than to actively reduce atmospheric concentrations.

Both flow from the fact that those taking the relevant decisions are unlikely to be personally affected by the current or future consequences of those decisions in climate terms. Addressing these problems has consequences both for international and national governance.

The debate over moral hazard is confused by confusion of the issue with rational economic choice. It is fairly common in the literature for NETs to be actively advocated as a reason to delay mitigation because they add flexibility. Technical analyses and modelling also suggest that the expected availability of NETs would reduce mitigation in the short term (eg Keith *et al* 2006, Azar *et al* 2006).

However such conclusions rely on three sets of questionable assumptions. First that the performance and costs of NETs in practice will match optimistic predictions, such that they become lower cost options than mitigation, and their deployment becomes possible at a rapid and unconstrained scale. Second that future political, economic and institutional conditions will be benign for the deployment of NETs (Parson, 2006). And third that the impacts of rising CO_2 concentrations will be broadly linear and reversible (rather than subject to tipping points).

None of these appear realistic according to the present assessment. Even if costs are lower than anticipated here, adequate and rapid uptake of NETs would be dependent on international agreement. This would require national targets and monitoring and verification regimes that would allow countries to deploy NETs as a contribution towards their targets.

In economic terms, because of their flexibility in application, NETs would theoretically establish a cap on any carbon price (whether in carbon trading markets, or a shadow price set by Governments). There would be no economic reason to adopt more expensive strategies to mitigate emissions at source, rather than paying the cost of a NET to clean up afterwards. However were such a carbon price cap to arise from the prospect of NETs, it would directly operationalise the both categories of moral hazard. This suggests a need to keep NETs outside of any carbon market.

While economically, NETs might be seen to cap the carbon price, morally, they can be argued to do the opposite, and set a floor on it (Kruger, pers comm). This relies on the view that the availability of a safe, robust and scalable carbon negative process would confirm a moral obligation to match each emission with an equivalent removal (an obligation which would be meaningless without the capacity to act on it). In turn this implies an obligation to set a carbon price which enables the uptake of that process.

It could be argued that the inclusion of NETs in carbon markets might accelerate their development by providing a financial incentive, but it would also mean they were effectively deployed as an offset. While this might be seen as an acceptable price to pay in the short term, in the long-term, inclusion in carbon markets would only result in an overall increase in mitigation with smaller carbon caps (which are opposed by vested interests). Inclusion of NETs in carbon markets would also be likely to make such markets more susceptible to speculation and irrational trading behaviour.

One effect of the moral hazard of NETs might be to depress investment in renewable energy, as a result of a belief that the use of fossil fuels could be further prolonged by the availability of NETs. However there are other important reasons for renewables development: for example, avoiding energy insecurity as a result of rising and more volatile prices for fossil fuels.

Moreover, without intervention, in conventional markets, the scope for NETs to offset specific emissions is unlikely to be allocated according to a rational policy hierarchy. Rather NETs as offsets are likely to be sold to the highest bidder. For example, one of the emerging companies seeking to bring its NET to market is openly hypothesising that it might sell negative emissions to, for example, a luxury car manufacturer, allowing the vehicles to be marketed as 'zero carbon' for a relatively small increment in price[6]. It is also possible to imagine financial markets establishing futures markets in NETs which allow the wealthy to purchase future offsets too. The general principle that (limited) NETs may be purchased as offsets for emissions that might be otherwise expensive or unpopular to mitigate creates distributional concerns for those groups (or countries) unable to afford NETs.

Direct financial incentives for NETs are likely to be necessary, as access to carbon markets is widely seen as the way in which capital intensive technology innovation in this field could be financially rewarded. In practice targeted incentives might prove more effective also. Experience with carbon markets and low-carbon energy in the UK indicates that carbon markets alone will not guarantee necessary investments and that even installing a carbon floor price may not be adequate to encourage developers to invest in well advanced technology (such as CCS) in the face of uncertainties in deployment costs and future.

To avoid the indiscriminate use of NETs as an offset (simply displacing other technically feasible mitigation), they should be excluded from carbon markets. But this will not eliminate moral hazard, so the development of NETs should be accompanied by measures to restrict the negative effects of moral hazard in both carbon markets and wider policy. If carbon markets are expected to play a role in future climate policy, the type of provision that could be usefully explored might include the imposition of bonds on commitments of future emissions reduction, and the development of levies on trade in carbon futures.

4.2 Challenges arising from the distribution and limits to geological storage for carbon dioxide.

Geological storage for compressed liquid CO_2 is required for several categories of NET, including direct air capture (DAC) techniques and BECCS. Geological storage underlies the development of carbon capture and storage technologies for fossil fuel combustion, and has therefore attracted intensive research. It has been demonstrated for several decades as a result of the use of reinjected CO2 for enhanced oil recovery. Estimates of storage capacity in disused oil and gas fields can therefore be treated as relatively robust, whereas estimates of capacity in other geologies, such as saline aquifers are much more uncertain.

In a major review the IPCC (2005) concluded that 200Gt CO_2 capacity may be considered 'virtually certain' and 2000Gt CO_2 'likely'. A reasonable cautious estimate might lie in the order of 400-500Gt CO_2, based on experience in validating capacity estimates in smaller areas (Haszeldine, pers comm) and the challenges of implementing storage in practice. The UK Climate Change Committee (2011) for example, while citing fairly generous estimates of total storage capacity, argue that limits to cost-effective CCS storage capacity could *"limit medium-term deployment of CCS in power generation, given the likely need for long-term use of CCS in energy-intensive industries"* (even while assuming no reservation of storage for NETs). Spread over 50 years, a total capacity of 400Gt would permit an average of no more than 8Gt pa negative emission (equivalent to approximately 50ppm). Globally reducing concentrations by 250ppm would take up all of the IPCC's 'likely' estimate, even assuming it was all reserved for NETs, and none was consumed by fossil CCS[7].

There is a clear prospect that we may approach feasible storage limits, especially if high levels of CCS deployment arise and continue throughout or beyond this century. But there is no simple reason to prefer use of storage for CCS or for NETs. The former is mitigation – but much more certain, while the latter has uncertain potential to reduce absolute atmospheric concentrations of CO_2. A practical way forward might be to permit trials of fossil CCS now, but to avoid mitigation strategies which favour fossil CCS over for example, energy saving or renewable energy, limiting the use of storage for 'offsets' (whether in the form of CCS or

6 http://www.carbonengineering.com/wp-content/uploads/2011/04/CarbonEngineering-AirCaptureFAQ.pdf

7 This uses Socolow *et al'*s figure of roughly 8 Gt CO2 per ppm, a 50 ppm reduction therefore requires removal of 400Gt CO2. A 200ppm reduction (from 550 to 350) requires removal of 1600Gt, and a 350 ppm reduction (say, from 700 to 350) would require removal of 2800Gt CO2. It should be noted that for several technologies including wet calcination and BECCS, because of the net energy consumption, a greater amount of CO2 will have to be stored than is removed from the atmosphere. This makes the apparent storage constraints more severe.

NETs). Early development of geological storage schemes, so as to better understand the resource and its limitations, should be followed by detailed review, rather than unregulated expansion of fossil CCS.

However, it must be noted that other storage techniques are being investigated. Rau (2011) has laboratory tested a method for scrubbing CO_2 from flue gas and storing in seawater as bicarbonate ions[8]. In situ mineralisation by injection into basaltic rocks (Kelemann & Matter, 2008; Oelkers, 2008) has shown some promising results and could potentially increase storage capacity dramatically. However it is at a very early stage. The estimates of capacity are highly uncertain, while the potential impacts and acceptability of the heating and fracturing potentially required to prepare the rock for storage are presently unknown. To rely on this for the deployment of NETs would add a further layer of moral hazard.

Geological storage is not distributed evenly between countries and this complicates the governance of storage and competing uses. The geopolitical disparities could be extreme. India, for instance, is estimated to have very little domestic storage capacity. Questions of how access to storage is distributed and if necessary rationed (by something more than a price mechanism) will need to be answered. If climate politics dictate that geological storage, and oceanic storage (if not biotic) are treated as the common property of all humanity this would reduce the UK's claim, for example, significantly below the estimated territorial availability of 8-50Gt (based on SCCS 2009, and CCC 2011). Assuming distribution of storage by population would reduce the UK share to 2-20Gt CO_2, and even on the basis of current emissions, to 3.5-35Gt CO_2[9].

The distribution of storage should be something of a 'non-issue' if the moral hazard in NETS were properly managed. In other words, if NETs are used to reduce atmospheric CO_2 concentrations in everyone's interest, it shouldn't matter which CO_2 gets stored and by whom. But in the real world such questions become intensely political. And if we accept that the moral hazard of using NETs as offsets is unlikely to be eradicated, then if storage is controlled by those wishing to use NETs as offsets then there is an serious risk of injustice.

All this implies a challenge for governance. At present, as with the atmosphere prior to global climate change negotiations, there are no mechanisms to share out the capacity of the planet's geology to store CO_2 over time. In this case simply recognising the issue is the first necessary step.

4.3 Implications of competition for biological productivity

A choice to store the carbon from biological productivity has consequences. At present that carbon may constitute a part of the natural world's productivity not yet appropriated for human use (and thus be critical to other species), or it may be used by humans in the form of food, fuel or material. Insofar as biological productivity can be increased sustainably there could be additional carbon available for sequestration through NETs, but otherwise a choice to store the carbon will compete with other uses, with distributional consequences, between species or between different groups of humans.

All the biotic technologies (eg tree burial) and BECCS could be of concern in this respect, including the oceanic biotic techniques, although the low current rates of human utilisation of oceanic biomass mean that there is little evidence on which to base consideration in that arena.

On the other hand, debates over biofuels – and potential conflicts with the production of food and fibre - have provided an evidence base on which to discuss the likely implications of NETs. They also indicate where better information is needed, and some of the generic strategies which could be deployed to minimise impacts.

Estimates of the sustainable supply of feedstock for bioenergy are highly variable. Cautious estimates would suggest a maximum sequestration of biomass carbon through BECCS of 3.3-7.5 Gt CO_2 pa globally (based on

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8 This would not contribute to ocean acidification, and may even alleviate it.
9 In each case using the IPCC's 200-2000Gt CO_2 as the baseline.

Woolf et al, 2010[10]). More optimistic forecasts, of 15-50Gt CO CO_2 sequestered[11] would require unrealistic substantial new areas of production and unsustainable increases in crop yields (Bauen *et al*, 2009; Ladanai and Vinterbäck, 2009) or conversion of 'abandoned cropland' (Lenton 2011) and would probably exceed the availability of geological storage.

The above maxima assume that biomass would be directed preferentially to BECCS. Lower figures would be achieved if bioenergy were focused on uses which cannot be otherwise decarbonised – especially heat requirements, as the Climate Change Committee (2011) suggest, or used for biochar. BECCS has both higher energy recovery and higher sequestration in comparison to biochar, but relies on access to geological storage, and is most likely commercial within a developed energy grid. Biochar might, however, be more appropriate for decentralised energy, and where geological stores or CO_2 pipelines are far distant, or exhausted.

An overall limit on biomass constrains the aggregate negative emission available through all indirect terrestrial routes and through increased timber use in construction. In the longer term higher biomass use and a higher standing stock of carbon in vegetation and soils might both be achieved. But the sustainable supply of biomass is practically limited in both total and in the rate of growth that could safely be achieved towards the theoretical upper limit. This is partly because in the short term increasing the overall level of biomass use would create a carbon debt which may last for decades (Bird *et al* 2010; and Walker *et al* 2010).

Future biomass conversion technologies such as 2nd generation biofuels will do little to reduce the land constraint on NETs, as they act primarily by increasing the energy conversion from a similar amount of biomass carbon.

The justice and governance implications of elevated biomass demand are serious. The example of biofuels suggests that a relatively small diversion of biological productivity away from food production helped raise food prices in a highly volatile manner (clearly exacerbated by market speculation). The implications for billions in poverty cannot be ignored. More locally, the appropriation of land for carbon forestry, biochar or biomass production could trigger serious injustice for prior users of that land, whether human or other species. The example of biofuels also demonstrates that without effective control, extension of production onto land used previously for food production, or into standing forest occurs alongside intensification of production (Bowyer & Kretchmer, 2011). Proposals to use only the product of intensification or to more efficiently use crop residues for biotic NETs therefore cannot be taken seriously without much stronger constraints on market functioning than exist today.

The negative impacts associated with biofuels could arise from the unregulated development of many botic techniques including BECCS, biochar, and wood burial. The impacts may arise through competition for use of forest land rather than agricultural, but would be no less real. On the other hand there may be much more sustainable potential (if not to the same absolute scale) for techniques such as soil management or regenerative grazing. Policy makers will need to devise effective targeted policy measures.

4.4 Other lessons from the selection, definition and application of the assessment criteria for the governance of current and future geoengineeering research, development and deployment.

Justice and distributional impacts

NETs could clearly have major implications for equity between generations if they allow mitigation to be postponed (as a result of moral hazard). If used as offsets, they also have very practical implications for distribution between countries. It would clearly be socially unjust if the easiest and cheapest deployment of NETs (enabled by carbon trading) was claimed to facilitate continued conspicuous consumption in rich countries, leaving poor countries needing to develop more expensive NET options to manage their

10 The feedstuffs considered sustainable included up to 80% of sawmill, yard and other wood wastes; rice husks, up to 20% of cereal straw, up to 25% of cattle manure, the product of up to 175 mha of tropical grassland converted to agroforestry; and the product of degraded or disused cropland not in other uses.

11 The net negative emission is lower at 10-33 Gt because of the higher direct emissions per unit energy generated from biomass compared with the fuel replaced.

recalcitrant emissions.

At a smaller scale, there may be localised distributional issues too. Imagine the availability of air-capture, but with facilities that are visually intrusive, consume large quantities of water, sterilise land from development, and perhaps have fugitive chemical emissions (all features of some DAC technologies on the drawing board). Communities would inevitably seek to have these established outside of their localities (or even outside of their countries), imposing an environmental injustice on communities least able to resist such actual or perceived 'bad neighbour' developments.

These are more than simply 'side-effects'. The distributional implications of NETs should be more explicitly addressed in assessment criteria.

Controllability

The criterion of controllability proved difficult to measure in any comparable way (it is omitted from table 2 for that reason), but it served an effective function in highlighting the issues around governance, such as the degree to which NETs might further raise concern about the role of private corporations in climate policy. While some techniques – like tree planting or peatland rewetting - are simple and widely available, and some others (notably Cquestrate (Jenkins *et al* 2011)) are being developed in a deliberately open fashion, the majority of NETs, and especially those with high potential capacity, are likely to be subject to multiple patents.

Most of the technological development – especially around direct air capture - is being undertaken by venture capital funded university spin-offs in the USA. Such start-up companies all clearly scent opportunities to make high profits from proprietary technologies. Many are investigating alternate paths to commercial viability which would involve selling captured CO_2 into markets such as enhanced oil recovery, or chemical and food uses. There appears to be little effort on either side of the Atlantic to claim a public share in the intellectual property arising even from publicly funded research, although the US Government might gain access to the intellectual property in any technology accepting a prize under the mechanism proposed by the Barasso-Bingaman draft bill.

In summary it is highly unlikely that any large-scale deployed NET would be free from corporate control or geo-politics, and a better defined measure of controllability in this respect would be valauble for future assessment.

Governance

Governance issues extend well beyond proprietary control over the technologies involved, to broadly parallel the complexities of international climate governance – if only because of the need to agree how NETs would be accounted for within international climate agreements and negotiations. Unlike solar radiation management (SRM) where unilateral implementation is imaginable, the use of NETs seems more likely to be hampered by concerns over potential free-riding.

To further complicate matters, parties at the Convention on Biological Diversity have imposed a *de facto* moratorium on geoengineering trials, stimulated in part by concerns over the potential side effects of ocean fertilisation techniques, but also by the general issue of moral hazard, which threatens compliance with the precautionary principle. At the London Convention a science working group is considering how to enable justified scientific trials involving deliberate introduction of material to the oceans.

Geoengineering researchers met at Asilomar in 2010, and discussed principles for the management of trials and field research (Wannier *et al* 2011). Notably these included the view that liability mechanisms were needed, even for research, and that the public should be involved in judgements over equity implications as well as there being sound, independent technical and risk assessments. But no country has yet developed such mechanisms for research, even in other controversial technology areas such as nanotechnology. In the UK some of the research councils are developing the concept of 'Responsible Innovation' which aims to better embed scrutiny of the ethics and risks of research at an early stage. A pilot of implementation of this approach has been applied to an SRM geoengineering research project (Macnaghten and Owen 2011).

It may prove possible to incorporate the challenges of governance of NETs (if not SRM) within the mechanisms developed under the auspices of the UNFCCC. However the challenges identified in this paper would suggest that the incorporation of NETs might necessitate signficant reorientation of the UNFCCC with respect to carbon markets, and with respect to development and enforcement of sustainability standards or constraints applied to mitigation and abatement measures.

5. Conclusion

This review of NETs has suggested that NETs will be necessary to balance global carbon budgets this century, yet the pursuit of NETs would carry significant risks, both to the delivery of essential accelerated mitigation; and to other important social and environmental factors. There has been an understandable reluctance in the policy and advocacy communities to engage with any forms of geoengineering so far. The time has come to engage with the challenge of devising just governance measures for geoengineering, if we are not to see economic and technological developments dictating both the form and uptake of the techniques regardless of human and environmental costs.

6. References

Azar, C, K Lindgren, E Larson and K Möllersten. 2006. Carbon capture and storage from fossil fuels and biomass – costs and potential role in stabilizing the atmosphere. *Climatic Change* vol.74 (1-3) pp.47-79

Azeez, G. 2009. *Soil carbon and organic farming A review of the evidence of agriculture's potential to combat climate change*. Soil Association, Bristol.

Baciocchi R, G Storti, and M Mazzotti, 2006. Process design and energy requirements for the capture of carbon dioxide from air. *Chemical Engineering and Processing* **45** pp1047–1058

Banerjee, R, A Phan, B Wang, C Knobler, H Furukawa, M O'Keeffe and OM Yaghi, 2008. High-Throughput Synthesis of Zeolitic Imidazolate Frameworks and Application to CO_2 Capture. *Science* 319 (5865) 939-943

Bauen, A, G Berndes, M Junginger, M Londo, F Vuille, R Ball, T Bole, C Chudziak, A Faaij and H Mozaffarian, 2009. *Bioenergy – a sustainable and reliable energy source: A review of status and prospects.* IEA Bioenergy. http://www.task39.org/LinkClick.aspx?fileticket=8IsypIOAwXs%3D&tabid=4426&language=en-US

Bird, N, N Pena & J Zanchi. 2010. *The upfront carbon debt of bioenergy*, Graz, Joanneum Research http://www.birdlife.org/eu/EU_policy/Biofuels/carbon_bomb.html

Bowyer, C and B Kretschmer, 2011. *Anticipated Indirect Land Use Change Associated with Expanded Use of Biofuels and Bioliquids in the EU – An Analysis of the National Renewable Energy Action Plans*. Institute for European Environmental Policy

Chmura, GL, SC Anisfeld, DR Cahoon and JC Lynch. 2003. Global carbon sequestration in tidal, saline wetland soils, *Global biogeochemical cycle*s, vol 17, no. 4, 1111.

Climate Change Committee, 2011. *The renewable energy review*. http://hmccc.s3.amazonaws.com/Renewables%20Review/The%20renewable%20energy%20review_Printout.pdf

Eisaman, MD, DE Schwartz, S Amic, D Larner, J Zesch, F Torres, and K Littau. 2009 Energy-efficient electrochemical CO_2 capture from the atmosphere. *www.parc.com/.../P2009086-Electrochemical-CO_2-Capture-Cleantech09.pdf*

Eisenberger, PM, RW Cohen, G Chichilnisky, NM Eisenberger, RR Chance, and CW Jones, 2009. Global Warming and Carbon-Negative Technology: Prospects for a Lower-Cost Route to a Lower-Risk Atmosphere. *Energy & Environment,* 20(6) pp 973-84

Eloneva, S, S Teir, J Savolahti, CJ Fogelholm, and R Zevenhoven, 2007. Co-utilisation of CO_2 and Calcium Silicate-rich Slags for Precipitated Calcium Carbonate Production (Part II). In: *Proceedings of ECOS 2007*, Padova, Italy, 25-28 June 2007, Volume II, p.1389-1396.

Hansen, J, M Sato, P Kharecha, D Beerling, R Berner, V Masson-Delmotte, M Pagani, M Raymo, DL Royer, & JC Zachos, 2008. Target atmospheric CO_2: Where should humanity aim? *Open Atmospheric Science Journal*, vol. 2, pp. 217-231

Hemcrete, undated. Hemp Lime Technology: Tradical® Hemcrete® Information Downloads. *Datasheet.* http://www.limetechnology.co.uk/pdfs/Tradical_Hemcrete_Datasheet.pdf

House, KZ, CH House, DP Schrag, and MJ Aziz, 2007. Electrochemical Acceleration of Chemical Weathering as an Energetically Feasible Approach to Mitigating Anthropogenic Climate Change *Environ. Sci. Technol.*, 41 (24), 8464-8470

Intergovernmental Panel on Climate Change (IPCC), 2000. *Emissions Scenarios: a summary for policy makers*. A Special Report of IPCC Working Group III.

Jansson, C, SD Wullschleger, UC Kalluri, and GA Tuskan,2010. Phytosequestration: Carbon Biosequestration by Plants and the Prospects of Genetic Engineering. *BioScience* 60: 685–696

Jenkins, BJ, *et al* 2010. *Ocean Sequestration of CO_2 by the Addition of Alkaline Oxides*. Cquestrate for Shell GameChanger.

Karlsson, H, L Byström and J Wiklund, 2010. *BECCS som klimatåtgärd*. Biorecro AB, Sweden

Keith, DW, Minh Ha-Duong and JK Stolaroff, 2006. Climate strategy with CO_2 capture from the air. *Climatic Change* 74: 17–45

Kelemen PB and J Matter 2008. In situ carbonation of peridotite for CO_2 storage. *Proceedings of the National Academy of Science*, November 11, 2008 vol. 105 no. 45 17295–17300

Kheshgi, HS, 1995. Sequestering atmospheric carbon dioxide by increasing ocean alkalinity. *Energy*, **20**, 915-922.

Köhler, P, J Hartmann, and DA Wolf-Gladrow, 2010. Geoengineering potential of artificially enhanced silicate weathering of olivine. *Proceedings of the National Academy of Science.* www.pnas.org/cgi/doi/10.1073/pnas.1000545107

Lackner, K, 2009. Capture of carbon dioxide from ambient air. *European Physics Journal Special Topics* **176**, 93–106 (2009) DOI: 10.1140/epjst/e2009-01150-3

Ladanai, S, and J Vinterbäck, 2009. *Global Potential of Sustainable Biomass for Energy*. SLU, Swedish University of Agricultural Sciences Department of Energy and Technology, Uppsala.

Lal, R, M Griffin, J Apt, L Lave, MG Morgan, 2004. Managing Soil Carbon. *Science* 304, 393.

Lenton, TM. 2010. The potential for land-based biological CO_2 removal to lower future atmospheric CO_2 concentration. *Carbon Management.* 1(1), 145–160

Lovell T, and B Ward, undated. http://www.soilcarbon.com.au/case_studies/pdf/08TL_SCCPPP_En.pdf

Lowe JA, LK Gohar, C Huntingford, P Good, D Bernie, A Pardaens, R Warren and SCB Raper, 2010. *Are the emission pledges in the Copenhagen Accord compatible with a global aspiration to avoid more than 2°C of global warming? A technical note from the AVOID programme*. http://ensembles-eu.metoffice.com/avoid/meetings/AVOID_Copenhagen_Accord_260310.pdf

Macnaghten P, and R Owen, 2011. Environmental science: Good governance for geoengineering. *Nature* 479, 293 (17 November)

McGlashan N., Shah N., Workman M., 2010: *The Potential for the Deployment of Negative Emissions Technologies in the UK.* Work stream 2, Report 18 of the AVOID programme (AV/WS2/D1/R18). Available online at www.avoid.uk.net

Nikulshina, V, C Gebald, and A Steinfeld, 2009. CO_2 capture from atmospheric air via consecutive CaO-carbonation and CaCO3-calcination cycles in a fluidized-bed solar reactor. *Chemical Engineering Journal,* 146 (2009) 244–248

Oelkers EH, SR Gislason and J Matter, 2008. Mineral Carbonation of CO_2. *Elements* , Vol 4, pp. 333–337 DOI: 10.2113/gselements.4.5.333

Parish, F., Sirin, A., Charman, D., Joosten, H., Minayeva, T, Silvius, M. and Stringer, L. (Eds.) 2008. *Assessment on Peatlands, Biodiversity and Climate Change: Main Report*. Global Environment Centre, Kuala Lumpur and Wetlands International, Wageningen. http://www.imcg.net/media/download_gallery/books/assessment_peatland.pdf

Parson, EA, 2006. Reflections on air capture: the political economy of active intervention in the global environment. *Climatic Change* 74: 5–15

Rau, GH and K Caldeira, 1999. Enhanced carbonate dissolution:: a means of sequestering waste CO_2 as ocean bicarbonate. *Energy Conversion and Management* 40 (17) pp 1803-1813

Rau, GH, 2008. Electrochemical Splitting of Calcium Carbonate to Increase Solution Alkalinity: Implications for Mitigation of Carbon Dioxide and Ocean Acidity. *Environ. Sci. Technol.*, 2008, 42 (23), pp 8935–894

Rau, GH, 2011. CO_2 Mitigation via Capture and Chemical Conversion in Seawater. *Environ. Sci. Technol.*, 2011, 45 (3), pp 1088–1092

*SCCS (*Scottish Centre for Carbon Storage) *2009. Opportunities for CO_2 Storage around Scotland - an integrated strategic research study. http://www.scotland.gov.uk/Resource/Doc/270737/0080597.pdf*

Schuiling, RD & P Krijgsman 2006. Enhanced weathering; an effective and cheap tool to sequester CO_2 *Climatic Change*, 74, nrs 1-3, p.349-354.

Shackley S and S Sohi (eds) 2011. *An assessment of the benefits and issues associated with the application of biochar to soil*. A report commissioned by the United Kingdom Department for Environment, Food and Rural Affairs, and Department of Energy and Climate Change. UK Biochar Research Centre (revised February 2011).

Shepherd, J et al. 2009. *Geoengineering the Climate: Science Governance and Uncertainty*. Royal Society, London.

Socolow, R *et al,* 2011. *Direct Air Capture of CO_2 with Chemicals* A Technology Assessment for the American Physical Society Panel on Public Affairs, April 28, 2011.

Strand, SE, and G Benford, 2009. Ocean Sequestration of Crop Residue Carbon: Recycling Fossil Fuel Carbon Back to Deep Sediments. *Environ. Sci. Technol.*, **43** (4), pp 1000–1007

Vlasopolous, N, 2010. *Novacem Carbon Negative Cement*. Presentation for Society of Chemical Industry 25 November. http://novacem.com/wp-content/uploads/2010/12/20101125-Technical-update.pdf

Walker, T. (Ed.) 2010. *Massachusetts Biomass Sustainability and Carbon Policy Study: Report to the Commonwealth of Massachusetts Department of Energy Resources*. Manomet Centre for Conservation Sciences, Natural Capital Initiative Report NCI-2010-03. Brunswick, Maine.

Wang, B, AP Côté, H Furukawa, M O'Keeffe & OM Yaghi, Colossal cages in zeolitic imidazolate frameworks as selective carbon dioxide reservoirs, *Nature*, 2008, (453), 207-211.

Wannier, GE, M Herzog and D Atkinson, 2011. Geoengineering Governance Systems. *Stanford Journal of Law, Science and Policy*, May.

Woolf, D, JE Amonette , FA Street-Perrott , J Lehmann & S Joseph, 2010. Sustainable biochar to mitigate global climate change. *Nature Communications* 1:56 DOI: 10.1038/ncomms1053

Zeng, N, A King, B Zaitchik, S Wullschleger, J Gregg, S Wang, D Kirk-Davidoff, 2011. Ecological carbon sequestration via wood harvest and storage: An assessment of its practical harvest potential. *Climatic Change* (in press)