Bio-Energy with Carbon Storage (BECS): a Sequential Decision Approach to the threat of Abrupt Climate Change

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Abstract

Abrupt Climate Change (ACC - NAS, 2001) is an issue that 'haunts the climate change problem' (IPCC, 2001) but has been neglected by policy makers up to now, maybe for want of practicable measures for effective response, save for risky geo-engineering. A portfolio of Bio-Energy with Carbon Storage (BECS) technologies, yielding negative emissions energy, may be seen as benign, low risk, geo-engineering that is the key to being prepared for ACC. The nature of sequential decisions, taken in response to the evolution of currently unknown events, is discussed. The impact of such decisions on land use change is related to a specific bio-energy conversion technology. The effects of a precautionary strategy, possibly leading to eventual land use change on a large scale, is modeled, using FLAMES. Under strong assumptions appropriate to imminent ACC, pre-industrial CO_2 levels can be restored by mid-century using BECS. Addressed to ACC rather than Kyoto's implicit focus on gradual climate change, a robust strategy related to Art 3.3 of the Convention may provide the basis for rapprochement between Kyoto Parties and other Annex 1 Parties.

Introduction

Taking steps to insure against abrupt climate change (ACC - NAS, 2001) was identified by Schelling (1992) as the primary rationale for greenhouse gas mitigation. ACC was recognized in the third Assessment Report of the IPCC as an issue that 'haunts the climate change problem' (IPCC, 2001). However, ACC has been neglected by policy makers, who, without regard to the specific technological requirements of ACC insurance, have struggled to achieve consensus through negotiated commitments to generalized emissions reductions in response to the 'absent problem' of gradual climate change (Michaelson, 1998). Recent advances in technological understanding (Obersteiner et al, 2001) suggest the availability of an insurance strategy that addresses the issue in terms of policy-driven technological change, whilst offering side benefits in terms of fuel security and sustainable development. Crucial to such a strategy – and not discussed in this paper – would be improved scientific understanding of ACC to yield the capacity to recognize precursor signals of an imminent bifurcation in climate dynamics. Also not discussed in detail in this paper is an aspect of the new technological understanding that is advancing rapidly, that is technologies for carbon capture and storage (CCS), disposing of CO_2 underground and maybe in deep oceans.

Both CCS and bio-energy are technology types rather than specific technologies. CCS involves either pre or post combustion separation of CO_2 in either new plant or retrofitted, and its disposal in a variety of receptors, including secondary oil recovery, coal bed methane, exhausted hydrocarbon reservoirs, saline aquifers, and maybe deep ocean. Bio-Energy can provide energy carriers to meet final demands for both stationary and transportation needs, through a variety of technology chains involving numerous sources of biomass raw materials derived from wastes or from dedicated land used for energy plantations or for annual energy crops. Whichever is specified, the combination of a pair of technologies involving one from each type leads to an energy system with negative emissions

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characteristics, i.e. Bio-Energy with Carbon Storage technology (BECS) and – in combination with raised energy efficiency and non-fuel renewables – it leads also to the potential to return rapidly to pre-industrial CO_2 levels (Obersteiner et al, *op cit*). Negative emissions energy systems are key to responding to ACC because – taking account of rising levels on non-CO_2 greenhouse gases, for which no means exists for accelerating natural removal processes – the need may be to get to CO_2 levels below pre-industrial. This cannot be done by natural absorption, even with zero emissions energy[3]. In this context it should be noted that the 'two times CO_2' criterion much cited in the literature, is a social construct devised as a basis for model comparison and influenced by outdated ideas as to what level it is feasible to aim for: it has no scientific basis as an indicator of what the FCCC's Art 2 'non-dangerous' level is, and does not indicate a threshold for precipitating ACC. In the absence of appropriately focused new research, and given the inertia of the climate system, that obscures the eventual possibly abrupt effects of current and past emissions, climate science cannot tell us whether any excursion above the pre-industrial levels of greenhouse gases, as has occurred in the last century, does or does not significantly increase ACC risks.

Sequential decisions in relation to ACC

Abrupt climate change is here taken to be a shift in climate regime that may have only minor impacts, to which adaptation is acceptable, or that may be more serious, even catastrophic. Of the latter variety are shifts into and out of the major reallocations of surface water that characterize both ice ages and ice free periods (of which the latter have not occurred since half a million years ago, when the present ice caps formed, and the former many times during that period, with the onset of some glaciation episodes having taken no more than a few decades). Such a rapid transition is a potential feature of non-linear dynamic systems, like earth's climate system, and are generally heralded by precursor signals: for instance, when heated, a kettle 'bumps' before the transition from convective circulation to mixed phase (steam-water) turbulent boiling. The detection of such pre-cursors in relation to ACC depends upon the type of climate transition that is anticipated, but given the timescale of the shifts that are of concern, precursor detection may be expected – or at least hoped – to give several decades warning, giving the prospect, where the driver in raised CO_2 levels and perhaps in other cases, of effective response using negative emissions energy technology.

Providing research is done to enable recognition of such precursors, climate scientists might (e.g. in relation to the melting of North polar sea ice, reported to be half as thick now as half a century back) state in 2020 that an Albedo driven climate instability would be initiated with, say, 10 per cent likelihood, unless a target reduction in CO_2 levels is achieved by a target date. Supposing that 10 per cent likelihood is the political trigger for a 'Manhattan project' style climate stabilization action plan, then timely preparations could make the difference between feasibility and infeasibility. This is illustrated in the following table, where caps Yes and No [YN] relates to the situation with a robust strategy involving preparedness for large scale use of BECS, as illustrated later in this paper, and lower case yes and no [yn] relates to initial business as usual, without preparedness measures.

Table 1

Target level	500	450	400	350	300	250	200ppm*
Target Date							
2030	Yn	Yn	Yn	Yn	Nn	Nn	Nn
2050	Yy	Yy	Yn	Yn	Yn	Nn	Nn
2070	Yy	Yy	Yy	Yn	Yn	Yn	Yn

*Note CO_2 equivalents of non-CO_2 gases are expected to reach 100 ppm by the end of this century

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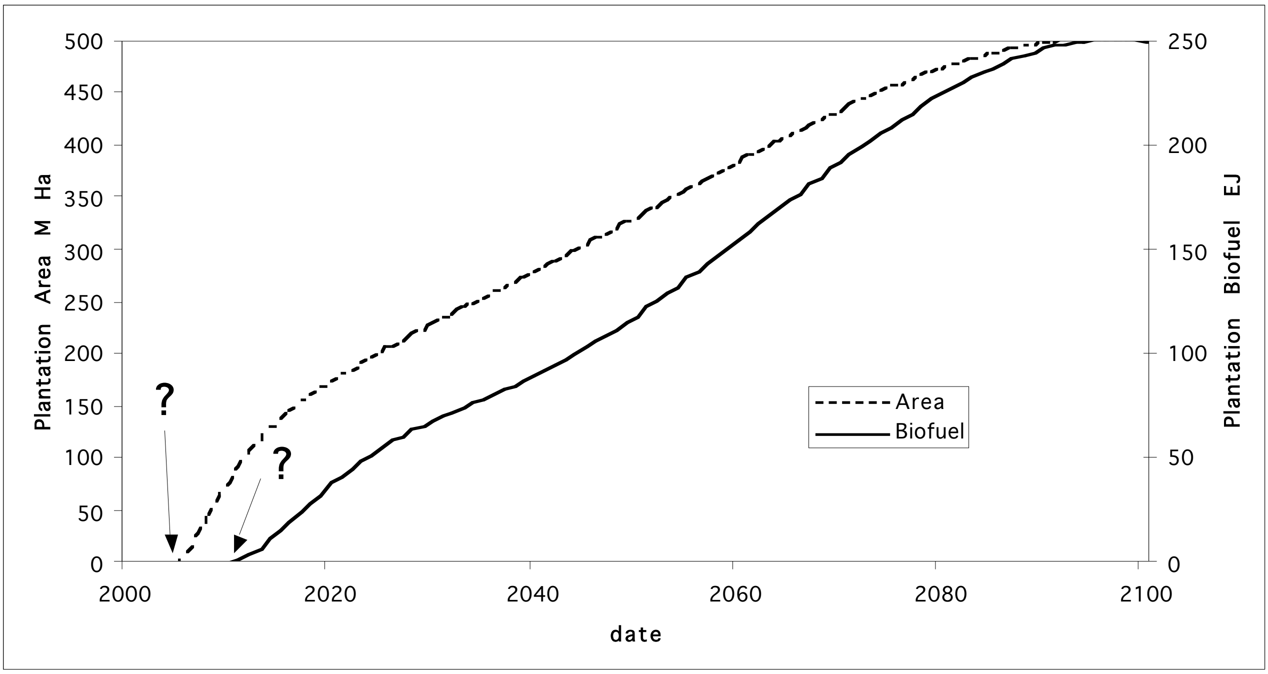
Achieving feasibility involves meeting the informational requirements for a robust strategy, i.e.:

- climate science capacity to recognize precursor signals of abrupt climate change
- development of CCS technology, and capability to link with bio energy systems

and initiating programmes that involve a long lead time, i.e.:

- a land use change program and related capacity building, potentially on a very large scale, to be prepared for bad scientific news that may reveal the need for 'Manhattan project' style carbon management

Thus a robust strategy requires a more technologically focused approach than is stimulated by Kyoto, including a more positive commitment to land use change as the basis for the major role for BECS that may be needed. It may be noted that such a programme of land use change is in any case needed for bio-energy to take the place that is envisaged for it in most non-nuclear low emissions scenarios. The threat of ACC may therefore serve to stimulate bio-energy development that is currently lagging behind these scenarios, frustrated, it would seem, by a coordination failure between landowners, as prospective biomass producers, and energy managers, as future biomass users, possibly separated by distance, time (given time to grow for plantations) and cultural barriers.



<u>Figure 1: Plantation bio-fuel (various scenarios) and needed land use change (Read, 2001).</u>

With these preparedness measures in place, BECS technology can then be envisaged in three stages of implementation: plantation establishment and growth, utilization of product for joint output of bio-energy and timber, and integration with carbon capture and storage. It should be noted that only the last stage is high cost, requiring a high price on carbon emissions, as appropriate under a Manhattan project style response to ACC threats.

These stages are taken to represent the outcomes of different sequential decisions in different places. In land rich but otherwise impoverished developing and least-developed countries, the first stage is to instigate a shift from unsustainable subsistence patterns of land use, with traditional bio-energy, to a cash-based agro-forestry rural economy with high efficiency domestic bio-energy; the second stage is to provide access to modern energy carriers in rural locations whilst yielding an import saving/liquid-bio-fuel-export led development strategy in the face of potentially rising oil prices; and the third stage, at higher cost, is in response to elevated carbon prices resulting from bad climate science news of precursor signals of imminent ACC. In developed countries, decisions on the three stages would be differently motivated – the first as a farm support policy that establishes a buffer stock of bio-mass fuel raw material in response to concerns over security of energy supplies; the second as a precautionary demonstration of the technology chains needed for a negative emissions energy system, thus driving learning by doing with BECS (learn then act – Manne and Richels, 1994); and the third, again, as a response to high carbon prices reflecting imminent ACC.

Modelling BECS

Order of magnitude

Assume 500GJ/Ha is produced over 500mHa globally by 2030. This is ~40 per cent of the usable land described by the FAO as surplus to agricultural needs in 2050 (when population is projected to peak) and a productivity less than half what is achieved commercially with best case sugar cane in Zambia and eucalypt in Brazil (Moreira, 2002). Then there is a supply of 250EJ annually which, with 30 per cent efficient conversion[4], can displace 115EJ of crude oil (assumed five eighths transportation fuel fractions) annually. Allowing for slow initial build-up, 8,000EJ of oil is displaced this century, equivalent to about 1.5 millions of millions of barrels, i.e. 1.5 times global proved reserves, or 50 times current annual consumption, and – with 12,000EJ renewable each subsequent century – plausibly sufficient to keep pace with rising demands for fuel for transportation, given continuing increases in plantation productivity, conversion efficiency and vehicle fuel economy (e.g. with fuel cells and bio-methanol as hydrogen carrier). With delivered costs of bio-energy raw material of under $2/GJ, and regardless of C_{at} considerations, there would seem to be a significant case on security of supply grounds for growing liquid fuel raw material as well as drilling for it.

Technological characterisation

Meeting the variety of demands for different final energy services with negative CO_2 emissions entails a portfolio of specific BECS technologies with the bio-energy component related to the pattern of demand and the carbon storage aspect related to local geo-physical potentials. In the current paper we are concerned with the Carbon in atmosphere (C_{at}) implications of BECS and take the characteristics of 'once through' Fischer-Tropsch joint production of liquid fuels and electricity (Larson and Jin, 1999) as typical. This conversion technology is suitable for linkage with community scaled biofuel plantations (Read, Sims and Adams, 2001) and, in combination with pre-combustion removal of CO_2 and disposal in saline aquifers (Stevens and Gale, 2002) is taken as a prototype BECS technology. Aggressive plantation development that is neglectful of local conditions is subject to fire hazard from aggrieved former land-users. Thus community scaled plantations are envisaged as the basis for socio-economically attractive sustainable rural development, to underpin a global expansion of bio-energy in line with low emissions scenarios.

Larson and Jin describe a plant that produces 493TJ liquids and 74GWh electricity annually from 1715TJ bio-mass feedstock. We assume this displaces 800TJ crude oil (five eighths transportation fuel content) and 666TJ coal in alternative 40 percent efficient generating plant, and that the fuel-oil fractions of displaced oil are replaced by renewable energy and increased end-use efficiency. This gives 90 per cent fossil carbon displacement (previous work with FLAMES has assumed 100 per cent), with 75 per cent of the carbon in the biomass raw material available for CCS treatment. In using FLAMES to model a 'Manhattan-project' response to ACC precursors, we assume below that only 30 per cent, or 40 per cent of what is available, is in fact sequestered underground.

The FLAMES model

1-region FLAMES (Read, 1998, 1999 containing a detailed model description) has been developed to illustrate the carbon dynamics of modern bio-energy involving, first, plantations that stock carbon[5] through the growth of biomass and, second its utilization, displacing future flows of high cost fossil fuels, leaving the latter *in situ* underground. FLAMES simulates the interaction of energy, timber and land markets under the impact of user-selected (policy-driven) land use change that yields joint product bio-energy and timber from plantations, with the bio-energy treated as a perfect substitute for fossil fuel as energy raw material. Two activities, short rotations mainly for bio-fuel, and long rotations mainly for timber, have been considered. Policy costs are spread across all fuel sales. C_{at} impacts are estimated as the aggregate of the stock and flow effects. Model parameters are adjusted under conditions of nil user-selected land use change to mimic standard C_{at} scenarios, and the impact of policy-driven land use changes are then simulated as perturbations on the reference scenarios.

Recently the model has been further developed (Read, Lermit and Kathirgamanathan, 2002) in multi-region form with inter-regional trade and, in the 1-region version, to illustrate the addition of a flow of CO_2 to underground under BECS technology, along with conventional carbon capture in fossil fuel systems. Most recently an optimizing version of the 1-region model has been developed to reflect the decisions of profit-maximizing landowners in relation to rotation length under model-consistent price expectations (Read and Lermit, 2003). Research is in hand to combine these advances to further illustrate the potential of BECS as a component in a robust strategy for responding to the risk of ACC. Here the model is used to illustrate the effectiveness of BECS in response to a 'Manhattan project' style policy decision adopted in 2020.

'Kyoto' Reference case and 'Be Prepared' policy case assumptions

Previous publications based on the FLAMES model have employed two reference scenarios, business as usual (b.a.u.) which mimics the IS92e or IS92f scenarios' C_{at} profile, and fossil free energy scenario (f.f.e.s.) which mimics the Tellus Institute's 1993 scenario C_{at} profile. The difference between the two mimic scenarios is achieved by changes in the parameters that relate to demand for fuel and to technological progress with fossil fuel and non-fossil energy supply (see Table 2). The 'Kyoto' reference case takes intermediate values for these parameters, on the basis that, without all Annex 1 Parties participating, and without the stimulus of scientific news of ACC pre-cursors that turns the 'absent problem' into a 'present problem', the Kyoto Protocol's second and later commitments are unlikely to achieve stabilization of greenhouse gas levels this century.

Table 2

Scenario	b.a.u.	f.f.e.s.	'Kyoto'
Parameter			
Growth of per capita fuel demand[a]	.0274	.0274-atp[b]	.0274-atp/2
Tech progress with fossil fuel supply	.035	.02[c]	.0275
Growth of fossil fuel supply emissions[d]	.015	0	.0075

a population increase averages .0076 (World Bank central projection) giving balanced supply and demand growth of 3.5 per cent and long term constant energy prices under b.a.u.

b accelerated technical progress with renewable energy and energy efficiency from year 10 to

30 with compensating later slowing to represent technical limits (see Read, 1999)

c fossil fuel research discouraged by policy, leading to more rapid cost increases

d assumes 2 % p.a. de-carbonization from fuel switching

Under the 'Be Prepared' policy case it is assumed that CCS technology is applied to fossil fuel on an initially small but expanding scale and that the land use change programme used in previous work with FLAMES is initiated from 2005. This programme (see Figure 2) has two components, first a long rotation (35 years) conventional forest rotation planted in a half sinusoidal pattern over years 1-35 of the 70 year modeled period, and felled as it reaches maturity for use partly as timber and partly as bio-energy, with the split dependant on the relative product price. And second a short rotation crop mainly for bio-energy planted on an initially small but exponentially increasing land area, to which is added half the long rotation land as it is cleared from year 35 (e.g. 2040) on.

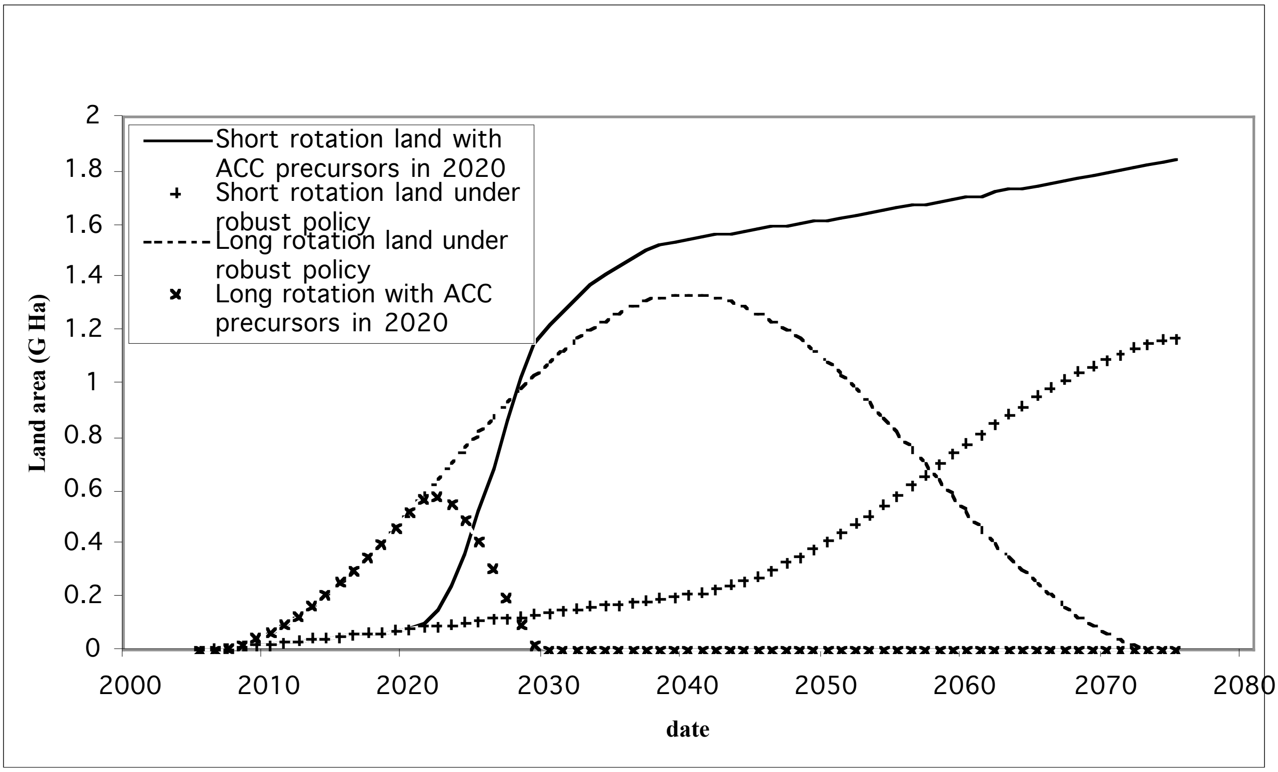


Figure 2: Land use under robust policy with and without an ACC precursor event in 2020

These activities are modeled to absorb carbon at 3tC/Ha yr, constant, for the mature forestry technology and 6tC/Ha-yr rising to 18tC/Ha-yr over the 70 year model time horizon, assuming bio-technological progress with novel energy cropping systems for the short rotation activity. If wholly used for energy, these figures correspond to ~120, 240 and 720 GJ/Ha and may seem conservative in relation to the figures for currently achieved commercial scale production noted above (Moreira, 2002). Carbon in biofuel is assumed to displace carbon in fossil fuel in the ratio 10:9, and carbon in timber is assumed to remain sequestered after felling, since the additional timber supply reduces demands to fell forests elsewhere, most likely where forest residues are left to decay.

Assumptions employed to represent a 'Manhattan project' style response to ACC precursors

It is assumed that in 2020, i.e. 15 years after a 2005 start date for the model, climate science convinces the political process of the existence of an unacceptable risk of ACC unless one of the more ambitious targets suggested in Table 1 is achieved – say 300ppm CO_2 by 2050. Then the following actions are undertaken in the decade 2020 to 2030:

1. Retrofitting of all large point source fossil and bio fuel emitters with CCS technology
2. All new large fossil and bio fuel plant fitted with CCS technology
3. A system of gathering pipelines installed to collect captured CO_2 and deliver to below ground storages
4. All long rotation policy land converted to short rotation bio fuel production (see Fig 2) with the part grown bio-mass material used wholly for biofuel
5. Shift from half to full atp (see table 2) for non-fuel renewable energy and technological progress.

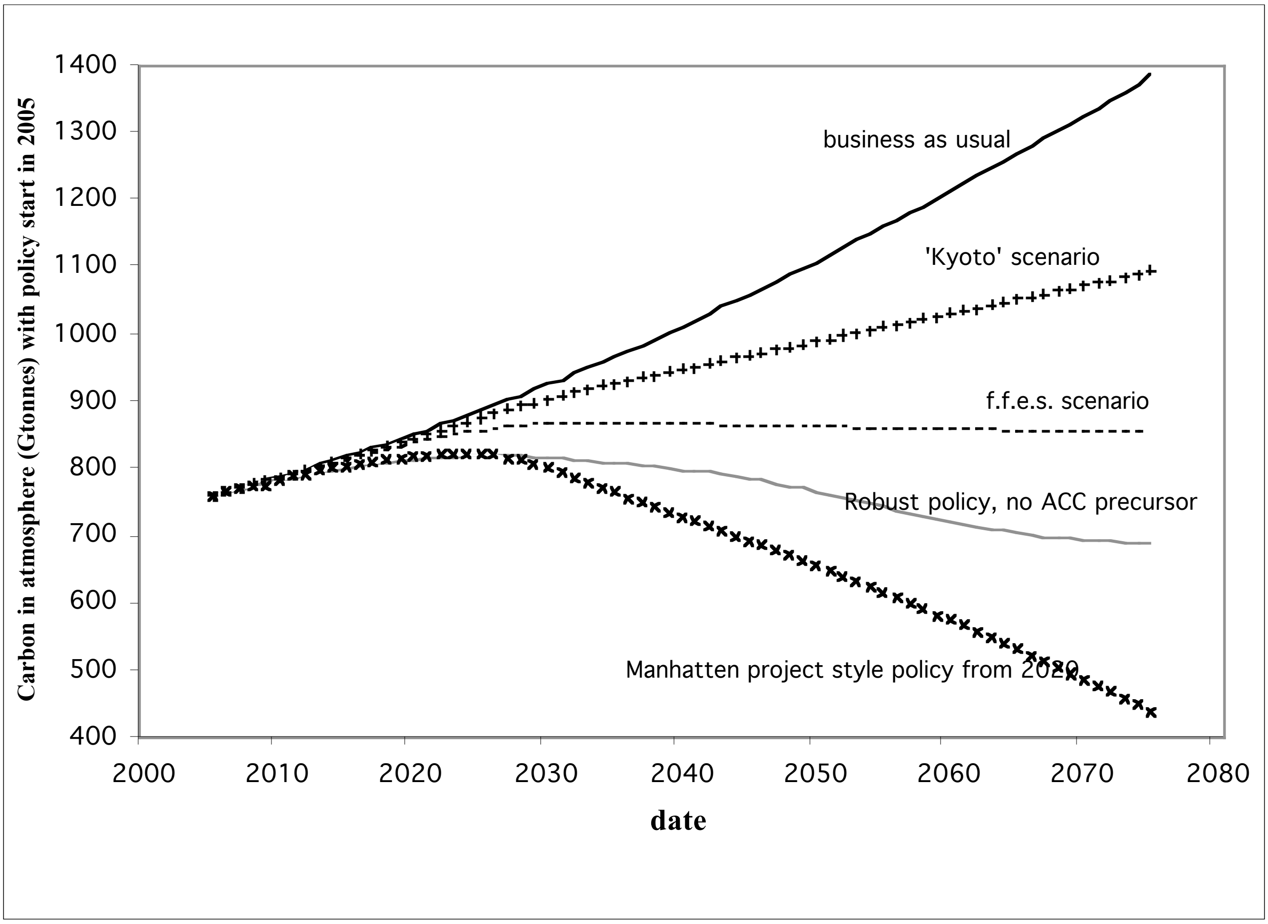


Figure 3: Carbon in atmosphere profiles under various reference scenarios and under robust policy with and without an ACC precursor event in 2020

The effect of these measures is that emissions per ton of fossil fuel fall from .025tC/GJ to .015tC/GJ and per ton of biofuel from zero to – 0.01tC/GJ, with biofuel supply rapidly dominating the market. The outcome in terms of Cat concentration is shown in Figure 3, which demonstrates that targets for CO_2 reductions that have so far seemed infeasible can be achieved with BECS technology providing that the necessary low cost measures to be prepared for bad news of ACC precursors are put in hand – 'learn then act' may be appropriate for gradual climate change, but Noah built the Ark before the rain started.

Caveats

It should be noted that, although the focus of the FLAMES model is on the additional impact of policy driven land allocations, the surprisingly low C_{at} levels noted previously (Read, 1998, IPCC, 2000) that result from large scale land allocations are only reached with the simultaneous application of the low and zero emissions energy technologies involved in the f.f.e.s. scenario: in other words, the large scale policy-driven land use allocations illustrated in this paper are a necessary but not sufficient condition for the achievement of the low C_{at} levels mentioned above. By the same token, for the below pre-industrial C_{at} levels illustrated in this paper, large scale negative emissions – achieved through widespread application of BECS technology – is a necessary but not sufficient condition.

Additionally, it should be noted that the very large land allocations that have been used in the FLAMES model are taken to be 'maximal'. No decision taken this decade can predetermine the land allocations that will be made some decades ahead, and the implication of modelling large allocations over such a long period is that the initial phases of the programme will be successful in meeting socio-economic and environmental constraints and hence stimulating – or at least not inhibiting – the on-going sequence of policy makers' and landowners' decisions that is represented by such a maximal programme. Thus such maximal allocations are a representation of the maximum amount of land that might be used for policy-desirable activities if the appropriate incentives were put in place, and sustained, to reward current landlords and land users so as to ensure they engage continuingly in such policy-desirable land use. Implicitly it is assumed that they desist from current land-profligate slash and burn subsistence, nomadic herding, forest clearance, etc., investing their rewards so as to meet their food and other land based needs better than at present, and more sustainably.

Conceptually the modelled maximal allocations are intended to represent the maximum possible policy-induced effect on the pattern of land use, constituting a change in the trend of land use and the following of a new path, starting from a near-future bifurcation in the evolution of land use policy and practice towards stewardship rather than exploitation. And, logically, no degree of policy urgency can accelerate land use allocations defined as maximal: if pushed too fast then disaffected communities will simply set fire to the plantations. This is not to claim that the land allocations modelled here are empirically maximal in this sense: if a better estimate of what is maximal can be made, then that estimate should replace the pattern modelled here. The point is that whatever can be done starting in 2010, more can be done, and ACC threats better managed, by starting in 2005.

Conclusion

Industry has been engaged in a massive geo-engineering project over the last 200 years, most intensively in the last 50, that has seen 200 billion tons of carbon moved from deep underground into the atmosphere, with additional amounts into near-surface absorbers. To reverse that outcome is equally a geo-engineering project, that, unlike most of the geo-engineering concepts that have been proposed, is benign in its side effects rather than 'expensive, unreliable, dangerous, ugly and unwise' in the view of many (Michaelson, 1998, who attempts to rebut this view in relation to a variety of geo-engineering concepts that do not include BECS). To use Michaelson's terminology of a 'Manhattan project' style approach is to recognize that this analogy is appropriate to the situation that would – or at least should – arise in the event of credible scientific demonstration of abrupt climate change precursors.

However, the earlier stages of the robust strategy that has been outlined constitute a measured and rational geo-engineering project in carbon management that aims to remedy the anthropogenic cause of climate change, rather than, as with other geo-engineering, respond to the symptoms. It should commend itself to environmentalists when their well intentioned objections[6] to 'sinks' in the Kyoto Protocol come to be seen as an over-zealous concern for the integrity of an emissions reductions target that, in reality, is a somewhat misdirected first step in a long process. Most clearly will it be seen to be misdirected when it is appreciated that it ignores the dictum that, in the long run, conflicts between environmental objectives and economic well-being have to be ameliorated by technological change (Kneese and Schultz, 1975). Then it becomes clear that a better direction for the long process is to drive the necessary transformation of energy technology directly (e.g. by renewable portfolio standards) rather than to penalize emissions, an approach that inevitably provokes resistance. Also, in focusing on limiting emissions, environmentalists have neglected the reality (see previous note 1) that even driving emissions to zero is inadequate for rapidly reversing the outcome of the last two centuries, as may be needed in the face of ACC, and that technology for carbon management that potentiates such rapid action is both necessary and potentially benign.

The benign side-effects of remedying the cause are discussed elsewhere (Read, 2002) but include:

- Stimulation of the pattern of land use change that is needed to meet the raw material demands of the bio-energy component embodied in most low emissions scenarios
- Restoration of the pre-industrial tree coverage (differently located, owing to human settlement, but restoring the former capability of forests to act as lungs to the living earth)
- Empowerment of many developing countries to initiate their own 'country-driven' projects as the building blocks of their own sustainable energy development path
- Potential export led growth for such countries as bio-based liquid fuels take an increasing role in global transportation fuel supply, stimulating global macro-economic growth
- Improved security of liquid fuel supplies, and reduced dependence on unstable mid-East oil supplies
- Improved farm support in agricultural surplus developed regions

These side benefits follow from the first two stages of the decision sequence discussed previously – at low, possibly negative, cost depending on the trend of oil prices under alternative, unsustainable, fossil fuel dependent energy sector evolution. The availability of the possibly costly third stage yields the separate and primary objective of robust policy, that is the capability to respond quickly to precursor signals of abrupt climate change. Such robustness, in relation to the threat of abrupt climate change due to warming of the unstable climate system induced by elevated levels of CO_2 (and maybe induced otherwise) involves three measures:

1. A greater focus in climate science research on characterizing possible climate instabilities and being able to recognize precursor signals of abrupt climate change
2. Continuing vigorous research into Carbon Capture and Storage technology, including linking it to bio-fuel based energy conversion systems
3. Initiation of a potentially large scale and enviro-socio-economically beneficial land use change program, as the prospective raw material supply for meeting projected bio-energy demands, and potentially linked to CCS technology to comprise a negative emissions BECS energy system.

It has also been suggested (Read, 2002) that this strategy, focusing on technology change rather than emission limitation, offers the prospect of an industry friendly approach to climate change mitigation that could provide the basis for rapprochement between those Annex 1 Parties to the UNFCCC that have ratified the Kyoto Protocol and those that have not.

References

IPCC, 2000. *Land Use, Land-use Change and Forestry,* C.U.P. (Sec. 4.5.2 and pp277-280).

IPCC, 2001. *Third Assessment Report, Contribution of Working Group III* C.U.P. (Sec. 10.1.2.4.)

Keith, D.W. and M. Ha-Duong, 2002. "Climate strategy with CO_2 capture from the air". GHGT-6, Kyoto, October; (see http://www.andrew.cmu.edu/user/dk3p/).

Kneese, A. and C. Schultz, 1975. "Pollution, Prices and Public Policy", Brookings Institution, Washington, DC

Larson, E.D. and H. Jin, 1999. "Biomass Conversion to Fischer-Tropsch Liquids: Preliminary Energy Balances" in *Proceedings of the 4th Biomass Conference of the Americas*, Oakland, CA; Elsevier Science, Oxford.

Manne, Alan S. and Richard Richels, 1992, *Buying Greenhouse Insurance - the Economic Costs of Carbon Dioxide Emissions,* MIT Press, Cambridge, MA.

Michaelson, J., 1998. "Geoengineering: a climate change Manhattan Project". Stanford Environmental Law Journal: http://www.metatronics.net/lit/geo2.html

Moreira, J.R., 2002. "Global Renewable Energy Potential". Third Workshop of Latin-American Network on Biomass – LAMNET, Brazilia, Dec. 2-5.

National Academy of Science, 2001. *Abrupt Climate Change:Inevitable Surprises*, N.A.Press, DC.

Obersteiner , M., C. Azar, P. Kauppi, M. Mollerstern, J. Moreira, S. Nilsson, P. Read, K. Riahi, B. Schlamadinger, Y. Yamagata, J.Yan, and J.-P. van Ypersele, 2001. "Managing Climate Risk", **Science 294**, (5543): 786b.

Read, 1998. "Dynamic Interaction of Short Rotation Forestry and Conventional Forestry in Meeting Demand for Bioenergy", **Biomass and Bioenergy**, **15**.

Read, P., 1999. "The Role of Biomass in Meeting Greenhouse Gas Reduction Targts: Land Allocation Modeling of Key Market Impacts". **Discussion Paper 99.16,** Department of Applied and International Economics, Massey University, Palmerston North.

Read,P., R.E.H. Sims and J.F. Adams, 2001. "Community scaled bio-energy systems", *1st International Congress on Biomass for Metal Production and Electricity Generation*, Belo Horizonte, October.

Read, P., 2002 "Precautionary climate policy and the somewhat flawed protocol: linking sinks to biofuel and the CDM to the Convention", **Climate Policy 2/1,** 89-95.

Read,P., J. Lermit and P.Kathirgamanathan, 2002. **"**Modelling Bio-Energy With Carbon Storage (BECS) in a Multi-Region Version Of Flames", GHGT-6, Kyoto, 2002 (Forthcoming Elsevier

Read,P., and J. Lermit, 2003. "Landowner decisions in the joint production of energy and timber under policy induced land use change" (in preparation for Second Annual Carbon Sequestration Conference, DC, May 5-8).

Schelling. T.C., 1992. "Some Economics of Global Warming", **AER**, 1-14.

Stevens, S. and J. Gale, 2000. "Geologic CO_2 Sequestration", **Oil and Gas Journal, 15,** May, 40-44.

3 This is because zero emissions will result in CO_2 levels converging asymptotically – eventually very slowly – on the levels in natural absorbers, in particular in the surface layers of the ocean that turn over very slowly, and which now have levels elevated above the pre-industrial due to a century of absorption from the atmosphere's raised levels. Note that, apart from BECS as a negative emissions energy technology, it has been proposed that power station sized CO_2 absorbers, one for each power station and roughly doubling the cost of power generation, could be located in non-fertile areas (Keith and Ha-Duong, 2002). If the power plant itself uses CCS, then the overall system is also a negative emissions energy system. We do not envisage this technology would have a role unless land shortages become acute.

4 This value corresponds to the prototype technology of the following section. Advances in technology may be expected to raise this figure towards 50 per cent yielding more oil displaced but less CO_2 in the 'smokestack' for capture and disposal underground.

5 The stock effect arises from the continual renewal of the plantation under commercial management, not from permanent conservation of a standing stock. This dynamic stock, maintained under commercial incentives, is, subject to good practice in maintaining a margin against fire hazard etc., as permanent as the need for bio-energy in a carbon constrained world. Given that demands for energy seem unlikely to go away, the ending of the dynamic stock will not precede the ending of concern over climate change, and the 'permanence issue' in relation to energy plantation stocks of carbon is illusory.

6 Save that is for 'deep environmentalists' who see the true causes in a perversion of human nature manifest as consumerism, and whose concern is to change the ways of society. However much sympathy one may have for that view, it seems an impractical approach to the problem of abrupt climate change, which may become acute in a decade or so as (if) climate science comes to focus on detecting its pre-cursors.