

**Holistic greenhouse gas management:
mitigating the threat of abrupt climate change in the next few decades.**

With reviewers comments and author rejoinders

P. Read and A. Parshotam***

This paper had been through the review process with *Climatic Change* three times before its third re-submission and subsequent rejection. Three accretions of additional material, incorporated in response to the comments of reviewers A to F, have resulted in this becoming a somewhat unwieldy accumulation. In conveying the comments of reviewers G and H, the editor Steve Schneider invited the corresponding author, Peter Read, to provide an editorial essay, now forthcoming, entitled "*Biosphere Management of Carbon Stocks: Addressing the threat of abrupt climate change in the next few decades*". That essay, and a paper in the Proceedings of the 30th Conference of the International Association of Energy Economists entitled "*Policy Instruments for a Sustainable Energy Future*" leave a residual content from this Working Paper that will, we hope before long, be redrafted and submitted for publication in a peer-reviewed journal. Meantime this Working Paper is available on line for readers to follow the calculations (mainly in the Appendix) which lead to the diagrams from this paper that are reproduced in the two papers mentioned above. The division of labour in this paper is that A.P. has been responsible for using the Bern model to calculate the projections of the level of CO₂ in atmosphere result from the emissions path detailed in Table 2. As the comments from reviewers G and H relate entirely to the contribution of P.R., responsibility for the rejoinders published here is his alone.

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**Institute of Fundamental Sciences, Massey University, New Zealand. We wish to thank several anonymous referees for help in clarifying numerous obscurities in three earlier versions of this article.

Holistic greenhouse gas management: mitigating the threat of abrupt climate change in the next few decades.

P. Read and A. Parshotam

“Practical men, who believe themselves to be quite exempt from any intellectual influences, are usually the slaves of some defunct economist.” (J.M. Keynes).

Abstract

The intellectual origins of the Kyoto emissions cap are traced and a potentially alternative holistic greenhouse gas management strategy, addressed to the threat of abrupt climate change in the next few decades, is described. Its first stage is the growth of a large-scale, global bio-energy market involving world trade in bio-fuels, and of a strategic reserve stock of biomass raw material in new plantation forests. Later stages, more costly – as needs may be in response to possible future precursors of imminent abrupt climate change – would involve linking CO₂ capture and sequestration to bio-energy, yielding a negative emissions energy system. Illustrative calculations point to the feasibility of a return to pre-industrial CO₂ levels before mid-century. This possibility result is subject to caveats, but, *prima facie*, the first stage can provide several environmental and socio-economic side-benefits while yielding a positive financial return if oil prices remain above 35\$/bbl. The ‘vision’ is that the polluter pays principle can be turned to energy sector investments in widespread land improvements that secure large scale biomass raw material supplies and offer some prospect of mitigating abrupt climate change should it become imminent.

Introduction

Policy to limit greenhouse gas levels has been driven by a tradition in economic theory initiated by Pigou [1] that puts a price on emissions (sic) that otherwise would ‘result in excessive demands on the assimilative capacity of the environment’ [2]. This can be achieved either by a pollution tax or, in a more recent development [3] by an emissions permit scheme that limits total emissions and, on the basis of the price-quantity equivalence [4], drives the price of polluting goods to the desired level. This provides the theoretic basis for the Kyoto Protocol’s emissions cap, to which the majority of developed country Parties, listed in its Annex B, have committed themselves. Since the principal source of anthropogenic greenhouse gas emissions is the burning of fossil fuels, Kyoto’s implementation has emphasized domestic action to reduce energy sector emissions.

This focus on reducing anthropogenic emissions, mainly from the energy sector, leaves a yawning gap between the responses perceived as politically feasible and perceptions of dangerous and/or abrupt climate change¹ [5,6]. Emissions reductions merely avoid putting more CO₂ into the atmosphere, thus relying on natural absorption to lower the CO₂ level. That entails a slow process governed by the rates of transfer from proximate absorbers to deep ocean and other very long term sinks. However, given the uncertainties that exist, the UNFCCC Article 2 ultimate objective of achieving a safe level of greenhouse gases cannot yet be quantified. It may require a return to pre-industrial levels. Since non-linear dynamic climate processes may be irreversible if continued beyond currently unknown thresholds, it may have a time-frame that is infeasible under a Kyoto-style emissions cap. Thus, in the face of imminent abrupt climate change at some future point in time, it may

¹ Hereafter we use the term ‘abrupt climate change’ to mean either abrupt climate change, as defined in the NAS report, or sustained rapid climate change, as implied by the upper end of the range in the IPCC’s Special Report on Emissions Scenarios [7]. [\[see page 16 for a possible extension to this footnote, if needed\]](#)

be necessary to actively fix atmospheric CO₂ and stock it elsewhere, as there is no other way of achieving low levels of atmospheric greenhouse gases within a specific timeframe.

Research presented to an expert workshop² [8] addressed the policy implications of potential abrupt climate change and – along with some additional research – led to the development of the holistic strategy of this article. Called ‘potentially alternative’ in our abstract, this is in the sense that, as shown in the illustrative calculations of this paper and within its half century time horizon, this strategy could fully displace the cap and trade approach of the Kyoto Protocol. In terms of Socolow’s “wedges” [9] the holistic strategy delivers a sufficient number of standard 1GtC/yr wedges, *prima facie* at low or negative cost, to make Pigovian emissions reduction strategies redundant. However, we enter several caveats later in this paper that suggest it would be folly to abandon the Kyoto approach. Furthermore there are obvious institutional and political barriers against doing so in the near or medium term.

Less controversial is to treat the holistic strategy as complementary to the Protocol, hanging from Article 3.3 of the Convention and dealing, as it is designed to do, with the threat of abrupt climate change. This would leave the Protocol, hanging from Article 4.2(d) through the Berlin Mandate, to address the gradual climate change projected by most large-scale climate models. It may be noted that the strategy is also complementary in the sense that it facilitates more ambitious commitments under the Protocol, both to the extent projects driven by the holistic strategy meet the criteria for JI and for the CDM under Articles 6 and 12 of the Protocol and because other activity under the strategy lowers the baseline below ‘business as usual’. Also, if implemented by an appropriate domestic policy instrument, the strategy can serve to reduce ‘leakage’ from the Kyoto emissions cap, thus enhancing its environmental integrity [10].

The expert workshop’s output was summarised for the Stabilisation2005 Symposium and a related need for further research outlined [11]. The workshop envisaged cost effective precautionary action under Article 3.3 of the Convention (without delay on account of the lack of full scientific certainty indicated by the need for that research). The workshop’s conclusion was [12] that “policymakers should be urged to stimulate the growth of a global bio-energy market, with world trade (mainly ‘South-North’ trade) in liquid bio-fuels such as ethanol and synthetic (e.g. Fischer Tropsch) bio-diesel”. The scientific basis for that conclusion (see our section below on Negative emissions systems) is that only photosynthesis actively removes CO₂ from the atmosphere, and only the use of produced biomass as fuel can make commercial use of it on a sufficient scale to be (hopefully) effective in response to imminent abrupt climate change.

It is not the aim of this article to promote that conclusion, of which the numerous side-benefits are adduced elsewhere ([11] – see especially Section 39.2, pp 374-375). But we note that its implementation would be within the current policy discourse focused on the energy sector, while opening the way to an eventual shift to the holistic strategy. Subject to a number of caveats, we find that the holistic strategy could achieve near term stabilisation of greenhouse gas levels below 400 ppm, with a return to pre-industrial levels on a decadal (e.g. by 2040) rather than centennial timescale, a capability that may (or may not) be adequate in the event of imminent abrupt climate change.

The holistic strategy

The holistic strategy aims to address uncertainty as regards the ultimate objective of the Rio Convention by taking initial low cost precautionary measures. These are designed to

² Paris, October 2004: for forthcoming peer reviewed papers visit www.acstrategy.org/simiti

enable medium-term (few decade, if needed) control of atmospheric CO₂ levels through subsequent, possibly costly, further measures. These initial precautionary measures are designed to enable the subsequent measures to be effective in the event that partial or complete resolution of the uncertainty points to the need for much quicker reductions in greenhouse gas levels than have so far been regarded as practicable.

These initial measures involve interventions in the full range of processes, largely biotic processes, by which greenhouse gases enter and leave the atmosphere. This is without the emphasis on energy sector emissions that has followed from regarding such emissions as pollution within the Pigovian tradition of environmental economic theory. The rationale is that greenhouse gas management is not analogous to the archetypical Pigovian problem of inhibiting the flow of sewage into a river to the point where the marginal cost of sewage reductions is equal to the marginal benefit from avoided damage, say by reduced fish-kill. Instead, the greenhouse gas problem is analogous to an additional, anthropogenic, flow of pure water into a dammed up lake, which raises its level to a point that threatens to flood surrounding land (gradual climate change) or burst the dam (abrupt climate change). With that problem, since the anthropogenic flow is indistinguishable from the natural flows once they are mixed in the lake, it is sensible to look at all the flows of water into the lake, and also at how water gets out of the lake.

The terrestrial biosphere absorbs and emits over twenty times as much CO₂ as the energy sector emits, and fixes about six times as much in the complex carbohydrates that constitute biomass. But the Pigovian theory's focus on emissions led to an initial neglect of CO₂ fixation in 'sinks' so that, under the Protocol, priority is in practice given to reducing energy sector emissions. Increases in absorption into sinks (potentially much greater, but limited to afforestation and reforestation during the Kyoto first commitment period, 2008-2012) attract a lower price than reductions in energy sector emissions [13].

This focus on domestic action in the highly capital-intensive energy sectors of industrialised countries is trebly cost enhancing, through the great difficulty of rapid change in a sector with very long lived assets, through its neglect of ~95 per cent of CO₂ flows into and out of the atmosphere, and through its focus on the small proportion of the global land surface occupied by those countries. Furthermore, the Protocol overlooks the potential for environmental and socio-economic benefit that may come from well-conceived investment in under-capitalised, and in many places degraded, land. Accordingly, it fails to capture the need to link climate change mitigation with sustainable development that emerged in the Millennium Development Goals [14]

Definition

The holistic strategy aims to control greenhouse gas levels by utilising the full range of technologies available for modifying the exchange of carbon dioxide (and other terrestrial greenhouse gas flows such as methane) between the atmosphere and the terrestrial biosphere, in order to address the question 'what needs to be done to be better prepared for worsening news – indicative of imminent abrupt climate change – from the climate science community?'

For instance, with ecosystem success dependant on resilience rather than efficiency, there is scope to enhance net primary productivity, and hence natural absorption, by simple investments such as, *inter alia*, fencing to protect seedlings from browsing animals, and organic soil improvement, e.g. from bio-char³ conditioning [15,16]. Accordingly, we have conducted a preliminary investigation of this holistic strategy that does not prioritise domestic action in industrialised countries' energy sectors, and is not constrained by

³ Powdered product from pyrolysis of biomass: 'charcoal' dust – see note 5 below.

consensus on ‘two times CO₂’ or ‘not more than 0.2 degrees Celsius per decade’. Collaterally, the strategy is responsive to the issues of unsustainable depletion of natural forests and biodiversity conservation, along with sustainable timber supply for the forest product industries and soil improvement in lieu of traditional soil degradation in the agricultural sector.

Negative emissions systems

Land using activities like forestry and agriculture are – from the perspective of climate change and the carbon cycle – scientifically different from zero-emissions systems, such as most renewable energy technologies. This is because, in their initial stage, i.e. the production of biomass raw material – whether for use as fuel or otherwise – they actively remove CO₂ from the atmosphere through the process of photosynthesis.

Zero-emissions systems simply avoid adding to the stock that is already there. As a consequence, even the universal adoption of those systems could achieve no more than asymptotic progress towards the level of CO₂ in the proximate sinks into which atmospheric CO₂ empties. These are the biosphere, and the ocean surface layers (where it forms carbonic acid) which, in turn, transfer into the deeper ocean. It may be noted that the biosphere is liable to become a net emitter under temperature stresses foreseeable with business-as-usual emissions scenarios [17] and that carbonic acid is already at a concentration that is threatening the food chains of ocean eco-systems [18].

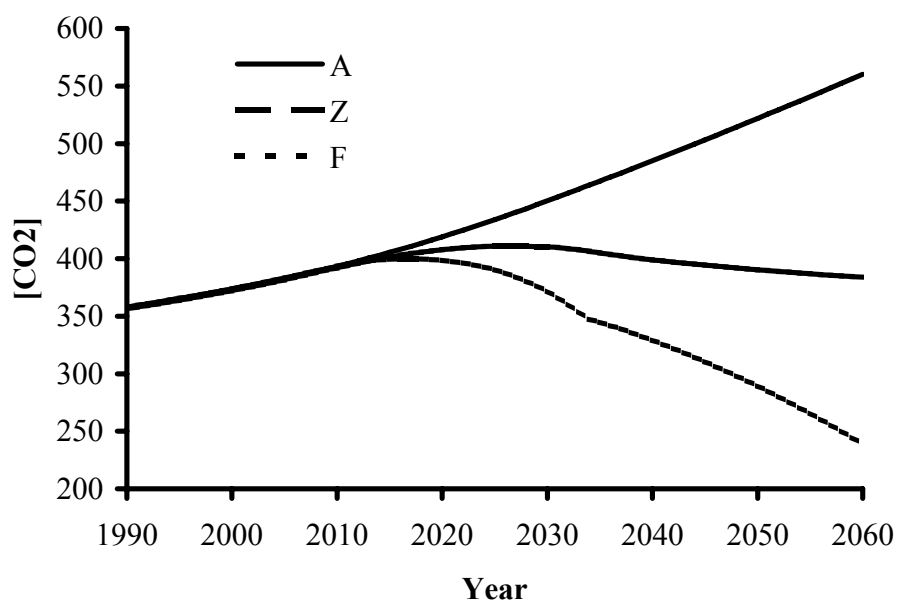
During the late 1990’s (after the start of the negotiation that led to the Kyoto Protocol) the concept of CO₂ capture, compression and sequestration (CCS) [19] came to the fore. This is a technology for turning the use of coal at large point sources of CO₂ emissions, typically thermal power stations, into a zero emissions energy system (or near-zero if the capture technology is less than 100 per cent efficient). Shortly afterwards the notion of linking Bio-Energy to CO₂ Sequestration (BECS) was announced⁴ [20].

BECS constitutes a negative emissions energy system in which the more bioenergy products are consumed, the less CO₂ remains in the atmosphere. Using revenues from bioenergy product sales to pay both for the acquisition and processing of biomass raw material and for the safe disposal of CO₂ waste product, BECS actively pumps CO₂ out of the atmosphere. Done on a sufficiently large scale, this can result in a reduction in atmospheric CO₂ levels below the asymptotic path mentioned above [21]. It may be noted that a negative emissions energy system is a sub-set of the negative emissions systems that yield economic benefits. These include quasi-permanent storage of carbon in timber artefacts or in soil, e.g. through bio-char soil amendment. In turn, a larger set includes systems that yield no economic benefit such as ‘pickling logs’ and the direct capture of CO₂ from the air and its storage underground [22].

The distinction between zero emissions systems and negative emissions systems is illustrated in Figure 1. Line Z assumes 100 per cent replacement of existing energy systems and other sources of anthropogenic emissions with zero emissions systems in a linear trend between 2011 and 2035. To provide comparison, that trend parallels the 25 year linear pattern of adoption of the set of negative emissions technologies discussed later in this article, and aggregated in line F, as detailed in the legend for Figure 2

⁴ Obersteiner’s e-mail 7.ix.2001 offers intellectual priority in the BECS concept to P. Read.

Figure 1



Comparison of zero emission systems and negative emissions systems in mitigating the level of CO₂ (in ppm) in the atmosphere

Legend

- A SRES-A2
- Z SRES-A2 with a transition to zero emissions technologies between 2011 and 2035
- F SRES-A2 with a transition to negative emissions technologies over the same period (for details see discussion of Figure 2)

Method

As illustration, we have calculated the impact on net CO₂ emissions of three land improvement technologies deployed over the 50 years 2010 to 2060. These impacts have been applied to the SRES A2 emissions scenario as perturbations on the projected emissions, and the resulting net emissions transformed to the profile of CO₂ levels over the period, using an adaptation of the Bern model [23]. The purpose of this method is to establish a possibility result, reported below as our key result.

Technologies

The three technologies considered, each of which yields economically valuable outputs in addition to carbon benefits, are:

A Co-production of timber and bio-energy [fermentation of cellulosic fractions of woody wastes plus power generation from ligneous residues or pyrolysis to bio-diesel with bio-char co-product] from new plantations on mostly non-arable land in temperate and tropical regions, leaving bio-diverse natural forest less disturbed by timber extraction [26]

B Co-production of animal feed and bio-energy from grass [extraction of protein, fermentation of cellulosic fractions plus power generation from ligneous residues] on existing or potential arable land in temperate regions [27]

C Co-production of sugar and biomass for bio-energy [fermentation of cane sugar syrup plus power generation from bagasse residues] on potential arable land in tropical regions [28]

Calculations of the carbon cycle impacts and energy outputs of these activities are in the Appendix, where we assume an initial four-year political decision and capacity building process. We then assume linear growth of the areas that benefit from these land use

improvements from 2011 to 2035, followed by 1.5 per cent per annum technological progress from 2035 to 2060, but with no further increase in the areas of land involved. In the case of long rotation forestry, where new plantations, as modelled, do not mature until 2035, it is assumed that a growing flow of biomass for bio-energy comes from existing forestry operations, as sustainable forestry practice is increasingly implemented, and from plantations in tropical regions that in practice mature more rapidly. We also assume that the new plantations enable the tailing off of tropical deforestation from 2023 onwards.

Land availability

Potential rain-fed arable land, net of protected land and urban settlement, has been estimated by Moreira [28] based on IPCC and FAO studies [29,30], viz:

| | Gha | %used | available (Gha) |
|----------------------------|------|-------|---|
| Sub Saharan Africa | 1.05 | 15 | .893 |
| North Africa and Near East | .04 | 100 | |
| North Asia Urals Eastwards | .28 | 64 | .101 |
| Asia and Pacific | .74 | 64 | .266 |
| South and Central America | .98 | 15 | .833 |
| North America | .43 | 54 | .158 |
| Europe | .32 | 63 | .118 |
| World | 3.82 | 38 | 2.38 of which 1.99 tropical .38 temperate |

These estimates may be compared with the total areas of natural biomes, totalling to the aggregate global land mass [30]

| | |
|--------------------------|-------------------------------------|
| Tropical forests | 1.76 |
| Temperate forests | 1.04 |
| Boreal forests | 1.37 |
| Tropical savannas | 2.25 |
| Temperate grasslands | 1.25 |
| Deserts and semi-deserts | 4.55 |
| Tundra | .95 |
| Wetlands | .35 |
| Croplands | 1.60 (cf above: 3.82 – 2.38 = 1.44) |

It appears that the 2.38Gha of unused potential arable land lies mainly in 3.5Gha of tropical savannahs and temperate grasslands, in areas of sparse open woodland that may have been categorised as forests, and in some tropical forests prior to the termination of tropical deforestation [29]. Apart from the question of arable quality, atlas inspection suggests 1.6Gha of rain-fed land in South America and South of the Sahel, excluding the Andes, the Amazon and Congo basins and the arid South-West of Africa. Europe West of the Urals and the Eastern part of the USA and Canada total around 1.1Gha of such land. Asia and Oceania also provide a very large land resource, but too broken up by regions of dense population and steep-land or mountains to provide a simple, atlas based, appraisal.

Noting that forestry, and also possibly intensive grass production, do not require arable quality land, we assume

- 1Gha (in very many small and medium size new plantations with substantial tree species variation), located mainly on non-arable land (logged over land, degraded and recovering forest land, savannah, and so on). This is in both tropical and temperate regions, but mainly tropical, and we use appropriate productivity. We arbitrarily assume that the product is used half for lumber and, of the residue, half

for ‘terra preta’ biochar⁵ plus bio-diesel from pyrolysis fluids and half for electricity plus ethanol or Fischer-Tropsch liquids [31].

- 1/5 of surplus tropic arable land, 0.43Gha, is devoted to sugar cane for energy – mainly ethanol.
- All surplus temperate arable land plus an equal area of currently used land ($0.36+0.36 = 0.72$ Gha) is employed in the co-production of food and bio-energy based on cropping perennial switch-grass in North America and similar crops elsewhere, native to other temperate regions. Reduced areas of temperate farmland are assumed to result from continuing improvements in agricultural productivity [30] and from some transfer of production to developing countries under continuing WTO pressure on agricultural protectionism.

Carbon flows

We neglect

- increased in-soil labile carbon resulting from the growth of new forest plantations and from a change from arable farming to the cropping of perennial grasses;
- increases in both in-soil and above-ground labile carbon stocks resulting from improved fertility due to soil improvement;
- use of biomass residues from areas outside those mentioned above (crop residues, forest residues, agricultural residues and municipal solid waste) variously estimated at 30 – 90 EJ/yr in medium term and 40 – 240 EJ by mid-century [28];
- carbon stocked in timber artefacts, with increased timber supplies driving substitution for energy intensive steel, aluminium and concrete;
- increasing use of CCS technology in the declining fossil fuel sector, beyond that included in the baseline SRES-A2 scenario.

In our estimates, we illustrate the tailing off of tropical deforestation from 2023, by when alternative supplies of timber and sustainable income generation are assumed to begin to become available. We also illustrate the possibility that decisions may be taken to ramp up low-cost sequestration of fermentation CO₂ from 2020 and, with increasing concern over potential abrupt climate change, high cost flue gas CCS from 2025. We assume flue gas CCS is 80 per cent effective in temperate regions where the prospectivity of saline aquifers is high, and 60 per cent in tropical regions, where prospectivity is lower [33]. Of course, all these assumptions are illustrative and do not represent any forecast of the outcome from possible sequential policy decisions

Cost aspects

While it is beyond the scope of this article to present a cost breakdown, or a cash flow analysis that separates investments from running costs, we may, as regards the viability of the holistic strategy, note the position in Brazil, where unsubsidised ethanol from sugar cane fermentation (the third of our three illustrative technologies) is widely available. Since the vehicle fleet there has a substantial number of flexi-fuel vehicles that can accept pure ethanol or pure gasoline, or any mixture of the two, ethanol is in direct competition with gasoline. When oil prices are above \$35 per barrel, as currently, it causes motorists to switch over to sugar cane based ethanol. It may be noted also that a similar oil price is the projected break-even for the switch-grass technology, discussed above and in the Appendix, whilst an early result from the modelling of co-produced high value timber and

⁵ Highly fertile *terra preta*, Portuguese for ‘black earth’, is found in localised areas in the otherwise low fertility yellow soils of the Amazon basin and have been shown by landscape archaeologists to be the legacy of pre-Columbian agrarian civilizations (the origin of the *El Dorado* myth). They contain long-lived biochar from by-gone kitchenfires, with the biochar acting as a nutrient-retaining substrate for the fungal and microbial activity essential to healthy root activity [15,16].

woody biomass as fuel raw material [24] was that, with reasonable assumptions on technological progress, the process required zero subsidy after an initial phase.

Also, one outcome of the holistic strategy is the supply of large quantities of biomass. Large-scale change to biomass as raw material supply for the energy sector may seem to belie the use of ‘holistic’, to contrast this strategy from other strategies that focus simply on reducing energy sector emissions. However, the holistic strategy does not reduce energy sector emissions since carbon fuel continues to be burned. This provides a second reason why we have characterised the initial stage of the strategy as low cost since other strategies impose more radical change on the energy sector.

With the holistic strategy, we can continue to rely on the stored chemical energy in fuels, as we have since the dawn of civilization saw the start of cooking and metal-working, with successive transitions from wood to coal to oil to gas. And soon to modern bioenergy – ‘defossilizing’ rather than decarbonising – is a transition within that tradition that is far less costly than the attempt to suppress carbon emissions through reliance on intermittent and – save for hydro-power – largely un-storable zero emissions ambient energy supplies. Thus very little infra-structural expenditure is required and very little of the existing asset structure becomes prematurely obsolete. For instance, existing systems for distributing liquid fuels and electricity do not need to be replaced by hydrogen distribution or transmission from remote windy locations, possibly offshore. Also, by postponing the high cost aspect of BECS, i.e. CCS, to the second stage, the separated off initial stage of the strategy, i.e. bio-energy, is relatively low cost (likely negative cost, as discussed above) compared with studies that treat BECS as a single option [34].

Additionally, as discussed in our ‘results’ section below, a large proportion of the stocking of carbon taken from the atmosphere is, in the initial stage, not achieved through costly CCS. Rather is it achieved through the creation of a strategic reserve stock of biomass raw material in the form of additional standing timber in new plantations, with plantation forestry a very low cost option for reducing atmospheric carbon levels.

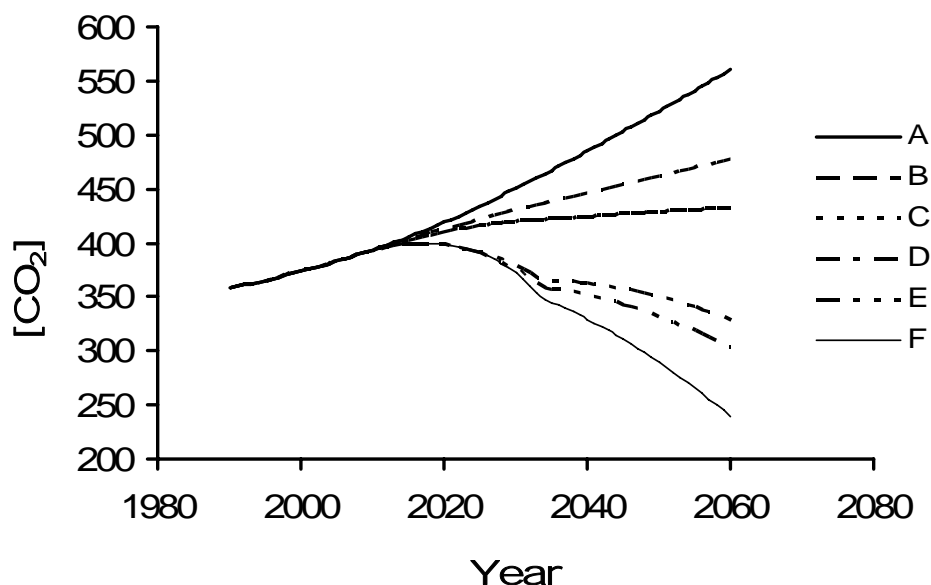
Whether or not the holistic strategy has negative, zero, or positive costs depends upon the current and future price trajectories of oil, timber, food and other co-produced outputs. If current oil prices around \$70/bbl are sustained into the longer term, the points noted above suggest that the initial stage of the two-stage strategy has negative cost. It may also be noted that, in the broad competition between incumbent and prospective new-entrant technologies – e.g. fossil fuel and renewable technologies – the latter can be ‘locked out’ by continued adoptions of the incumbent technologies that frustrate the potential cost reductions that would come with adoptions of the new entrants [25]. Thus, in implementing policy that allows or prevents that situation, relative costs are, in part at least, determined by policy rather than being a determinant of policy.

Results

The effects on the level of CO₂ in the atmosphere (in parts per million) in relation to the SRES A2 scenario, of deploying the three value-adding land use improvement technologies, and the additional effects of deploying the cost enhancing CCS technologies, are illustrated in figure 2. Leading data from the estimates detailed in the Appendix, and spreadsheet estimations⁶ of the carbon cycle impacts aggregated to 2035 and 2060, are summarised in table 1 below. The year-by-year carbon flows are summarised in table 2, in the Appendix.

⁶ Available from the corresponding author at p.read@massey.ac.nz

Figure 2



Bio-Energy with Carbon Storage (BECS) – impacts on level of CO₂ in atmosphere

Legend

- A SRES-A2
- B SRES-A2 with sugar cane land use change activity [lower case refers to figure 3 with land areas halved]
- C SRES-A2 with sugar cane and switch-grass land use change activities
- D SRES-A2 with sugar cane, switch-grass and forestry land use change activities
- E SRES-A2 with three land use change activities and low cost capture and storage (CCS) of fermentation CO₂
- F SRES-A2 with three land use change activities CCS of fermentation and flue gas CO₂

The key result of the research reported here and depicted in Figure 2, is that, through the holistic strategy, and with implementation of its second, possibly high cost, stage it is possible to achieve a return to pre-industrial levels of atmospheric CO₂ within a few decades. It is believed that no other scenario has been presented that suggests this is possible [35]. This result is subject to the caveats advanced in the discussion section below, particularly as regards soil disturbance.

Examination of Figure 2 reveals that neither the sugar cane nor the switch-grass technology result in a reduction in greenhouse gas levels, though they substantially slow its rate of growth. This is because both of them, as modelled, are zero emissions energy technologies with (in the context of our introductory remark, that “it may be necessary to actively fix atmospheric CO₂ and stock it elsewhere”) no element of ‘stocking carbon (or CO₂) elsewhere’ involved. For each of these the stocking elsewhere comes later, as a result of CCS applied under the second stage of the holistic strategy, and arises mainly after 2035 as illustrated with lines E and F. Before 2035, the main out-of-atmosphere stock arises from the creation of a strategic reserve of biomass raw material through the development of 1bHa of new forest plantations (an area equal to about half the forest area lost since the beginning of industrialisation). The size of this effect pre-2035 (~80 per cent of the distance between lines C and D) illustrates the importance of devising policies that not only influence flows of carbon (and CO₂) but also promote the creation of stocks of carbon elsewhere than in the atmosphere.

It may also be noted that the maximum carbon reduction in Table 1, 1120Gt, corresponds to ~528ppm CO₂ in atmosphere, compared with ~300ppm reduction in Figure 2. This suggests that ~43 per cent of the aggregate increase in net carbon flows from the

atmosphere would have been out-gassed from proximate absorbers (such as ocean surface layers, thereby reducing ocean acidification).

Table 1: Summary of key illustrative data

| Outputs | linear increase to2035 | then 1.5% tech progress till 2060 |
|---|------------------------|-----------------------------------|
| Forestry | | |
| Lumber | 10Gt/yr | 14.5Gt/yr |
| C content of Biochar | 1.2Gt/yr | 1.74Gt/yr |
| Biodiesel | 20EJ/yr | 29EJ/yr |
| Electricity | 23.1EJ/yr | 33.5EJ/yr |
| Ethanol | 31.4EJ/yr | 45.6EJ/yr |
| Stock of C in bio-char soil improvement | 15Gt | 52Gt |
| Stock of C in standing plantation | 120Gt | 183Gt |
| Stock of C in avoided deforestation | 8Gt | 38Gt |
| Stock of C from CO ₂ of fermentation | 2.4Gt | 11.5Gt |
| Stock of C from flue gas CCS | 9Gt | 60Gt |
| Sugar Cane | | |
| Ethanol | 115EJ/yr | 167EJ/yr |
| Electricity | 85EJ/yr | 123EJ/yr |
| Stock of C from CO ₂ of fermentation | 7.2Gt | 34.7Gt |
| Stock of C from flue gas CCS | 9.2Gt | 60.5Gt |
| Switchgrass | | |
| Ethanol | 113EJ/yr | 163EJ/yr |
| Electricity(net) | 4.8EJ/yr | 7.0EJ/yr |
| Stock of C from CO ₂ of fermentation | 8.6Gt | 41.6Gt |
| Stock of C from flue gas CCS | 13.8Gt | 90Gt |
| Aggregate energy supplies | | |
| Ethanol | 259EJ/yr | 376EJ/yr |
| Biodiesel | 20 EJ/yr | 29EJ/yr |
| Electricity | 113 EJ/yr | 164 EJ/yr |
| Carbon cycle impacts | | |
| C in oil displaced by bio-fuels | 8.38Gt/yr | 12.2Gt/yr |
| \C in coal displaced by bio-electricity | 4.23Gt/yr | 6.14Gt/yr |
| Stock of C left as in situ fossil fuel | 164Gt | 549Gt |
| Stock of C in standing plantation | 120Gt | 183Gt |
| Stock of C in avoided deforestation | 8Gt | 38Gt |
| Stock of C in bio-char soil improvement | 15Gt | 52Gt |
| Stock of C from CO ₂ of fermentation | 18Gt | 88Gt |
| Stock of C from flue gas CCS | <u>32Gt</u> | <u>210Gt</u> |
| Total C reduction in atmosphere and proximate sinks (e.g. ocean surface layers) <u>with</u> | 357Gt | 1120Gt |
| and <u>without</u> flue gas CCS | 325Gt | 910Gt |

Discussion

The choice of technologies used for this illustration is a small set, one applicable in temperate latitudes, one in the tropics, and one climatically non-specific, for which data is to hand. Many other crops and technologies are available for biomass production and its conversion to modern commercial energy products. Some crops are tolerant to poor soils and climatic variability and others are less so, e.g. cassava, jatropha, oil palm, beets, sweet sorghum [36,37]. Some technologies, like gasification, flash pyrolysis, and Fischer-Tropsch conversion, involve large scale and sophisticated management, while others are

more suited to localised deployment in emerging rural economies, e.g. oil extraction, traditional pyrolysis ('charcoal' making), anaerobic digestion, composting, etc. [38].

Some are available for immediate deployment while others are dependent on foreseeable technological advances [38,39]. Thus there is no technological impediment to an early start to implementing the first stage of the holistic strategy, i.e. the process of developing a large-scale global market in biofuels. However, research and development may be expected to lead to an expanded production possibility frontier, lowered costs and to opportunities for local optimisation as entrepreneurs' knowledge of the potential of land improvement technologies expands. In support of this process, a public good research programme could provide market guidance through delineating a globally optimum – or at least a negotiable and preferred – scenario.

Each of these technologies may – though at a cost and with no further economically valuable outputs – be linked to CO₂ capture and storage (CCS – first of fermentation CO₂ and, second on account of greater cost, of pre-combustion⁷ and/or flue-gas CO₂) to yield negative emissions energy systems [20,21]. Those involving pyrolysis can, with some reduction in energy outputs, alternatively be linked to 'terra preta' soil improvement [15,16] storing long-lived bio-char in the land and potentially yielding economic returns through increased crop productivity.

A vision⁸

Contrary to the priority given so far by the policy community to emissions reductions through 'domestic action' in the energy sector, the contention here is that a strategy that focuses on managing the whole carbon cycle through sustainable land use improvement on a worldwide basis should, *ex ante*, have equal priority in policy-making. *Ex post*, consideration of beneficial environmental and socio-economic developmental externalities, and of concerns regarding potential abrupt climate change, suggests that the technology types involved should have priority over deploying zero-emissions technologies.

Concerns that there is a shortage of land neglect the reality that the majority of the world's potential arable land is unused [28, 29]. *Prima facie*, there is not a shortage of land but of the investment in land that can raise soil net primary productivity and prospectively meet all global demands for food, fibre and fuel, along with the economic aspirations of many rural peoples. Subject to land use controls to shape the pattern of land use improvement, there is, under the holistic strategy, and again *prima facie*, enough land left over from productive uses to provide the conservation areas and migration routes that are needed to sustain remaining global bio-diversity.

Funding for that can come from the wealth created by the direct foreign investment of developed country energy firms informed by a new vision for future raw material supply. This is that future raw material supply will be secured not by prospecting and drilling for it, but through cropping increased primary production from the widespread deployment of land improvement technologies. This change of managerial vision can be driven by policies in developed countries that are motivated by concerns for energy security and by agricultural policy reform, as well as by the need to manage greenhouse gases.

⁷ i.e. gasification plus shift reaction to provide hydrogen for combustion and a pressurised and more concentrated CO₂ stream for separation, compression and storage.

⁸ Fransman [40] notes that boundedly rational humans, unable to comprehend all information, select from it according to their vision of the world to constitute their personal knowledge (which may be correct or not). He cites IBM management in the 1980's, having better information than anyone about the potential of the PC but wedded to the mainframe computer, as the classic case of a mistaken vision leading to commercial disaster. The vision presented here is in contrast to the Protocol's vision of greenhouse gases as pollutants.

The vision for policy-makers is that the ‘polluter pays principle’ (or, in relation to our overflowing lake problem, the ‘emitter pays principle’) can lead to the advancement of developing countries located in regions of high potential net primary soil productivity, as well as to meeting the multiple concerns of developed countries noted above.

A new assumption

Under this vision, land use change that was assumed previously to be ‘maximal’ [21] we now assume to be beneficial and not limited by food competition, even though experience with well-intentioned land use change has not always been happy [41]. For that reason we have referred to it elsewhere in this article as land use improvement rather than land use change.

However, the timing of a benign outcome in the least developed countries will follow after more rapid market penetration in countries with well developed institutions, secure land tenure, etc. Thus it is to be expected that the initial development of a large-scale bio-energy market will be linked to reforms of agricultural protection in developed countries, where ‘smart farmers’ are well accustomed to following policy-driven market signals. For this, the switch-grass technology is significant, along with sugar cane in those advanced developing countries – notably Brazil – able to take advantage of export opportunities presented by a developing world market for liquid bio-fuels. The least developed countries, or at least those amongst them that have favorable climates, may be eventually expected to become the lowest cost and most profitable producers, supporting long-term market expansion.

Caveats

Some caveats are needed. Resistance to economically rational land use may prove to be very great, technological progress with biomass production and conversion may be disappointing, and population trends may put greater pressure on land than is currently projected.

Sustainable Development

In the past good intentions have sometimes failed to reconcile worldwide market demands with local socio-economic development and environmental quality [41]. Consistent with our new assumption, and the notion of land use improvement, the prospect is that on-going commercial demands for food, fibre and fuel (conditioned by climate change policy measures, and mediated, as regards sustainable development desiderata, by effective monitoring and certification procedures) will prove more reliable than good intentions.

For this, a participatory framework is needed to ensure the involvement and commitment of populations living on the land in question. So, for the developmental potential of the holistic strategy to be realised, a necessary first step is a large-scale capacity building program. This is needed to train people in the countries involved to initiate country-driven projects that align the aspirations of local communities with their nation’s development strategy, and to provide on-going technical and commercial back-up [42].

Thus the full realization of the vision depends upon establishing effective synergy between climate change mitigation and sustainable development. This is problematic, with no consensus as to what is needed to modify social and cultural processes in the ways that are crucial for technological progress and improved human welfare [43].

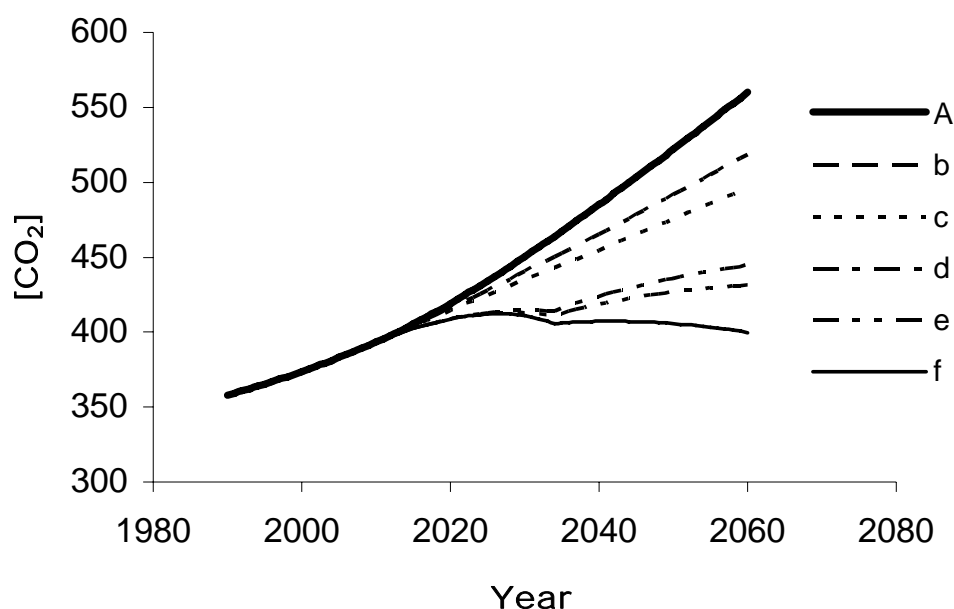
One possibility could be the initiation of the holistic strategy through a series of bi-lateral arrangements, where prospective gains from trade (under long-term higher oil prices) motivate both an intending importer to support the development of appropriate institutions in a selected developing country and the latter to accept externally negotiated criteria for

its sustainable development. The selection of the developing country partner by a developed importing country would be based upon effective market institutions, good governance, and local empowerment [44]. Learning from varied experience could provide the basis for convergence towards an agreed and effective general model, as the basis for negotiating a second protocol under the Rio Convention's Article 3.3, to formalize multilateral precautionary action in relation to potential abrupt climate change.

Scale

For many, the proposition will seem preposterous that the way in which land is used should be improved in response to policy measures on the scale of 1 + 0.72 + 0.43 billion hectares over 25 years (equivalent to an area about the size of France in low latitudes and Germany in temperate regions, every year from 2011 to 2035). For those readers we suggest the proposition may be regarded as a thought experiment.

Figure 3



BECS with Areas of Land Use Change Involved in Figure 2 Halved

Legend

- A SRES-A2
- b SRES-A2 with sugar cane land use change activity [lower case refers to figure 3 with land areas halved]
- c SRES-A2 with sugar cane and switch-grass land use change activities
- d SRES-A2 with sugar cane, switch-grass and forestry land use change activities
- e SRES-A2 with three land use change activities and low cost capture and storage (CCS) of fermentation CO₂
- f SRES-A2 with three land use change activities CCS of fermentation and flue gas CO₂

However, what may seem far-fetched now – as would have seemed the Manhattan project⁹ from the perspective of 1940 – may seem less so under urgency driven by imminent abrupt climate change. And to restore a billion hectares to tree cover would still leave the earth less forested than at the start of the industrial revolution. Also, change that focuses on the co-production of current outputs with biomass raw material is different from the single purpose cropping of biomass for low-value energy raw material supply

⁹ Code name for the militaristically organised industrial effort that delivered the atom bomb in 1945.

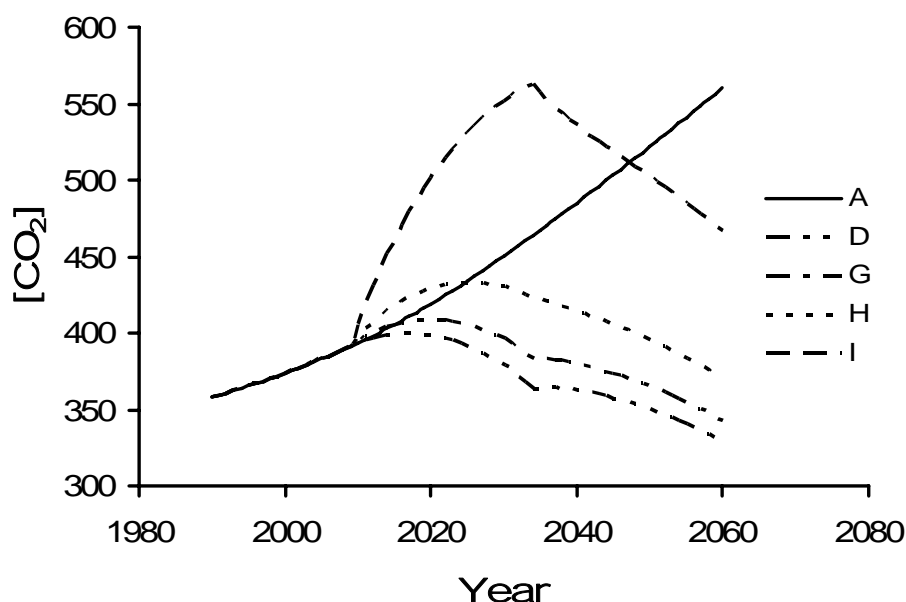
which has dominated consideration of the economics of bio-energy. It is different because, by increasing net primary productivity and value added from the land, it can yield improved livelihoods, motivating the involvement of the people living on it.

But, even if it is consistent with the new assumption stated above, the scale of operations and organization involved is daunting. An alternative scenario, involving half the land considered above, is illustrated in Figure 3 above. It leaves much to be done in other ways, including the comprehensive adoption of CCS in the remaining fossil fuel sector, if imminent abrupt climate change demands an outcome like line F in Figure 2 above. None of these other possible actions deliver the potential environmental and developmental benefits claimed here for the holistic strategy.

Soil disturbance

Soil disturbance at the time of land use change can result in the mineralisation of soil organic matter, and of above-soil biomass. This will act as an offset from the net CO₂ emissions reductions that result from using the specified technologies [45]. We have accordingly calculated the net effect in relation to the SRES A2 scenario perturbed by the

Figure 4



Bio-Energy with CO₂ release at time of land use change

- A SRES-A2
- D SRES-A2 with sugar cane, switch-grass and forestry land use change activities
- G SRES-A2 with three land use change activities and 30 tC per ha released through land use change
- H SRES-A2 with three land use change activities and 90 tC per ha released through land use change
- I SRES-A2 with three land use change activities and 300 tC per ha released through land use change

three productive technologies only, i.e. without CCS (line D in figure 2) on alternative assumptions that the loss of C per Hectare is 30, 90, and 300 tons C per ha. We take these to roughly correspond, respectively, to the conversion of pasture to arable land, to the burn-off of incomplete canopy woodland/scrub in temperate regions, and to the burn-off of dense tropical forest, in order to make room for the land using technologies¹⁰. The

¹⁰ We do not propose these types of land use change, and nor are they implicit in the land use improvements under discussion. These calculations are to illustrate the need to use sustainable best practice at the time of land use change – e.g. ensuring that cleared biomass is used as bio-energy raw material or that a large proportion of its carbon content is converted to biochar and stored more or less permanently in the soil.

effects of allowing for such CO₂ release at the time of the land use change are illustrated in figure 4.

Conclusion

The land use improvements analysed above are illustrative and based upon plausible average parameters for the small selection of technologies discussed and on ambitious areas of land use improvement. Many other crops exist, either as potential energy crops or co-producing energy with other commercial products of the land, along with a wide variety of conversion technologies, which would be employed in particular combinations where these are preferable to those we have analysed. Thus from a technological perspective, this article presents a lower bound to the potential of the holistic strategy.

As regards the areas of land involved, only time can tell whether increased understanding of the factors involved in development success, and building on successes where they occur, can snowball into sufficient participation on the ground to give effective control of atmospheric CO₂ on the decadal scale illustrated in Figure 2, line D, E or F. Also, only time can tell whether sufficiently effective monitoring and certification procedures can evolve to avoid the outcome illustrated in Figure 4 line I.

So, although our results are relative to the ‘hard case’ SRES A2 baseline, their status is *prima facie* and we do not suggest that all policy eggs should be put in the land use improvement basket. Even if the holistic strategy were to provide a complete alternative to Kyoto, very low greenhouse gas levels may require, in addition, greater energy efficiency and increased use of non-fuel renewables. And if they were not required for that purpose, the deployment of such other technologies would enable a stronger focus on land use improvement, e.g. the production of more bio-char for soil amendment, with reduced bioenergy co-products, and greater land management resilience in the face of climatic variability.

Also, it should be noted that our time horizon is the next half century, with the object of being able to return within that period to pre-industrial levels of carbon in atmosphere, or even below, if advances in science show that to be what is necessary to offset having stayed for too long above thresholds that are currently unknown, and that may already have been passed. This has no implications for what may be desirable land use policies towards the end of the century, when population growth or the dietary choices of richer societies (e.g. for increased meat eating) may put greater pressure on land productivity than during the first half century of predicted land surplus. Having reached pre-industrial levels of CO₂ by 2040 (line F in Figure 2 – or maybe 100 ppm below by 2070, in order to offset higher levels of non-CO₂ greenhouse gases) climatic security may be little increased by reaching lower levels still, through further implementation of negative emissions energy systems.

By then energy needs will likely be met increasingly by low cost photo-voltaic power, and advances with other zero emissions technologies. Also, decisions reached in the first three decades of this century to implement the first and second stages of the holistic strategy will not preclude policy makers of the future from implementing further changes in priorities as regards sustainable land use. Whatever those changed priorities may be – in the light of changing circumstances, and supposing that abrupt climate change over the next few decades has been avoided – it seems reasonable to assume that they will more easily be met if the land use improvements entailed by the holistic strategy have meantime been implemented.

Our purpose here has been to illustrate the capability of the holistic strategy – maybe driven by the 2005 G8 decision to launch a global bio-energy partnership – as a

precautionary response to potential abrupt climate change in the next few decades. Also, we have suggested that much can beneficially be done for energy security, farm policy in advanced economies and for sustainable development elsewhere, if land use change is managed sustainably. For that, land use change needs to constitute land use improvement, both from the perspective of communities living on the land, as well as of environmental sustainability, and therefore comes to be no longer regarded as the last resort amongst policy options.

Adoption of a holistic greenhouse gas management strategy would point to the need for detailed, spatially and temporally differentiated, modelling of the evolution of technology choices. This needs to be based on a multi-criterion analysis on a vector of desiderata relevant to land user choices – including climatic incentives, energetic values, socio-economic factors, and environmental constraints – with no ‘one size fits all’ recipe [41]. It is not the purpose of this illustrative work to pre-judge the results of such research, but merely to establish the *prima facie* likelihood that it will lead to low-cost and effective control of greenhouse gas levels. And also to note that initiating the holistic strategy, if done under Art 3.3 of the UNFCCC in response to threats of dangerous or irreversible climate change, need not await resolution of the scientific uncertainty that is evident from the need for such research.

Possible extension of footnote 1

In the last year have occurred a number of climate events that support the view that we may be close to a threshold for abrupt climate change, i.e. a regime change in the non-linear dynamic system that we call climate. Observations of potentially irreversible or runaway processes include

- Observation: progressively more rapid retreat of Arctic summer sea ice
 - Process: less ice, less reflection of sunlight and more absorption, warmer exposed ocean, less ice, etc., etc.
- Observation: thawing of West Siberian tundra.
 - Process: thawed tundra releases trapped methane which is a more powerful GHG than CO₂, causes more warming and more thawing, etc., etc.
- Observation: accelerating loss of land based ice on Greenland and Antarctica
 - Process: previously unsuspected tele-connection of glaciers – warmer ocean melts anchor points of land based ice shelves, calving of massive ice-bergs and acceleration of glaciers, raising ocean levels, and melting of more anchor points, etc., etc.
- Observation: increased biotic uptake of CO₂ into terrestrial sink due to “CO₂ fertilisation”.
 - Process: reflects modelling of biosphere response to climatic change, with negative (stabilising) feed-back with respect to CO₂ concentration but positive feedback with respect to temperature: with climatic warming plants will increasingly emit CO₂.
- Observation: slowing of ‘Gulf Stream’ North Atlantic drift
 - Process: warmer oceans evaporate more clouds resulting in more rain in N Atlantic and freshening of water, weakening high density sinking of cold and salty water that drives the ‘great conveyor belt’ oceanic convection (a local negative feedback effect).

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Appendix Details of data and assumptions used in deriving Table 1

These calculations mostly lead to numbers that are carried to the year 2035 in Table 2 and then extrapolated forwards with the assumed 1.5%p.a. technological progress, and backwards with the assumed linear take up of the land based technologies from the various start dates mentioned in the main text and/or below. As noted in footnote 5, detailed spreadsheets are available from the corresponding author at p.read@massey.ac.nz.

A Forestry co-production of timber and woody biomass

Growth: we assume land use change on **40Mha per year** [500km x 800 km] for 25 years with 20t/ha-yr productivity yielding 500 t/ha = ~250tC/ha = 10,000GJ/ha at felling. [Best current case commercial eucalypt 1000GJ/ha-yr = 50odt/ha-yr*20GJ/o.d.t. Average commercial plantation productivity in Aracruz, Brazil = 450GJ/ha-yr]

| |
|--|
| ~ 0. 5tC and ~20GJ per oven dry tonne biomass |
|--|

C absorbed per planted hectare = ~10t/ha-yr → absorption in plantations rises from 0.4 Gt in 2011 to 9.6 Gt in 2034 with absorption in 2035 onwards balanced by loss due to felling, save for increment due to technological progress.

→ C stocked in 10E9ha standing timber ≈ 125 Gt by 2035, then growing at 1.5% p.a.

Note, no crop from new plantations before 2035 as modelled here. In the event, production in tropical regions would likely be on shorter rotations, e.g. 10 yrs in Brazil, with woody biomass supplies prior to 2035 derived from these shorter rotations along with increasing thoroughness in collection of wood industry wastes and from woody biomass collected from land clearance for new plantations (Figure 4 in main text shows need to avoid short term emissions during process of land use change).

Utilisation of 20Gt woody biomass per year:

Assume 10Gt as lumber displacing unsustainable logging

(i.e. substantial expansion of current world supply by 2035, meeting new uses in lieu of energy intensive steel, aluminium and concrete and tapering off of tropical de-forestation of 1.2GtC/yr from 2023 to 2035).

Of remaining 10GT/yr in 2035, growing at 1.5%p.a., assume arbitrary split:
5Gt/yr to biochar process, yielding ≈1.2GtC/yr to soil improvement and 20 EJ/yr biodiesel.
5Gt/yr (100EJ) to ethanol-plus-electricity yields pro-rated to (see below) sugar cane process
→ 23.1 EJ electricity; 31.4 EJ ethanol (assumes, as with switchgrass below, success with commercialisation of cellulosic fermentation process*)

Sequestration

C stocked in avoided deforestation ~1.2*13/2 = 7.8Gt by 2035, 37.8 Gt by 2060

C stocked in soil improvement = 1.2*25/2 = 15Gt by 2035, 51.6 Gt by 2060.

31.4 EJ ethanol = 1.153 Gt → 0.60 Gt C in ethanol, 0.3Gt C in CO₂ of fermentation

Assume stored on linear pattern from 0 in 2020 to 0.3 in 2035, then 1.5% annual growth → 0.3*16/2 = 2.4 Gt by 2035, 11.55 by 2060.

Flue gas C = 10Gt feedstock → ~50%C – biochar C – biodiesel C – ethanol C

= 10Gt * 0.5 – 1.2 Gt – 0.4 Gt – 0.6 Gt = 2.8 Gt

Assume stored with 60% efficiency on linear pattern from 0 in 2025 to 1.68 in 2035, then 1.5% annual growth

→ 1.68*11/2 = 9.24 Gt by 2035, 60.5 by 2060.

* e.g. announcement by Danish company Novozymes, cutting enzyme costs of cellulosic fermentation from \$5/gallon of ethanol to < 20 cents www.renewableenergyaccess.com/rea/news/story?id=25046

Fossil fuel displacement

Taking ethanol and biodiesel as equivalent to refined fuel, 51 EJ results in 76 EJ of crude oil left underground → 1.52Gt C/yr in 5 (providing ~25 EJ thermal demands that would be met by heating oil if the crude oil were extracted are instead met renewably, e.g wood pellet by-product from lumber processing wastes)

Taking thermal power as otherwise raised 50 per cent by coal fired thermal plant with 33% Rankine cycle efficiency, and 50 per cent renewably, then 23 EJ/yr results in ~34.5 EJ/yr of coal left underground containing 0.86Gt C/yr in 2035.

| |
|--|
| 0.02 tC / GJ oil 0.025 tC / GJ coal |
|--|

Assume linear increasing pattern from 2010 to 2035, 1.5% technological progress thereafter, cumulated C stored = $(1.52+0.86)*(25/2) = 19.76\text{Gt}$ by 2035, 57.76Gt by 2060.

B Sugar cane fermentation to ethanol with power from bagasse residues

Growth and utilisation

Moreira's results [28] assume 0.143Gha by 2030, with 3% /yr. technical progress. Alternatively, assume 1.5% annual t.p. to 2035 and scale to 0.430Gha → **17.2 Mha/yr** → multiply his results by 2.24, resulting in 45Gt/yr of sugar cane raw material by 2035 .

Note that 0.43Gha equals the maximum area of tropical land that Moreira considers suitable for rain-fed sugar plantations (personal communication). The assumption here is that, if there are competitive other uses for this land then 25 years of investment in land (including irrigation schemes that save a significant proportion of tropical river waters from being lost in the oceans, and/or widespread adoption of *terra preta* style land improvement, etc.) will result in a substantial increase in the area of land suitable for cropping sugar cane. Alternatively cassava (a starchy crop – that can be fermented for 'kava' beer – and, since it can tolerate poor soils and intermittent drought, has an important role as a standby subsistence crop [35]) can be developed as a co-product crop for ethanol production.

Products in 2035 are: electricity, 85EJ from 212EJ bagasse; and ethanol, 115EJ from 157EJ sugar syrup.

Sequestration

We have 115EJ ethanol ≈ 4.2Gt ethanol/yr, which embodies 1.8Gt C that becomes dispersed emissions in the transportation system with 0.9 Gt C emitted in pure CO₂ of fermentation.

Remaining C in bagasse feedstock = 2.8Gt, emitted in mixed flue gases from power generation and process steam raising. (Note, if the demand for power exists then additional 'barbojo' – green 'tops' normally left behind at harvest – can be used, up to about 60 per cent of the bagasse energy fraction, without prejudice to soil quality¹¹).

Assume pure CO₂ captured and stored in linear increasing pattern from 2020 to 2035, 1.5% annual growth thereafter, cumulated C stored = $0.9 *(16/2) = 7.2\text{Gt}$ by 2035, 34.66 by 2060

Assume flue gas CO₂ captured with 60% efficiency and stored in linear increasing pattern from 2025 to 2035, 1.5% annual growth thereafter, cumulated C stored = $2.8*.6 *(11/2) = 9.24\text{Gt}$ by 2035, 60.50 Gt by 2060

Fossil fuel displacement

Taking ethanol as equivalent to refined fuel, 115 EJ results in 173 EJ of crude oil left underground → 3.46Gt C/yr in 2035 1.5% annual growth thereafter (providing ~60EJ thermal demands that would be met by heating oil if the crude oil were extracted are instead met renewably).

Taking thermal power as otherwise raised 50 per cent by coal fired thermal plant with 33% Rankine cycle efficiency, and 50 per cent renewably, then 85 EJ/yr results in ~127EJ/yr of coal left underground containing 3.19Gt C/yr

Assume linear increasing pattern from 2010 to 2035, 1.5% technological progress thereafter, cumulated C stored = $6.65*(25/2) = 86.5.1\text{Gt}$ by 2035, 289Gt by 2060.

¹¹ Moreira, J.R., Personal Communication

C Switchgrass co-production of protein and bio-energy¹²

Biomass production

Currently 5 oven dry short ton/acre-yr; 10 expected in 'future'.
Assume 8 in 2035 \approx 18 o.d. tonne/ha-yr and then 1.5% annual technical progress
LCV dry switchgrass = 7285btu/lb = 14.57Mbtu/short ton = 16.95GJ/tonne

| |
|--|
| 2.471 acres/ha 1.1023 st/tonne 2204.6lb/tonne 1.0551Mbtu/GJ |
|--|

Take 0.36 unused potential rain-fed arable land in N.America, Europe and N Asia, plus an equal area of land currently in use \rightarrow 0.72Gha \rightarrow **28.8 Mha/yr**

0.72Gha*17.9 o.d.t/ha-yr \rightarrow 12.91Gt/yr (14.22 Gs.t/yr)

Raw material energy supply = 220EJ/yr (219.6)

| |
|--|
| 92500btu/gallon * .8327USgallon/gallon = 77025 btu/gallonUS 77025* 97.4 = 7. 502 Mbtu = \sim 0.51 * 14.57 Mbtu 3412 btu/kWh * 93.9 = 0. 3205Mbtu = \sim .022 * 14.57Mbtu |
|--|

Biomass conversion

Product split and embodied per cent of feedstock energy

97.4 US gallon ethanol/dry short ton feedstock (51.0%)

0.08short ton protein/dry short ton feedstock (8.2%)

337.2 kWh gross electricity/dry short ton feedstock (7.9%)

93.9kWh electricity/dry short ton feedstock net of plant requirements (2.2%)

Overall process thermal efficiency = 61.4%

| |
|--|
| 6.59 lb/gallonUS of ethanol \rightarrow 97.4gallon = 642lb = 0.321 st |
|--|

2035 yields: 1385 billion US gallons ethanol (113 EJ)
1.04 billion tonnes protein for animal feed (18 EJ)
1335TWh (4.8 EJ net of plant requirements, 17 EJ gross)

| |
|---|
| 12.9 Gt*1.1023 st/t = 14.22E9st/yr 7. 502Mbtu = 7. 915 GJ \rightarrow *14.22 = 112.6 93.9kWh = 0.338 GJ \rightarrow *14.22 = 4.81 |
|---|

Sequestration

We have 0.321t ethanol/t switchgrass \approx 4.14Gt ethanol/yr.

4.14Gt ethanol embodies 2.16Gt C with 1.08 Gt C emitted in pure CO₂ of fermentation.

Mass fraction of C in feedstock = 0.493 \rightarrow 6.36Gt total

Remaining C in feedstock = 6.36 - 3.24 = 3.12Gt emitted in mixed flue gases from power generation and raising process steam.

Assume pure CO₂ captured and stored in linear increasing pattern from 2020 to 2035, 1.5% annual growth thereafter, cumulated C stored = 1.08 *(16/2) = 8.64Gt by 2035, 41.6 Gt by 2060

Assume flue gas CO₂ captured with 80% efficiency and stored in linear increasing pattern from 2025 to 2035, 1.5% annual growth thereafter, cumulated C stored = 3.12*.8 *(11/2)
= \sim 13.75Gt by 2035, 90.3Gt by 2060

| |
|--|
| (check: = 113EJ ethanol with LCV= 27.17GJ/t \rightarrow 4.159 Gt -- ok) |
|--|

Fossil fuel displacement

Taking ethanol as equivalent to refined fuel, then 113 EJ results in 170 EJ of crude oil left underground \rightarrow 3.4Gt C/yr from 2035 (providing \sim 57EJ thermal demands that would be met by heating oil if the crude oil were extracted are instead met renewably)

Taking exported thermal power as otherwise raised 50 per cent by coal fired thermal plant with 33% Rankine cycle efficiency, and 50 per cent renewably, then 4.8EJ/yr results in \sim 7.2EJ/yr of coal left underground containing 0.18Gt C/yr

Assume linear increasing pattern from 2010 to 2035, 1.5% technological progress thereafter, cumulated C stored = 3.58*(26/2) = 46.54Gt by 2035, 156Gt by 206

¹² The original data are presented in non-SI (engineering) units requiring the application of numerous conversion factors detailed in the boxes. I am indebted to Mark Laser (personal communication) for his help with the details of this process.

Table 2

| | cane only | C&grass | C,G&trees | CG&T+loseq | CG&T+allseq | CG&T-C30 | CG&T-C90 | CG&T-C300 |
|---------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|-------------|
| 2010 | | | | | | -2.58 | -7.74 | -25.8 |
| 2011 | 0.266 | 0.4092 | 0.9044 | 0.9044 | 0.9044 | -1.6756 | -6.8356 | -24.8956 |
| 2012 | 0.532 | 0.8184 | 1.8588 | 1.8588 | 1.8588 | -0.7212 | -5.8812 | -23.9412 |
| 2013 | 0.798 | 1.2276 | 2.8132 | 2.8132 | 2.8132 | 0.2332 | -4.9268 | -22.9868 |
| 2014 | 1.064 | 1.6368 | 3.7676 | 3.7676 | 3.7676 | 1.1876 | -3.9724 | -22.0324 |
| 2015 | 1.33 | 2.046 | 4.722 | 4.722 | 4.722 | 2.142 | -3.018 | -21.078 |
| 2016 | 1.596 | 2.4552 | 5.6764 | 5.6764 | 5.6764 | 3.0964 | -2.0636 | -20.1236 |
| 2017 | 1.862 | 2.8644 | 6.6308 | 6.6308 | 6.6308 | 4.0508 | -1.1092 | -19.1692 |
| 2018 | 2.128 | 3.2736 | 7.5852 | 7.5852 | 7.5852 | 5.0052 | -0.1548 | -18.2148 |
| 2019 | 2.394 | 3.6828 | 8.5396 | 8.5396 | 8.5396 | 5.9596 | 0.7996 | -17.2604 |
| 2020 | 2.66 | 4.092 | 9.494 | 9.494 | 9.494 | 6.914 | 1.754 | -16.306 |
| 2021 | 2.926 | 4.5012 | 10.4484 | 10.6004 | 10.6004 | 7.8684 | 2.7084 | -15.3516 |
| 2022 | 3.192 | 4.9104 | 11.4028 | 11.7068 | 11.7068 | 8.8228 | 3.6628 | -14.3972 |
| 2023 | 3.458 | 5.3196 | 12.3572 | 12.8132 | 12.8132 | 9.7772 | 4.6172 | -13.4428 |
| 2024 | 3.724 | 5.7288 | 13.4116 | 14.0196 | 14.0196 | 10.8316 | 5.6716 | -12.3884 |
| 2025 | 3.99 | 6.138 | 14.466 | 15.226 | 15.226 | 11.886 | 6.726 | -11.334 |
| 2026 | 4.256 | 6.5472 | 15.5204 | 16.4324 | 17.0184 | 12.9404 | 7.7804 | -10.2796 |
| 2027 | 4.522 | 6.9564 | 16.5748 | 17.6388 | 18.8108 | 13.9948 | 8.8348 | -9.2252 |
| 2028 | 4.788 | 7.3656 | 17.6292 | 18.8452 | 20.6032 | 15.0492 | 9.8892 | -8.1708 |
| 2029 | 5.054 | 7.7748 | 18.6836 | 20.0516 | 22.3956 | 16.1036 | 10.9436 | -7.1164 |
| 2030 | 5.32 | 8.184 | 19.738 | 21.258 | 24.188 | 17.158 | 11.998 | -6.062 |
| 2031 | 5.586 | 8.5932 | 20.7924 | 22.4644 | 25.9804 | 18.2124 | 13.0524 | -5.0076 |
| 2032 | 5.852 | 9.0024 | 21.8468 | 23.6708 | 27.7728 | 19.2668 | 14.1068 | -3.9532 |
| 2033 | 6.118 | 9.4116 | 22.9012 | 24.8772 | 29.5652 | 20.3212 | 15.1612 | -2.8988 |
| 2034 | 6.384 | 9.8208 | 23.9556 | 26.0836 | 31.3576 | 21.3756 | 16.2156 | -1.8444 |
| 2035 | 6.65 | 10.23 | 15.1904 | 17.4704 | 23.3304 | 15.1904 | 15.1904 | 15.1904 |
| 2036 | 6.74975 | 10.38345 | 15.57795 | 17.89215 | 23.84005 | 15.57795 | 15.57795 | 15.57795 |
| 2037 | 6.85099625 | 10.53920175 | 15.31920175 | 17.66811475 | 23.70523325 | 15.31920175 | 15.31920175 | 15.31920175 |
| 2038 | 6.953761194 | 10.69728978 | 16.36241836 | 18.74656505 | 24.87424033 | 16.36241836 | 16.36241836 | 16.36241836 |
| 2039 | 7.058067612 | 10.85774912 | 16.75943063 | 19.17933953 | 25.39892994 | 16.75943063 | 16.75943063 | 16.75943063 |
| 2040 | 7.163938626 | 11.02061536 | 17.15969209 | 19.61589962 | 25.92878389 | 17.15969209 | 17.15969209 | 17.15969209 |
| 2041 | 7.271397705 | 11.18592459 | 17.56325148 | 20.05630212 | 26.46387964 | 17.56325148 | 17.56325148 | 17.56325148 |
| 2042 | 7.380468671 | 11.35371346 | 17.97015825 | 20.50060465 | 27.00429584 | 17.97015825 | 17.97015825 | 17.97015825 |
| 2043 | 7.491175701 | 11.52401916 | 18.38046262 | 20.94886572 | 27.55011228 | 18.38046262 | 18.38046262 | 18.38046262 |
| 2044 | 7.603543336 | 11.69687945 | 18.79421556 | 21.4011447 | 28.10140996 | 18.79421556 | 18.79421556 | 18.79421556 |
| 2045 | 7.717596486 | 11.87233264 | 19.21146879 | 21.85750187 | 28.65827111 | 19.21146879 | 19.21146879 | 19.21146879 |
| 2046 | 7.833360434 | 12.05041763 | 19.63227483 | 22.3179984 | 29.22077918 | 19.63227483 | 19.63227483 | 19.63227483 |
| 2047 | 7.95086084 | 12.23117389 | 20.05668695 | 22.78269638 | 29.78901886 | 20.05668695 | 20.05668695 | 20.05668695 |
| 2048 | 8.070123753 | 12.4146415 | 20.48475925 | 23.25165882 | 30.36307615 | 20.48475925 | 20.48475925 | 20.48475925 |
| 2049 | 8.191175609 | 12.60086112 | 20.91654664 | 23.72494971 | 30.94303829 | 20.91654664 | 20.91654664 | 20.91654664 |
| 2050 | 8.314043243 | 12.78987404 | 21.35210484 | 24.20263395 | 31.52899386 | 21.35210484 | 21.35210484 | 21.35210484 |
| 2051 | 8.438753892 | 12.98172215 | 21.79149041 | 24.68477746 | 32.12103277 | 21.79149041 | 21.79149041 | 21.79149041 |
| 2052 | 8.5653352 | 13.17644798 | 22.23476077 | 25.17144712 | 32.71924626 | 22.23476077 | 22.23476077 | 22.23476077 |
| 2053 | 8.693815228 | 13.3740947 | 22.68197418 | 25.66271083 | 33.32372696 | 22.68197418 | 22.68197418 | 22.68197418 |
| 2054 | 8.824222457 | 13.57470613 | 23.13318979 | 26.15863749 | 33.93456886 | 23.13318979 | 23.13318979 | 23.13318979 |
| 2055 | 8.956585794 | 13.77832672 | 23.58846764 | 26.65929706 | 34.55186739 | 23.58846764 | 23.58846764 | 23.58846764 |
| 2056 | 9.09093458 | 13.98500162 | 24.04786866 | 27.16476051 | 35.1757194 | 24.04786866 | 24.04786866 | 24.04786866 |
| 2057 | 9.227298599 | 14.19477664 | 24.51145468 | 27.67509992 | 35.8062232 | 24.51145468 | 24.51145468 | 24.51145468 |
| 2058 | 9.365708078 | 14.40769829 | 24.97928851 | 28.19038842 | 36.44347854 | 24.97928851 | 24.97928851 | 24.97928851 |
| 2059 | 9.506193699 | 14.62381377 | 25.45143383 | 28.71070024 | 37.08758672 | 25.45143383 | 25.45143383 | 25.45143383 |
| 2060 | 9.648786605 | 14.84317097 | 25.92795534 | 29.23611075 | 37.73865052 | 25.92795534 | 25.92795534 | 25.92795534 |
| total to 2060 | 289.3678936 | 445.1479025 | 820.7989059 | 908.6107551 | 1119.652613 | 756.2989059 | 627.2989059 | 175.7989059 |
| total to 2035 | 86.45 | 132.99 | 306.9104 | 325.1504 | 357.3804 | 242.4104 | 113.4104 | -338.0896 |

Final review of Read and Parshotam (Review G)

After reading the response [to reviewers E and F – PR] by Read and Parshotam, it becomes clear where the confusion between reviewers and authors is coming from (although I have to guess for the other reviewers of course).

From the communication it becomes clear what the real focus of the paper is: introduction of short-term C reductions (even through C uptake, thus decrease in CO₂ concentration) to prevent possible extreme events in the near term. However, and this may be caused by my quick reading, this focus of the paper is not stated as sharp as in the response. Indeed, the Introduction is pretty clear about this objective of the paper, but in the Methodology this objective is obscured by very detailed information on technologies that can be applied and how much C can be gained from these.

The detail is provided [largely in an Appendix] to ensure that the reader can check that the results are correctly derived from the assumptions and to form an opinion on the assumptions. That is how Reviewer H has used the detail, although s/he appears to have misunderstood some aspects.

The paper would greatly benefit from a proper structure where the most important statements are backed by scientific literature. The detailed table 1 is only distracting the reader from this more theoretical objective.

Though the paper has become somewhat unwieldy, due to accretions in response to comments, some misguided, by referees A to F, nevertheless it has what to me is a proper structure. An Introduction explaining the background, a descriptive section defining the holistic strategy, a methods section explaining the calculations (which are detailed in an appendix), a results section, a discussion section including some caveats and a Conclusion. The most important results are backed by the scientific literature, specifically references 26 to 30. The detailed table 1 demonstrates the capability of the strategy both to meet prospective energy demands and to remove carbon from the atmosphere on the scale needed to yield Figures 1 and 2. This, I would have thought, was essential for any paper that purports to deal with a problem of excess carbon in the atmosphere due to past and prospective demands for energy.

So I would expect more attention to the following statements:

1. Is abrupt climate change expected in such a short notice (coming 2 or 3 decades) as the authors state (and use this as a basis for the rest of their calculations)? I would say: no. The current footnote 1 is not addressing this issue properly. And given the importance of this assumption for the rest of the analysis, the authors should clearly describe this literature instead of mentioning it very briefly. For example, there is a lot of literature on the THC, but most of these papers where scientists dare to say something of a possible slowdown (no collapse!), they are talking about next century or maybe the end of this century. This is not providing a good basis to have C reduction strategies within the first few decades. This is true for most of the “abrupt changes” that are mentioned in footnote 1. This material deserves more than the current footnote, I would say.

The paper is about a precautionary strategy not about whether abrupt climate change is imminent. Nobody knows if abrupt climate change is imminent. There are things we know we don't know, such as the threshold for runaway methane emissions from boreal tundra, and there may be surprises, things we don't know we don't know. As Crutzen remarks “The chances of unexpected climate effects should not be underrated, as clearly shown by the sudden and unpredicted development of the antarctic ozone hole”. By the time we do know it will probably be too late unless

precautionary steps have been taken. Noah did not build the Ark when it started raining: that was the time to get the animals in, two by two. With this reviewer, we will be knee deep in water while still sawing up the logs to make the planks.

2. The next statement would be that there are enough technologies or biomass options that can sequester carbon to the extent as the authors state. Again, a thorough discussion of the literature is still lacking. Most of the carbon gains are expected from second generation biomass productions and not from the first generation (biofuels from crops like sugar). Where's the discussion on this crucial issue? How important is the assumption of having a second generation available within next decades for the results? The technologies are described in great detail, but not the phasing in of these technologies, which is the crucial factor when the point of short-term mitigation efforts is made.

At one moment this referee complains about too much description of technological detail and the next about too little discussion of the phasing of the technologies. As is clear from the discussion on page 9, most of the out-of-atmosphere stocking of C in the early stages of the strategy comes in the form of a strategic reserve stock of biomass through the development of a very large area of new forest plantation. No technological wizardry there (but see also comments below on reviewer H points 9 and 10). The caveats recognize the possibility that second generation bio-energy technology may not advance as rapidly as expected (e.g. ref 37)

3. And then the costs. Thanks for adding this section. However, it's not satisfactory. The authors state that it goes beyond this paper to have a detailed cost breakdown. I tend to disagree. If the main objective is to show that short-term actions need to be taken and they are feasible, the authors should prove that, indeed, it is economically feasible. There is a lot of literature on cost estimates of all options (including biomass options; see literature from Azar, IIASA, RIVM etc.). And in their analyses most of the biomass and BECS options come in after 2050. Why is this different in this analysis? This is really crucial to substantiate the statement that short-term actions with even carbon uptake are needed *and* feasible.

The reason that Azar et al (and I guess IIASA and RIVM) do not introduce BECS before 2050 is because it is a high cost technology if treated as a single item. As noted on p8, second whole para, BECS is split into two parts in our treatment, first low cost bio-energy, second (if needed) linkage to high cost CCS. (Probably high cost, but don't discount the potential of technological progress to bring costs down, as for instance with flue gas desulphurization, originally projected as prohibitively costly). And as regards costs of bioenergy itself, I believe that the analyses for the studies mentioned by the reviewer pre-date the oil price rises of 2005-2006 which have led to a rapid expansion of biofuels production but with no safeguards regarding the sustainability of the production methods used (see our footnote 10) .

Summarizing, the aim of the paper is clear in the Introduction, but the rest of the paper is focused too much on very technical explanations of some technological options, whereas I would expect to read a more in-depth elaboration of phasing issues, especially in connection with current costs and C gains of biomass for energy use.

My feeling is that, given the quite surprising nature of our main result – that a return to pre-industrial CO₂ levels within a few decades is feasible – that it is important to substantiate fully the technological basis for the claim. As regards phasing, the intent is clearly to implement the second, likely costly, stage of the holistic strategy if and when abrupt climate change appears imminent, and the detailed calculations show staged phasing of low cost CCS of fermentation CO₂ and high cost CCS of flue gas CO₂ (and of the ending of tropical deforestation (“avoided deforestation” in the current policy dialogue). I believe there is room for a lot more research to explore the implications of the result, including optimisation of successive policy stages in the context of sequential revelation of climatic risks and sensitivity analyses on the

phasing issues raised by this reviewer. But such research is for the future: let's get the main idea across first. If it is 'breathtaking' (see below) let's state it as simply as possible in the first instance.

In the end, I would say the paper still needs a major revision, which is too much considering the many rounds of reviews that have been already. But I leave this decision to the editor of course.

REVIEW H

The paper "Holistic greenhouse gas management ... " by P Read and A Parshotam (RP) makes several interesting claims. But there is something very strange with it. Many previous reviewers have noted this too.

The nature of the paper is very unclear. It is unclear whether it is a scientific paper offering new results or whether it is an advocacy paper arguing in favour of a large scale biomass response to the climate problem. In the end my feeling is that it is more of an advocacy paper than a scientific paper and that it for that reason does not deserve to be published.

I do not think that advocacy precludes science. I think that RP is a combination, advocacy based upon an important scientific feasibility result that has been overlooked by the policy community. However, that advocacy now appears as an editorial essay in *Climatic Change* and a new paper will be written more focused on the science.

I am a bit nervous drawing this conclusion since I also think that advocacy papers can be part of the scientific debate about how to respond to the climate problem, but there are so many strange features with the paper that it can not get in through that "channel" either.

Strange I think in the sense of 'unfamiliar'. What is strange, in the sense of 'peculiar', is that it is unfamiliar, since the gist of the story was in my 1994 book 'Responding to Global Warming', carrying commendations from Michael Grubb, the late Alan Manne and Thomas Schelling, and widely receiving favourable reviews. What is peculiar is that the policy community has steadfastly ignored the win-win-win potential of biosphere management. Instead it has persisted with a framework based in dogmatic adherence to the economists' Panglossian fantasy that 'getting prices right' is all that is needed for all problems to solve themselves. Specifically, in relation to climate change, a price on carbon, despite Nobel Laureate Schelling's prediction in his 1992 Presidential address to the AEA that it wouldn't work. And which is manifestly not working (what "demonstrable progress" by 2005? – as Crutzen points out, what happened was demonstrable regress). Meanwhile the policy community negotiated endlessly. [Well, it came to an end with the Marrakesh Accords – almost, but for a few details over the compliance mechanism]. Which is not for a moment to say that prices don't matter – they matter very much, especially if price expectations are arrived at mistakenly. I.e. without regard to the win-win-win potential of a policy option that has been missed, owing to a mistaken vision that it is a very long term problem and that it requires high cost decarbonisation rather than low cost defossilization. Since those price expectations are so formidable they have paralysed the will to act, possibly till too late. With Stern's recognition that the cost of inaction is too great for such inaction to be sustained, hopefully defossilization will get a look in and, with that, a revision of price expectations to something very little different from business as usual.

Let me explain why:

- 1) RP claim that they have presented a holistic greenhouse gas management strategy. I think that this is misleading, well to be honest erroneous. Their approach is less holistic than

other approaches, since it only focuses on one strategy, and not seeing this strategy as part of a broader strategy.

Holistic does not mean all-inclusive. The strategy is claimed holistic because it addresses the whole problem (i.e. it starts by recognising that what is dangerous is defined by what the outcome is (Sir David King, reference [7] in the Editorial Essay) and thus faces the need to be prepared for a possible necessity to achieve much lower levels of CO₂ than are available through 'emissions reductions'. It treats the whole carbon cycle, instead of focusing on reducing energy sector emissions. It notes the inadequacy of measures based on an economic theory that treats CO₂ as a pollutant and that neglects investment behaviour. And it addresses the North-South equity issue.

- 2) RP spend quite some time arguing against a pigouvian approach portrayed as something completely different than their Holistic approach. I simply cannot see the reason why they need to make that case. A pigouvian approach, in essence a tax on emissions or a cap-and-trade system, would work fine if complemented with a subsidy for those who withdraw CO₂ from the atmosphere (as is accepted in the Kyoto protocol if it is done in carbon sinks, but to a limited extent which might be reasonable during these initial stages). I do not see why a "Pigouvian" person who would oppose this. In addition, a pigouvian approach would in reality be more holistic than the RP approach since the pigouvian would also generate incentives to carry out efficiency improvements, fuel switches in the energy sector etc (the price mechanism offers incentives to reduce where it is cheapest to do so, there claim that this is not the case must be stated much better or not at all). To mention one more example: PR write their approach would make pigouvian emission reduction strategies redundant, but if carbon reductions through pigouvian emission reductions are less costly than their approach, why should making it redundant be an objective.

The reviewer completely misses the point. Environmental problems are resolved, if at all, by technological change (Kneese and Schultz, 1975). Their resolution must therefore involve some regard for entrepreneurial behaviour, and the dynamics of innovation, including the beneficial learning externality. This means that the competitive general equilibrium based comparative static analysis of the Pigouvian approach, that was pioneered by Baumol and Oates (also in 1975) cannot capture the essence of successful policy. That is why Kyoto is not working well – it is based on the wrong kind of economics. If emissions caps and carbon taxes deliver results, it is a slow, painful, and inefficient business. As noted by Lempert, energy firms continue with the same old technology till Kingdom come, upgraded from time to time by maintenance and refurbishment. But a change of technology only comes with regulation, as with flue gas desulphurisation.

However, I recognise that it would be quite easy for the referee to miss the point in this paper, which as noted on the cover sheet, has become a somewhat unwieldy accumulation. This aspect of the holistic strategy is now dealt with in a paper in the Proceedings of the 30th Conference of the International Association of Energy Economists entitled "*Policy Instruments for a Sustainable Energy Future*" (visit www.vuw.ac.nz/iaee07/)

- 3) RP are similarly spending time arguing against the Kyoto Protocol and its emphasis on domestic action. See e.g., footnote 8: "The vision presented here is in contrast to the protocol's vision of greenhouse gases as pollutants". Here it is again unclear and unnecessary: in Kyoto you are also allowed to plant trees in the South and gain credits for that. The reason why avoided deforestation is not included depends largely on the fact that it is technically very difficult. The whole critique against Pigou and the K. Protocol seems misplaced, like a red herring. Why not focus on their main task?

Avoided reforestation is not technically difficult. What is difficult is monitoring and measuring its effect and determining the baseline, all of which is necessary under the accountant's paradise created by the cap and trade approach. But if you are just

obligating energy companies to grow new forests, and if you establish effective sustainability conditionality (that includes sustainable forestry practice in existing forests) then you can achieve avoided deforestation without incurring all the difficult accountancy. This is but one example of the general problem with Kyoto – that its cap and trade framework limits and constrains managements, setting up a bureaucratic nightmare of approved methodologies and carbon accountancy, rather than liberating entrepreneurial ingenuity to get ahead of the pack, innovating and deploying the technologies that can deal effectively with the problem.

- 4) The main result in the paper is, as stated in the abstract: “illustrative calculations point to the feasibility of a return to pre-industrial CO₂ levels before mid-century”. But in a paper, cited by PR, and written by Read and Lermitt and published in 2005 in *Energy*, the international journal a similar conclusion is offered “Modeling shows that, using BECS, and under strong assumptions appropriate to imminent ACC, preindustrial CO₂ levels can be restored by mid-century.”

Unfortunately, there was an error in the modelling of the CO₂ net emissions to CO₂ levels process in Read and Lermitt (originally an IAEE paper, Prague, 2003, and restricted to the forestry technology only), which resulted in an over-estimate of its effectiveness. I became aware of this in discussions with some carbon cycle experts at the Exeter conference in February 2005, by when it was too late to correct the paper in press. So the calculations for RP contain corrected modelling of the emissions-to-levels process for which I am indebted to my colleague Parshotam. But our calculations also involved two more land using processes (sugar cane and switchgrass). The effect of these changes was to bring forward the return to pre-industrial levels to 2040. It is good to see that this reviewer, unlike most before him so far as I can detect, has delved into the background material in the appendix.

- 5) Many reviewers have problems with the economics of the paper. I share these views (as already indicated). They diffuse a feeling that returning to very low concentration levels can be done without cost, or at low costs, and that the plantations are value adding to the land etc. The only piece of information they offer is that with oil prices above 35 USD/barrel ethanol in Brazil is profitable. This is the only argument in favour of the much more general statement (from the abstract): “the first stage can provide several environmental and socio-economic side-benefits while yielding a positive financial return if oil prices remain above 35 USD/barrel.” This generalization of the argument is simply not true. Even if ethanol in Brazil may be profitable at an oil price above 35 USD/barrel, this does not mean that biomass for electricity generation wins over coal – which cost less than biomass (even in tropical countries with short rotation forestry). Further, ethanol from 5 Mha of plantations in Brazil, well fed with rain and well managed, is different from the 2 billion ha plantation proposal that they offer, much of which would end up at places much more limited in rain than the 2000 mm, or more, per year levels that Brazilian plantations enjoy.

1 billion Ha (only) of forestry, .72GHa of temperate switchgrass, .43Gha of sugar cane. There is no reason to suppose that Brazillian rain is any different from African rain, in well watered parts of Africa close to the equator. Or in parts of southern and SE Asia and tropical Australia. The competitiveness at 35\$/bbl relates to sugar cane, and, over a 25 year period, there is no reason to suppose that what is done in Brazil cannot be done elsewhere, given inputs of capital from an oil industry deterred by policy from further investment in Athabasca. I believe that the world record for sugar cane productivity, 1300GJ/Ha-yr, was achieved in Zambia. Our paper assumes considerably slower technological progress than Moreira [28]. \$35/bbl is also the projected breakeven price, given foreseeable technological progress, for ethanol from the cellulosic fermentation process, detailed in relation to switchgrass by Greene et al [27] but equally applicable to the processing of woody biomass, and now teetering on the brink of commerciality.

Turning to power generation, my understanding is that energy crop biomass is competitive with coal if the latter is burdened with CCS. But throughout the technology discussion it should be noted that biomass for power is the ligneous residual of crops that have been used initially for high value food/fibre, and after cellulosic fractions have been converted to medium value ethanol.

As regards land, much would come from degraded and logged over tropical forest (and from further deforestation until it can be stopped) which presumably remains well watered. That seems likely (there are widely varying estimates of how much land actually is degraded) to last for a decade, by which time both the level of concern over ACC and understanding of the effectiveness of the holistic strategy will have evolved and decisions taken regarding the need to intensify the strategy (e.g. by moving on to more land and to the second stage, by linking bioenergy to CCS). Beyond degraded land, open woodland and savannah would likely be used, with reduced rainfall compensated for by technological progress with appropriate cultivars, likely including GM (where the concerns shared by many, including me, regarding its incautious exploitation are diminished if, as with forestry, the end-uses of the product do not include its entering the food chain). The essence of any precautionary policy is to take early steps that enable subsequent more drastic steps to be taken if the later situation warrants it. Whether it was desirable to complete the Long March is for history to decide, but what is certain is that it would not have been completed without taking the first step. Our paper is simply to demonstrate that a return to pre-industrial levels in a few decades is feasible and to argue that the first steps are likely low cost and widely beneficial. As regards later steps, that is for current schoolchildren to decide. But they may not thank us if we deny them opportunity to take that decision.

- 6) Another aspect with the economics is that the paper never really explains why a biomass + biomass with carbon capture and storage strategy should be preferred over a broader approach. I am even uncertain whether that is what they are proposing, but it certainly seems so.

The reviewer fails to grasp the crucial importance of negative emissions systems for controlling CO₂ levels fast, if needed in response to the threat of ACC. If the reviewer knows of some other technology for extracting CO₂ from the atmosphere (apart from David Keith's proposal for washing it out with amine solutions) I would be glad to hear of it, especially if it also produces useful fuel.

Meanwhile, in logic (though I don't advocate it) we need an inefficient energy system entirely fuelled by biomass linked to 100 percent efficient CCS.

Then CO₂ removals =

((Final demand for energy – fossil fuel supply – non-fuel renewable supply)/energy efficiency) X CCS efficiency,

Thus, with 400EJ/year final demand, zero fossil fuel and wind generators etc., 10 per cent energy conversion and 100 per cent efficient CCS,

Removals = $\{[(400 - 0 - 0)/0.10] \times 1\} \times .095 \text{ GtCO}_2/\text{EJ in dry biomass}$

= 380 GtCO₂/year = ~50ppm and we are back to pre-industrial levels by 2010

- 7) On page 11, they write: "... suggests that the technology types involved should have priority over deploying zero emissions technologies". This statement comes right out of the blue. There is no explicit reason explaining why this should be the case, would costs be lower, or what? This is one example of why the economics of the paper is not really satisfying.

The reviewer appears not to have read the first half of the sentence, which reads

"Consideration of beneficial environmental and socio-economic developmental externalities, and of concerns regarding potential abrupt climate change suggests..."

nor to be keeping in mind that the rationale of the holistic strategy is on preparedness for the threat of ACC becoming imminent. That it also seems to be more effective than 'emissions reductions' in addressing gradual climate change is a bonus but is not central to the two-stage strategy.

- 8) Footnote 4, where they write that Obersteiner offers intellectual priority in the BECS concept to Read is very strange (seems like an internal discussion they have had, but why is it relevant to the reader?). The option was discussed already in Ekström, C., Blumer, M., Cavani, A., Hedberg, M., Hinderson, A., Svensson, C.-G., Westermarck, M., Erlström, M., and Hagenfeldt, S.: 1997, Technologies and costs in Sweden for capture and storage of CO₂ from combustion of fossil fuels for production of power, heat, and/or transportation fuels (in Swedish), Vattenfall Utveckling AB, Stockholm, Sweden, 1997. This is long before the 2001 paper by Obersteiner et al (read was a co-author).

Perhaps a little self-regard there, but it is of interest to some to know whose idea it was. Science editors presumably thought it was original when they published our letter. A pity Ekstrom et al did not realise the significance of the concept and draw more attention to it in 1997 – maybe we would by now be better advanced with dealing with Climate Change if they had. If the reviewer is who I think he is, he was one of the co-authors of the letter to Science and should have drawn our attention to Ekstrom et al at the time.

- 9) Finally, two comments on the content. First of all, the area supposed to be used for these plantations is enormous. Two billion hectares covered by monocultures, or short rotation forestry. It is simply breathtaking. They do write that “experience with well-intentioned land use change has not always been happy”. But think of a process where a land area larger than that currently in use for agricultural suddenly should be added to the existing demand for land. We know that the expansion of a few million ha of soybean plantations in Brazil has caused an influx of farmers into the amazon, palm oil plantations are expanding in Malaysian and Indonesian rainforests, the state of espirito santos in Brazil has prohibited an expansion of eucalyptus. What they are proposing as attractive is no easy feat. Is it a reason for suggesting that the paper be not published? Whether 2 billion ha should be used or not is a value judgement rather a scientific statement about what the world looks like, so perhaps it is not a reason for not publishing. Nevertheless, one cannot avoid concluding that a sense of surrealism is created around their claim that we might reach pre-industrial levels already by 2040.

It is good to at last have a reviewer who appears to have read the appendix. But it is, as noted above, not 2bHa of forest but 1 bHa, the remaining 1.15 being in switchgrass and sugar cane. And not 'suddenly' but over 25 years starting in 2010. It restores to forest cover only half of what has been lost since 1800. 400GJ is a commercial average of some years ago from a region of Brazil with good climate and good management. 450GJ now according to the reviewer's data. As noted above, in relation to item 5) Brazil is not the only place with good climate, and, to start with, much land is available in degraded former tropical forest, and more will be before tropical deforestation is finally stopped. I see no reason why South-South technological transfer with Brazilian know-how should not result in similar average yields in Africa and Asia in the near to medium term future. The spontaneous expansion of bio-energy in Asian rainforests is mentioned explicitly in the editorial essay as being unsustainable, and implicitly in Line I of Figure 4 of RP

- 10) As regards their yield levels, this too must be considered extremely optimistic. They assume yields in short rotation forestry equal to: 20 ton DM/ha/year (equivalent to 400 GJ/ha/year). They cite data from Aracruz, but this is probably one of the best performing companies in the world, on good soils and in rainy areas (keep in mind that Aracruz have been prohibited from expanding plantations in one of its main areas, espirito santo). See

the following cite from a report on Jari a competitor: “Furthermore, while in North America the average yield from a forest in 2000 was 3.0 m³/ha/year, Jari’s yield rate was closer to 29 m³/ha/year (Brazilian competitor Aracruz led the eucalyptus market with 45 m³/ha/year)” (see http://www.oikos-foundation.unisg.ch/homepage/oikos_online_Jari.pdf#search=%22average%20yield%20aracruz%22). (In order to get tonnes per ha/year, divide by two).

It may also be compared with yield levels of cereals, which on average over 800 mha of land, “only” amount to a little bit less than 3 ton grain, and perhaps 6 ton /ha/year above ground biomass.

As regards prospects for technological progress it may be noted that, although coppicing is possible with the eucalypt cultivars used in Brazil, plant breeding programmes are so successful that plantings are replaced with new cultivars after the first crop. 1000GJ/Ha-yr is the small plot record from advanced eucalypt cultivars. The Strategy involves a progressive programme, no doubt starting with the most promising locations first, for 40 MHa.p.a. for 25 years with continuing technical progress both before and after 2035. Increasing management experience and special plant breeding for more difficult conditions may enable the extensive margin to match the average productivity of earlier converted areas. Most likely the average reached at any point in time would be high productivity intra-marginally and lower productivity on the fringe. Yes, it is breathtaking, but not quite so breathtaking as the consequences outlined in the Stern Report of ignoring potential abrupt or very rapid climate change.

In summary, clearly, their yield levels are attainable on individual plots and in areas with lots of precipitation, but reaching them on 2 billion ha of lands (currently not in used for agriculture) seems very hard. I am sceptical. Is it a reason for not publishing? I do not know. But once again it creates an aura of science fiction around the whole paper. The authors may for instance consider calculating how much water would be needed in order to produce all this biomass – the answer is clearly much higher than the total amount of water withdrawn for the current global agricultural system (see paper by Berndes 2002 in *global environmental change* for an assessment of water requirements for much less optimistic scenarios).

Water is of course an increasing problem. Too much of it in some places [amazingly Somalia, as I write] too little elsewhere. With the engineering and organising capability of the oil industry focused on tilling rather than drilling, no doubt their ability to manage huge capital projects can be turned to shifting fresh water to where it is needed and stopping quite so much of it being wasted in the oceans. Recharging depleted aquifers in times of flood would be a good start. I calculate that for every MJ generated by NZ hydro-electric schemes, 10 MJ could be got from biomass grown on water-constrained land that could be irrigated from the Hydro lakes. Admittedly heat from biofuel combustion is not the same thing as electricity, but neither does hydro take any CO₂ out of the atmosphere or thereby offer potential to stock carbon elsewhere.

An overall comment in relation to this extended review process

In retrospect, I feel somewhat remiss in my response to reviewer F who pointed me towards the emf 21 exercise, with which I became better acquainted when reviewing the WG3 contribution to AR4. I must confess that, having at least twice suggested to the emf people that they do an exercise on land use change, I was a bit surprised to find that it had happened without anyone telling me. Or perhaps they did, and I was so pre-occupied with convening the expert workshop [footnote 2 of our paper, selected peer-reviewed articles in Mitigation and Adaptation Strategies for Global Change, 11/2] that it passed me by.

However that may be, I now feel that the interaction with reviewers has run at cross purposes and may (hopefully not) become the start of a re-run, in relation to land-use-change mitigation, of the 1990's top-down//bottom-up confrontation over the cost of energy sector emissions reductions. My best recollection of that debate is that it was resolved by the development of MARKAL style models that embedded a macro-economic representation of demand in a technology-rich dynamic optimisation of energy supply. Looking at some of the emf 21 papers reviewed in Chapter 3 of AR4/WG3 they use methodology that is clearly incapable of encompassing the kinds of technological change depicted in our paper.

Specifically they do not

- Model a range of crops that are unused commercially but which become of significance in a carbon management framework
- Model the potential of biochar soil improvement or of ramial wood
- Model potential policy-induced change in traditional land-use practices [forestry rotation a joint function of wood price, fuel price and carbon price// a shift to no-till or minimum-till arable practice // under-cover vs outdoor stock husbandry, and many other]]
- Model co-production of energy with traditional products of the land
- Model induced technological change, implicit in the RP claim for low costs (Gritsevskiy & Nacicenovic 2000, Barker, Pan, Kohler, Warren and Winne, 2006)
- Model the potential of improved water management under large capital inputs.

So, not surprisingly, they vastly underestimate the potential of land-use change, a.k.a. the holistic strategy. So far as I recollect, the outcome of the debate in relation to energy sector mitigation was (in soccer score terms) Bottom Up 4, Top Down 1. Hopefully top-down modelers of land use change mitigation will be careful to state the limitations of their kind of analysis in their future publications and thereby avoid misleading the policy community with gross under-estimates of the potential of mitigation strategies that envisage a technologically innovative approach to biosphere management.

Without developing a MARKAL-style model to include the full range of potential land using and product-of-the-land processing technologies and potential induced technological improvements, and endogenising agent choices over spatially differentiated data sets, there can be no methodologically acceptable analysis of the holistic strategy (or any other mitigation strategy that takes account of the main exchanges of CO₂ between the atmosphere and the terrestrial environment). Could take a decade or so. Meantime we have Art 3.3 of the Convention telling us not to wait for full scientific certainty.

In due course we intend to rewrite the paper, leaving out the advocacy, which is now appearing as an editorial essay in Climatic Change, and the critique of the Pigovian approach, which is in my paper for the 30th IAEE annual conference being held this year in Wellington, and comparing our results to the relatively disappointing results of the top-down literature.