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Bio-energy with carbon storage (BECS): a sequential decision approach to the threat of abrupt climate change

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Abstract

Abrupt climate change (ACC) is an issue that 'haunts the climate change problem' but has so far been neglected by policy makers. This may have been because of an apparent lack of practicable measures for effective response, apart from risky geoengineering. If achieved on a sufficiently large scale, a portfolio of Bio-Energy with Carbon Storage (BECS) technologies, yielding a negative-emissions energy system, may be seen not only as benign geoengineering, free of the risks associated with other geoengineering, but also as one of the keys to being prepared for ACC. The nature of sequential future decisions is discussed; these will need to be taken in response to the evolution of future events, which is as yet unknown. The impact of such decisions on land-use change is related to a specific bio-energy conversion technology. The effects of a precautionary strategy, possibly leading to eventual land-use change on a large scale, is modeled using FLAMES (see Appendix A). Modeling shows that, using BECS, and under strong assumptions appropriate to imminent ACC, preindustrial CO_2 levels can be restored by mid-century. Addressed to ACC rather than gradual climate change, a robust strategy related to Article 3.3 of the Convention may provide the basis for rapprochement between Kyoto Parties and other Annex 1 Parties.

1. Introduction

It has been suggested in a US National Academy of Science Report [1] that the threat of abrupt climate change (ACC) may be increased by raised levels of greenhouse gases. Taking steps to insure against ACC was identified by Schelling [2] as the primary rationale for early greenhouse-gas

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mitigation by industrialized countries. Moreover, ACC was recognized in the Third Assessment Report of the IPCC [3] as an issue that 'haunts the climate change problem'. ACC has, however, been neglected by policy makers, who have struggled to achieve consensus by negotiating commitments to emissions reductions in response to the 'absent problem' [4] of gradual climate change. This has been without regard to the specific technological requirements of ACC insurance. However, recent advances in technological understanding [5] suggest the availability of an insurance strategy that addresses the issue in terms of policy-driven technological change while offering side benefits in terms of fuel security and sustainable development. Crucial to such a strategy—and not discussed in this paper—would be improved scientific understanding of ACC to yield the capacity to recognize precursor signals of an imminent abrupt change in the climate system. Also not discussed in detail in this paper is an aspect of the new technological understanding which is advancing rapidly, namely, technologies for carbon capture and storage (CCS), disposing of CO_2 underground and, possibly, in deep oceans.

Both CCS and bio-energy are technology types rather than specific technologies. CCS involves either pre- or post-combustion separation of CO_2 in either new or retrofitted plant and its disposal in a variety of receptors, including secondary oil recovery, coal bed methane, exhausted hydrocarbon reservoirs, saline aquifers, and even deep ocean. Bio-energy can provide energy carriers to meet final demands for both stationary and transportation needs, through a variety of technology chains involving numerous sources of biomass raw materials derived from wastes or from dedicated land used for energy plantations or annual energy crops. Whichever is specified, the combination of a pair of technologies involving one from each type leads to an energy system with negative emissions characteristics, i.e. Bio-Energy with Carbon Storage (BECS). In combination with raised energy efficiency and non-fuel renewables, this system also provides the potential for a rapid return to preindustrial CO_2 levels [5]. Negative emissions energy systems are key to responding to ACC because—taking account of rising levels on non-CO_2 greenhouse gases for which there are no means of accelerating natural removal processes—there may be a need to get to CO_2 levels that are below preindustrial. This cannot be done by natural absorption, even with zero emissions energy.[1]

In this context it should be noted that the 'two times CO_2' criterion, much cited in the literature, is a social construct devised as a basis for model comparison and influenced by outdated ideas as to what level it is feasible to aim for. It has no scientific basis as an indicator of what the FCCC's Article 2 'non-dangerous' level is, and does not indicate a threshold for initiating ACC. In the absence of appropriately focused new research, and given the inertia of the climate system that obscures the eventual effects—possibly abrupt—of current and past emissions, climate science cannot tell us whether *any* excursion above the preindustrial levels of greenhouse gases, as has occurred in the last century, does or does not significantly increase ACC risks.

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[1] This is because zero emissions will result in CO^2 levels converging asymptotically—eventually very slowly—on the levels in natural absorbers, in particular in the surface layers of the ocean that turn over very slowly, that now have levels elevated above the preindustrial because of a century of absorption from the atmosphere's raised levels. Note that, apart from BECS as a negative-emissions energy technology, it has been proposed that power station sized CO_2 absorbers, one for each power station and roughly doubling the cost of power generation, could be located in non-fertile areas [21]. If the power plant itself uses CCS, then the overall system is also a negative-emissions energy system. We do not envisage this technology would have a role unless land shortages become acute.

2. Sequential decisions in relation to ACC

ACC is a sudden shift in climate regime. It may have only minor impacts, to which *post hoc* adaptation is acceptable. In this chapter, the focus is on other ACC events that may be more serious, even catastrophic, and for which the policy focus is taken as one of preparedness for strong mitigation, or attempted prevention, in the event of precursor symptoms. Of this latter variety are shifts into and out of the major reallocations of surface water that characterize both ice ages and ice-free periods. An ice-free period has not occurred for half a million years, when the present ice caps formed. There have, however, been several ice ages during that period, with the onset of some glaciation episodes having taken no more than a few decades. Such rapid transitions are a potential feature of nonlinear dynamic systems like Earth's climate system, and are generally heralded by precursor signals: compare, for instance, a kettle that, when heated, 'bumps' before the transition from convective circulation to mixed phase (steam-water) turbulent boiling. The detection of precursors of ACC depends upon the type of climate transition that is anticipated. But given the timescale of the shifts that are of concern, one may expect—or at least hope—that precursor detection will give several decades' warning. Where the driver is raised CO_2 levels, and perhaps in other cases, this offers the prospect of effective response using a negative emissions energy system.

Provided that research is done to enable recognition of such precursors, climate scientists might state in 2020 that a climatic instability would be initiated with, say, 10% likelihood, unless a target reduction in CO_2 levels is achieved by a target date. For example, this might be in relation to the melting of North-Polar sea ice, reported to be half as thick now as half a century ago. The total loss of this sea ice may lead to an Albedo-driven instability in which an ice-free Arctic Ocean would absorb summer sunlight, rather than this being reflected by ice, as at present. Supposing that 10% likelihood is the political trigger for a 'Manhattan project'[2] -style climate-stabilization action plan, then timely preparations could make the difference between feasibility and infeasibility. This concept is illustrated in the Table 1 below, where upper-case Yes and No [Y,N] relate to the possible situation with a robust strategy involving preparedness for large-scale use of BECS, as illustrated later in this paper, and lower case yes and no [y, n] relate to the alternative possible situation with initial business as usual, without preparedness measures. Note that this table is hypothetical except to the extent that the present work suggests that 380 ppm in 2030, 300 ppm in 2050 and 250 ppm in 2070 might be feasible given Manhattan Project-style urgency from 2020 onwards (see Fig. 4 below, where the vertical axis is calibrated in Gt, with 1 ppm = ∼2.1 Gt).

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

- climate science capacity to recognize precursor signals of ACC; and
- development of CCS technology, and capability to link with bio-energy systems; as well as initiating programs that involve a long lead time, i.e.
- a land-use change program, potentially on a very large scale, and a related program of capacity building, to be prepared for bad scientific news that may reveal the need for Manhattan project-style carbon management.

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[2] 'Manhattan Project' was the code-name given to the vast scientific and technological effort to develop the atomic bomb in the United States during World War II, under conditions of extreme secrecy and militaristic discipline and organization.

Table 1
Hypothetical feasibility of dated CO_2 target levels with and without ‘be prepared’ policy

Target level/ date	500	450	400	350	300	250	200 ppm[a]
2030	Yn	Yn	Yn	Nn	Nn	Nn	Nn
2050	Yy	Yy	Yn	Yn	Yn	Nn	Nn
2070	Yy	Yy	Yy	Yn	Yn	Yn	Yn

[a] Note CO_2 equivalents of non-CO_2 gases are expected to reach 100 ppm by the end of this century.

Thus a robust strategy requires a more technologically specialized approach than is stimulated by Kyoto, including a more positive commitment to land-use change as the basis for the major role for BECS that may be needed. It may be noted that a substantial program of land-use change is in any case needed if bio-energy is to take the place that is envisaged for it in most non-nuclear low-emissions scenarios [6].

The threat of ACC may therefore serve to stimulate bio-energy development that is currently lagging behind these scenarios, as illustrated in Fig. 1 (taken from Ref. [6]) where the plantation biofuel curve (right-hand axis) is drawn through a set of points representing biofuel utilization in a variety of scenarios, after allowance is made for the use of non-plantation biomass raw material from various agricultural and other organic wastes. The land needed for this biofuel production is plotted to the left-hand axis, with an assumption of rising productivity due to learning processes. (Note that the convergence of these two graphs is of no significance, being due to choice of scales on the two vertical axes).

The arrows and question marks indicate the extreme unlikelihood that the 2020 outcome will be achieved, hence prompting the view that bio-energy is lagging. Bio-energy technology is frustrated, it would seem, by a market coordination failure between landowners, as prospective biomass producers,

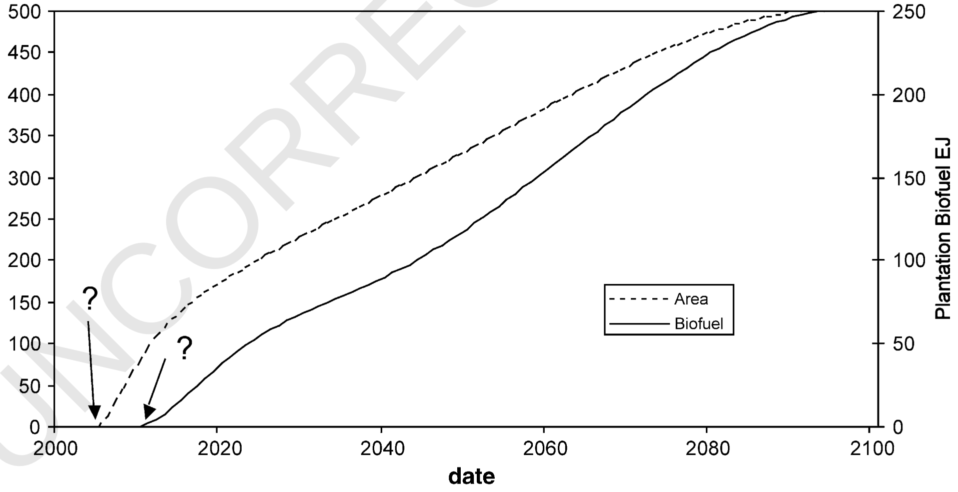

Fig. 1. Plantation biofuel (various scenarios) and needed land-use change [6].

and energy managers, as future biomass users, possibly separated by distance, time (given time to grow for plantations), and cultural barriers.

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

These stages are taken to represent the outcomes of different sequential decisions in different places. In land-rich but otherwise low-income developing or impoverished least-developed regions, the first stage is a shift from unsustainable subsistence patterns of land use, with traditional bio-energy, to a cash-based agro-forestry rural economy with high-efficiency domestic bio-energy. The second stage is to provide access to modern energy carriers in rural locations while yielding an import saving and/or liquid-biofuel-export-led development strategy. In this, the scale and timing of exports would be related to the pace of oil price rises in the context of prospective peaking of conventional oil supply. And the third stage, at higher cost, is in response to elevated carbon prices resulting from bad climate-science news of precursor signals of imminent ACC.

In developed countries, decisions on the three stages would be differently motivated—the first as a farm-support policy that establishes a buffer stock of biomass fuel raw material in response to concerns over security of energy supplies; the second as a precautionary demonstration of the technology chains needed for a negative-emissions energy system, thus driving ‘learning by doing’ with BECS (learn then act— [7]); and the third, again, as a response to high carbon prices reflecting precursor signals of imminent ACC.

It may also be noted, in relation to both developed and developing countries, that the creation of a long-rotation buffer stock on otherwise unforested land increases the global area of managed forest as a source of jointly produced timber and biofuel raw material. In the event that threats of ACC are not substantiated, entailing likely continuation of the current premium market value of timber products, this increase in managed supply may serve both to relieve pressure on biodiverse natural forests and ease long-range concerns of the paper and pulp industry regarding raw material supplies.

3. Modeling BECS

3.1. Order of magnitude

To acquire a feel for the potential of policy-driven land-use change, we first consider a simple ‘back-of-envelope’ calculation. Assume 500 MHa of policy-driven biofuel oriented plantations globally by 2030. This is ∼40% of the usable land described by the FAO as surplus to agricultural needs in 2050 (when population is projected to stabilize—United Nations [8]). Five hunderd MHa is also about 40% of the 2040 ‘maximal’ long-rotation land illustrated in Fig. 2 below (see Section 5.1 for a discussion of the ‘maximal’ concept). And it is about 30% of the very large land area under short-rotation bio-energy cropping that is envisaged, in Fig. 2, to be achieved after half a century, beginning 2020, of a sustained Manhattan Project- style effort to avert imminent ACC.

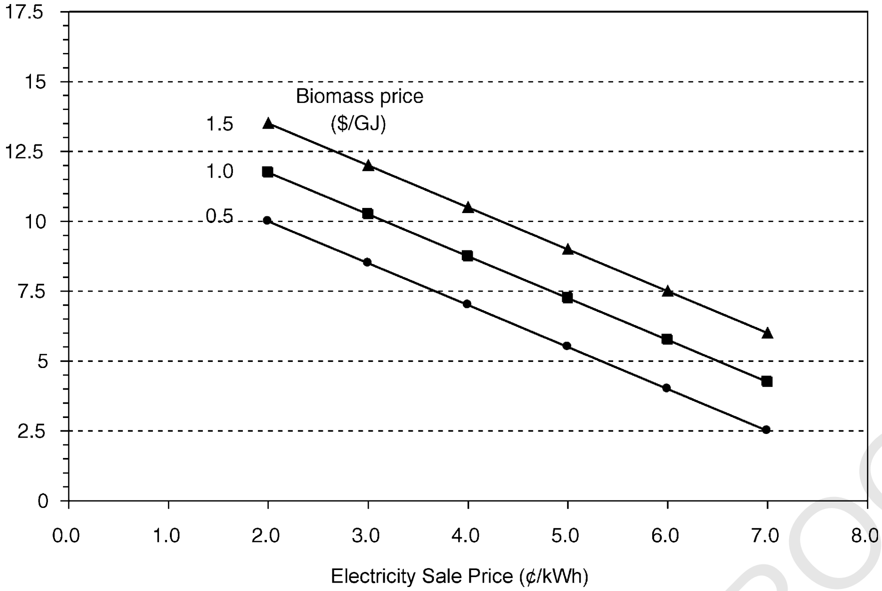

Fig. 2. Estimated production cost of Fischer-Tropsch LPG from biomass in a ‘once-through’ facility as a function of sale price for co-produced electricity.

Assume also productivity of 500 GJ/Ha as an average,[3] across land areas and productivities, in a variety of regions where policy-driven land-use change could take place. This productivity is less than half that presently achieved commercially [8] with best-case sugar cane—1300 GJ/Ha in Zambia—and best-case eucalypt—1000 GJ/Ha in Brazil. Thus the biomass productivities already achieved in tropical conditions, which are under continuing improvement, far exceed what is feasible in temperate conditions. The latter is less than 200 GJ/Ha, and any future production of bio-energy raw material in these regions would be the outcome of a shift, over the coming decades, in the pattern of rural community support from the current pattern of food production subsidies to one of enhanced energy security and environmental stewardship.[4] With low rents, lower wages, and higher primary land productivity, the costs of biomass raw material in tropical regions are a fraction of those that obtain in temperate regions.

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[3] The potential supply of biomass raw material, i.e. land productivity times land area used, has been analyzed in depth in a recent PhD Thesis ([23] Chapter 3) which suggests that the land area proposed in this order of magnitude arithmetic is on the low side and the productivity is on the high side. Under four SRES scenarios applied to the Image 2 model database, and involving perspectives on technological progress, CO^2 fertilization and exclusion by priority uses, aggregate energy cropping is put (in EJ per year) at 657, 311, 451 and 322 in 2050 and 1115, 393, 699 and 525 in 2100. The value of 250 EJ used in the text appears to be moderately conservative. However, it should be noted that the most important land-use change involved in Hoogwijk’s estimates is abandoned agricultural land, which becomes available because of the expectation of a global population plateau around 11b from ~2050 and assumed continuing increases in agricultural productivity

[4] It is beyond the scope of the present paper to discuss the transformation of agricultural production subsidies into the hoped-for land stewardship incentives deriving from a global reappraisal of commercial land use and tourism-driven ecosystem conservation, post-Cancun and in the context of EU enlargement and US budgetary and energy security concerns: the extent to which it is sensible to shift bulky energy products rather than higher-value food products over long distances is an under-developed field of research.

Under these assumptions, there is a supply of 250 EJ annually which, with 30% efficient conversion, can displace 115 EJ of crude oil (assumed five-eighths transportation fuel fractions) annually. This efficiency corresponds to the prototype technology of the following section, from which high-grade waste heat feeds thermal electricity generation as the basis for distributed energy for sustainable rural development. Advances in technology may be expected to raise this figure toward 50%, displacing more oil but with less CO_2 'in the smokestack'[5] for capture and disposal underground, and proportionately less electricity (for which local market opportunities could not be expected to grow in line with an export market for bio-based liquid fuels, expanding as conventional oil declines).

Allowing for slow initial build up, 8000 EJ of oil is displaced this century, equivalent to about 1.5 million barrels, i.e. 1.5 times the global proved reserves or 50 times the current annual consumption, and—with 12,000 EJ renewable each subsequent century—plausibly sufficient to keep pace with rising demands for fuel for transportation, given continuing increases in plantation productivity, conversion efficiency, and vehicle fuel economy (e.g. with on-board reforming of bio-methanol as hydrogen carrier for high-efficiency fuel cells).

The significance of meeting transportation demands renewably is that these represent dispersed sources of emissions for which CCS is—just like the various forms of ambient energy conversion such as wind generation—infeasible. Thus an overall zero (or negative) emissions energy system must—in the possibly quite-extended interim prior to the arrival of the hydrogen-energy economy—address these emissions through bio-energy (linked to CCS at the processing plant in the case of a negative emissions system). It will be noted that the assumptions employed below to represent a Manhattan Project-style response to imminent ACC include, inter alia, the fitting and retrofitting of CCS technology to all large (stationary) point source emitters of CO_2, both fossil and biofueled.

Nevertheless, in relation to concerns regarding possible 'peaking' of global oil supplies, and with delivered costs of bio-energy raw material of under $2/GJ, and regardless of C_{at} considerations, there would seem to be a significant case, on security of supply grounds alone, for growing liquid fuel raw material as well as drilling for it. Of course, while the bulk of supply would still be internationally traded, it would be sourced from a wide variety of biomass-producing countries. In the absence of large rents, such as are captured through exploiting low-cost conventional oil reserves, global bio-energy trade could be expected to approximate the benign characteristics of perfectly competitive markets.

3.2. Technological characterization

Meeting the variety of demands for different final energy services with negative CO_2 emissions entails a portfolio of specific BECS technologies with the bio-energy component related to the pattern of demand and the carbon storage aspect related to local geophysical potentials. There is no guarantee that permanent storage places such as saline aquifers are located near the biomass production regions; moreover, compression and long-distance transmission of CO_2, possibly expensive, is part of the envisaged high-cost response to imminent ACC threat under the third stage of sequential decisions discussed above.

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[5] In practice Fischer-Tropsch technology would enable the separation of CO^2 to be done precombustion, after a shift reaction is used to provide a hydrogen-rich reaction gas.

In the current paper we are concerned with the carbon in atmosphere (C_{at}) implications of BECS and take the characteristics of ‘once through’ Fischer-Tropsch joint production of liquid fuels and electricity [9] as typical. This conversion technology is suitable for linkage with community-scaled biofuel plantations [10] and, in combination with precombustion removal of CO_2 and disposal in saline aquifers [11], is taken as a prototype BECS technology.

Larson and Jin describe a plant that produces 493 TJ liquids and 74 GWh (266 TJ) electricity annually from 1715 TJ biomass feedstock. The described case was designed to produce LPG as a substitute for cooking kerosene in Northeast China, but the process can be tuned to deliver other liquid fuels such as synthetic gasoline or diesel. We assume this displaces 800 TJ crude oil (five-eighths transportation fuel content) and 666 TJ coal in alternative 40%-efficient generating plant, and that the fuel-oil fractions of displaced oil are replaced by renewable energy and increased end-use efficiency. This gives 90% fossil carbon displacement (previous work has assumed 100%), with 75% of the carbon in the biomass raw material available for CCS treatment. In modeling a Manhattan-Project response to ACC precursors, we assume below that only 30%, or 40% of what is available, is in fact sequestered underground.

Viability rests on the costs of biomass raw material, the market value of the joint products, and the reward for C_{at} reductions established in the emerging international market for CO_2 emissions permits. The relationship for this prototype technology in the case of zero reward for CO_2 reductions is illustrated in Fig. 2, reproduced from Larson and Jin’s paper. With 90% fossil fuel displacement, the \$0.5/GJ spacing of the lines is equivalent to a CO_2 price of 6.1\$/tonne thus, e.g. costs are met with a biomass/CO_2/fuel liquids/electricity price vector = [1.5,12.2,5.0,5.3].

To supply this plant, a single energy plantation of 5 km radius, or several smaller ones linked by dedicated rail transportation, would be required for each prototype plant, with the number—one, several, or many—depending on the sparseness of settlement of the existing communities. This is because aggressive plantation development that is neglectful of local conditions is subject to fire hazard from aggrieved former land users. Thus community-scaled plantations are envisaged as the basis for socioeconomically attractive sustainable rural development and for supporting a global expansion of bio-energy markets, in line with the low-emissions scenarios summarized in Fig. 1.

3.3. The FLAMES model

FLAMES [12,13] see also Ref. [14] for a detailed model description summarized in Appendix A) has been developed to illustrate the market impacts and carbon dynamics of large-scale modern bio-energy. This involves, first, plantations that stock carbon[6] through the growth of biomass and, second its utilization, displacing future flows of high-cost fossil fuels, leaving the latter in situ underground. FLAMES simulates the interaction of energy, timber, and land markets under the impact of user-selected (policy-driven) land-use change. Plantations yield both bio-energy and timber as joint products, with the outputs treated as perfect substitutes, respectively, for fossil fuel as energy raw material and for other timber supplies in the forest products industry. Two fixed rotation activities—short rotations mainly for

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

biofuel, and long rotations mainly for timber—have been considered. Policy costs are spread across all fuel sales. C_{at} impacts are estimated as the aggregate of the stock and flow effects mentioned above.

An important methodological aspect, essential to representation at this high level of aggregation, is that model parameters used to generate new scenarios are not derived empirically. Clearly it would be wrong to search for a single world price for fossil fuel—still more so to build scenarios from a long-run projection of such a fiction. Rather, the approach used is to select model parameters so that the model mimics scenarios generated by others, e.g. using integrated assessment methods. Thus parameters are adjusted, under assumed nil user-selected (i.e. policy-simulating) land-use change, to mimic well-known C_{at} scenarios, and the impact of policy-driven land-use changes are then simulated as perturbations on these reference scenarios.

Recently the model has been further developed [15] in multiregion form with interregional trade. Most recently an optimizing version of the 1-region model has been developed to reflect the decisions of profit-maximizing landowners in relation to variable rotation length under model-consistent price expectations [16]. Research is in hand to combine these advances to further illustrate the potential of BECS as a component in a robust strategy for responding to the risk of ACC. In the current paper, the original 1-region simulation version is used to illustrate the effect of a flow of CO_2 from atmosphere to underground, under BECS technology, along with conventional carbon capture in fossil-fuel systems. In particular, the model is used to illustrate the effectiveness of BECS in the context of a Manhattan Project-style policy decision adopted in 2020.

4. Kyoto reference case and be prepared policy case assumptions

Previous publications based on the FLAMES model have employed two reference scenarios. Business as usual (b.a.u.) mimics the IPCC's IS92e or IS92f scenarios' C_{at} profile. Fossil-free energy scenario (f.f.e.s.) mimics the C_{at} profile of the scenario of that name prepared for Greenpeace by the Tellus Institute [17]. Each of these reference scenarios involves a fairly small role for bio-energy, making it appropriate to take them as the starting point for considering the impact of a large-scale additional bio-energy supply. The difference between the two mimic scenarios is achieved by changes in the parameters that relate to demand for fuel and to technological progress with fossil-fuel and non-fossil energy supply (see Table 2). The 'Kyoto' reference case takes intermediate values for these parameters on the basis that, without all Annex 1 Parties participating, and without the stimulus of scientific news of ACC precursors that turns the 'absent problem' into a 'present problem', the Kyoto Protocol's second and later commitments are unlikely to achieve stabilization of greenhouse-gas levels this century.

Under the 'be prepared' policy case it is assumed that CCS technology is applied to fossil fuel on an initially small but expanding scale and that the land-use change program used in previous work with FLAMES is initiated from 2005. This program (see Fig. 3) has two components: first a long rotation (35 years) conventional forest rotation planted in a half sinusoidal pattern over years 1–35 of the 70-year modeled period, and felled as it reaches maturity for use partly as timber and partly as bio-energy, with the split dependent on the relative product price; and, second, a short-rotation crop mainly for bio-energy planted on an initially small but exponentially increasing land area, to which is added half the long rotation land as it is cleared from year 35 (e.g. 2040) on (with the balance used for food and fiber supply to an increased but stabilizing global population).

Table 2
Parameters and leading results for various scenarios mimicked by the FLAMES model

Parameter	Scenario				
	b.a.u.	f.f.e.s	Kyoto	Precautionary (no ACC)	Precautionary (ACC precursor in 2020)
Initial fuel demand in 2000 (EJ) of which supplied by fossil fuel (EJ)	318	318	318	318	318
	300	300	300	300	300
Growth of per capita fuel demand[a]	0.0274	0.0274-atp[b]	0.0274-atp/2	0.0274-atp/2	Reduces after 2020
Technological progress with fossil-fuel supply	0.035	0.02[c]	0.0275	Trends downward both these scenarios	
Growth of fossil-fuel emissions[d]	0.015	0	0.0075	Trends downward through these scenarios because of CCS technology, faster after 2020 with ACC precursors	
Fuel demand in 2070[e] (EJ) of which supplied by fossil fuel (EJ)	3677	808	1690	1702	771
	3645	777	1660	831	15[f]

[a] Population increase averages.0076 (United Nations [8]) giving balanced supply and demand growth of 3.5% and long-term constant energy prices under b.a.u.

[b] Accelerated technical progress with renewable energy and energy efficiency from year 10 to 30 with compensating later slowing to represent technical limits (see Appendix A).

[c] Fossil fuel research discouraged by policy, leading to more rapid cost increases.

[d] Assumes 2% p.a. decarbonization from fuel switching.

[e] Fuel demand increase = increase in demand for final energy services minus increases in efficiency of conversion and utilization and minus increased use of ambient energy (wind, solar, etc.).

[f] High cost of CCS contracts demand and policy-led biofuel supply drives fossil fuel out of the market.

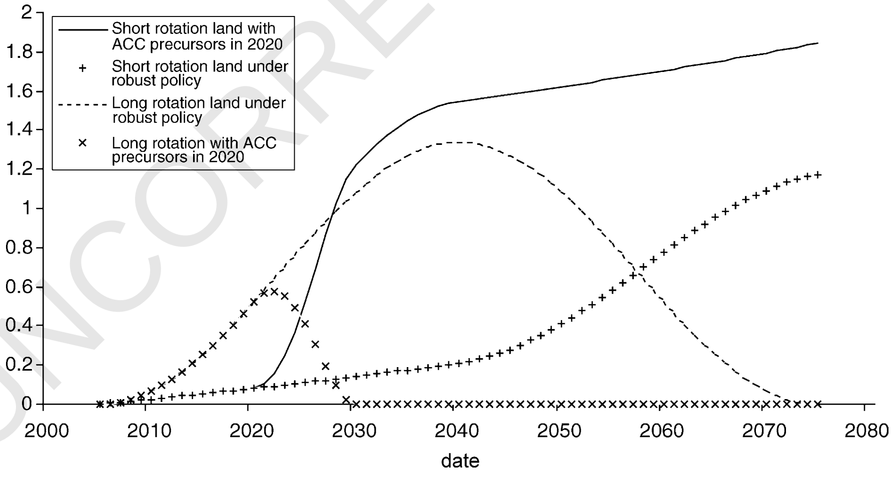

Fig. 3. Land use under robust policy with and without an ACC precursor event in 2020.

These activities are modeled to absorb carbon at 3 tC/Ha yr, constant, for the mature forestry technology and 6 tC/Ha yr rising to 18 tC/Ha yr over the 70-year-model time horizon, assuming biotechnological progress with novel energy cropping systems for the short rotation activity. If wholly used for energy, these figures correspond to ∼120, 240 and 720 GJ/Ha and may seem conservative in relation to the figures for currently achieved commercial scale production noted above [8]. Carbon in biofuel is assumed to displace carbon in fossil fuel at a ratio of 10:9, and carbon in timber is assumed to remain sequestered after felling as the additional timber supply reduces demand to fell forests elsewhere (most likely where forest residues are left to decay).

5. Assumptions employed to represent a Manhattan project-style response to ACC precursors

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

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

The effect of these measures is that emissions per tonne of fossil fuel fall from.025 to.015 tC/GJ and per tonne of biofuel from zero to −0.01 tC/GJ, with biofuel supply rapidly dominating the market. The outcome in terms of C_{at} concentration can be seen in Fig. 4. This shows that targets for CO_2 reductions that have so far seemed infeasible can be achieved with BECS technology provided that the necessary low-cost measures are taken in preparation for bad news of ACC precursors. ‘Learn then act’ may be appropriate for gradual climate change, but Noah built the ark before the rain started.

5.1. Caveats

The focus of the FLAMES model is on the additional impact of policy-driven land allocations. However, the surprisingly low C_{at} levels that result from large-scale land allocations that have been noted previously [13,18] require the simultaneous application of the low- and zero-emissions energy technologies involved in the f.f.e.s. scenario: in other words, the large-scale, policy-driven, land-use allocations illustrated in this paper are a necessary but not sufficient condition for the achievement of the low C_{at} levels mentioned above. By the same token, for the below-preindustrial C_{at} levels illustrated in this paper, large-scale negative emissions—achieved through widespread application of BECS technology—is a necessary but not sufficient condition.

Additionally, it should be noted that the very large land allocations that have been used in the FLAMES model are taken to be ‘maximal’. No decision taken this decade can predetermine the land

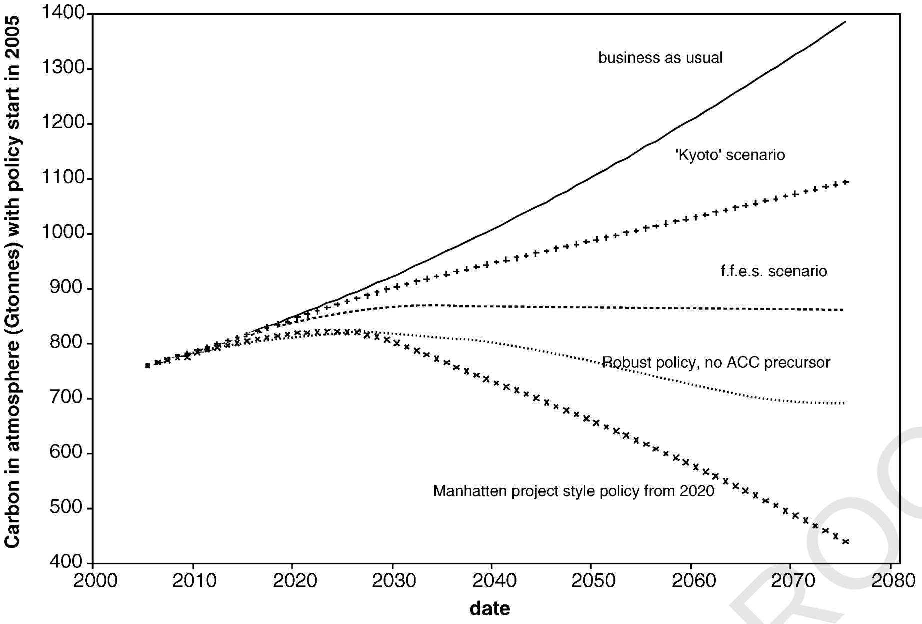

Fig. 4. Carbon in atmosphere profiles under various reference scenarios and under robust policy with and without an ACC precursor event in 2020.

allocations that will be made some decades ahead. Thus the implication of modeling large allocations over such a long period is that the initial phases of the program will be successful in demonstrating achievement in meeting socioeconomic and environmental acceptability constraints. If so, the initial phases can facilitate—or at least not inhibit—the ongoing sequence of policy makers' and landowners' decisions that is represented by such a maximal program. Thus such maximal allocations are a representation of the maximum amount of land that might be used for policy-desirable activities if the incentives were put in place—and sustained, to reward current landlords and land users sufficiently well to ensure that they continue to engage in such policy-desirable land use. Implicitly it is assumed that they desist from current land-profligate, slash-and-burn subsistence, nomadic herding, forest clearance, etc. investing their rewards so as to meet their food and other land-based needs better than at present, and more sustainably.

Conceptually the modeled maximal allocations are intended to represent the maximum possible policy-induced effect on the pattern of land use. This would constitute a change in the trend of land use and the following of a new path, starting from a near-future bifurcation in the evolution of land-use policy and practice toward stewardship rather than exploitation. And, logically, no degree of policy urgency can accelerate land-use allocations defined as maximal; if pushed too fast then disaffected communities will simply set fire to the plantations. This is not to claim that the land allocations modeled here are empirically maximal in this sense: if a better estimate of what is maximal can be made, then that estimate should replace the pattern modeled here. The point is that whatever can be done starting in 2020, more can be done and ACC threats better managed, by starting in 2005.

6. Commentary

Industry has been engaged in a massive geoengineering project over the last 200 years, most intensively in the last 50, that has seen 200 billion tonnes of carbon moved from deep underground into the atmosphere, with additional amounts into near-surface absorbers. To reverse that outcome is equally a massive geoengineering project. But unlike most of the geoengineering concepts that have been proposed, it is benign in its side effects rather than 'expensive, unreliable, dangerous, ugly and unwise' in the view of many ([4] who attempts to rebut this view in relation to a variety of geoengineering concepts that do not include BECS). The use of Michaelson's terminology of a Manhattan Project-style approach to carbon management is to recognize that this analogy is appropriate to the situation that would—or at least should—arise in the event of credible scientific demonstration of abrupt climate-change precursors.

However, the earlier stages of the robust strategy that has been outlined constitute a measured and rational geoengineering project in carbon management that aims to remedy the anthropogenic cause of climate change, rather than, as with other geoengineering, respond to the symptoms. It should commend itself to environmentalists when their well-intentioned objections[7] to 'sinks' in the Kyoto Protocol come to be seen as an over-zealous concern for the integrity of an emissions-reductions target that, in reality, is a somewhat misdirected first step in a long process. This will be seen more clearly when it is appreciated that Kyoto ignores the dictum that, in the long run, conflicts between environmental objectives and economic well-being have to be ameliorated by technological change [19]. Then it becomes clear that a better approach to the long process is to drive the necessary transformation of energy technology directly (e.g. by renewable portfolio standards) rather than to penalize emissions, an approach that inevitably provokes resistance by the energy interests most affected. Moreover, in focusing on limiting emissions, environmentalists have neglected the reality (see end note 1) that even driving emissions to zero is inadequate if ACC is imminent, and that bio-energy deployment that makes possible effective carbon management through BECS, i.e. future linkage with CO_2 capture and storage, is both a needed precaution and benign in its side effects.

The benign side-effects of remedying the cause are discussed elsewhere [20] but include:

- stimulation of the pattern of land-use change that is needed to meet the raw material demands of the bio-energy component embodied in most low-emissions scenarios;
- restoration of the preindustrial tree coverage (differently located as a result of human settlement, but restoring the former capability of forests to act as lungs to the living earth);
- empowerment of many developing countries to initiate their own 'country-driven' projects as the building blocks of their own sustainable energy development path;
- potential export-led growth for such countries, stimulating global macroeconomic growth, as bio-based liquid fuels take an increasing role in global transportation fuel supply;
- improved security of liquid fuel supplies, and reduced dependence on unstable Middle-East oil supplies; and
- improved farm support in agricultural surplus developed regions.

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[7] Apart, that is, from 'deep environmentalists' who see the true causes in a perversion of human nature manifest as consumerism, and whose concern is to change the ways of society. However much sympathy one may have for that view, it seems an impractical approach to the problem of ACC, which may become acute in a decade or so as, or if, climate science comes to focus on detecting its precursors.

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

1 a greater focus in climate science research on characterizing possible climate instabilities and being able to recognize precursor signals of ACC;
2 continuing vigorous research into CCS technology, ncluding into the problems of linking it to biofuel-based energy conversion systems; and
3 initiation of an environmentally, socially, and economically beneficial land-use change program (potentially on a large scale), as the basis for raw material supply to meet projected bio-energy demands, and potentially linked to CCS technology to comprise a negative-emissions BECS energy system if needed.

It has also been suggested [16] that this strategy, focusing on technology change rather than emissions limitation, offers the prospect of an industry-friendly approach to climate-change mitigation that could provide the basis for rapprochement between those Annex 1 Parties to the UNFCCC that have ratified the Kyoto Protocol and those that have not.

7. Conclusion

BECS, the linking of two technologies types—bio-energy and CO_2 capture and storage—that were considered separately in the Third Assessment Report of the Intergovernmental Panel on Climate Change, provides a powerful tool for reducing CO_2 levels faster than has hitherto been reported to policy makers as feasible. Provided that steps are taken to detect precursors of ACC, and provided that a long-term strategy of policy-driven sustainable land-use change is put in hand sufficiently soon, BECS may, in the future, help to enable imminent ACC events to be averted. Furthermore, the implementation of a global bio-energy program as part of a ‘be prepared’ strategy could provide numerous side-benefits. However, the practicability of these outcomes is entirely dependent on what the maximal allocation of land to bio-energy, discussed above under ‘Caveats’, proves to be in practice, an outcome for which confident estimates can be made only with cumulating experience of policy-driven land-use change.

8. Uncited reference

[22].

Appendix A. The FLAMES model

FLAMES (Fuel/Fibre/Food Land Allocation Model for Energy/Environment Sustainability) is designed to illustrate as simply as possible the impact in key markets (i.e. those markets most affected) and consequential impact on carbon in atmosphere (C_{at}) of large-scale land allocations (such as those in Fig. 3 above) driven by policy concerns to mitigate the C_{at} levels projected in long-term scenarios developed elsewhere (reference scenarios). The parameters in FLAMES are adjusted until the C_{at} projection of a reference scenario (chosen by the model user) is mimicked by FLAMES under conditions of nil policy-driven land allocation. Subsequently the effects of policy-driven land allocations on two activities, long-term (35-year rotation plantation forestry) and short-term (annual cropping, e.g. of sugar, or short-rotation energy plantations), are derived as a perturbation of the reference scenario. The key markets are those for fuel, for non-fuel forest products (‘timber’), and for land. These are modeled in a simple demand-and-supply (partial equilibrium) framework. The partial equilibrium approach is preferred to the competitive general equilibrium (CGE) methodology adopted in most integrated assessment models both for reasons of transparency to potential policy maker and market-player end users, to whom a general equilibrium approach is a ‘black box’, and because the CGE approach seems inappropriate to the modeling of ongoing technological change.

In the basic 1-region (global) model, there are three market equations which are connected by the full substitutability of biomass raw material for fossil-fuel raw material in supplying fuel demands, by the partial substitutability—in the market for biomass raw material—of demand for biofuel raw material by demand for timber, and by the substitutability of demand for land to produce biomass by demand for land for conventional farming, broadly conceived. These imply that, given the availability of appropriate technology for its conversion to marketable energy carriers, biomass raw material can meet any type of demand that can be met by fossil-fuel raw materials; that biomass raw material can only partially be used for conventional timber products, with residues available as fuel (but if timber product prices fall relatively, all biomass raw material can be used for fuel); and that farm-land and/or non-barren wilderness can be used for producing energy crops. The commodities traded in these three markets are very broadly conceived aggregates that require considerable interpretation as policy-driven land-use change generates changes in the quantities traded in the three markets. For instance, in the context of a business-as-usual scenario, the supply of bio-energy would likely be used mainly for decentralized combined power and heat, whereas a larger proportion would be converted to iquid fuels in a low-emissions scenario where much power is generated from ambient solar or wind energy.

The three market equations involve four prices, rent on (undeveloped) land, and the prices on timber, on biomass as fuel raw material, and on fossil fuel. The difference in price between biomass fuel and fossil fuel is equal to a tax on carbon in fossil fuel sales that is determined in a fourth equation, where the tax revenue equates to the additional costs of producing biomass fuel in lieu of fossil fuel. This method of recycling carbon tax revenues spreads the cost of bio-energy innovation across fuel sales as a whole, and mimics the effect of a renewable portfolio standard requiring a proportion of bio-energy in the energy supply mix. This contrasts with the marginal cost approach adopted in most models (under which all fuel prices would be raised to the level of the most costly bio-energy supply, with surplus revenues needing to be re-cycled through lower general taxes). It reduces the welfare costs of market contraction while increasing the rate of supply-side change, thus capturing the dynamic benefits of learning by doing with policy-desirable technologies.

In all markets, the price-dependent demand curves (for fuel, for timber, and for farmland) shift progressively to the right (i.e. more demand for a given price) by rising population and by rising per capita consumption but countered by the macroeconomic impact of the carbon tax (in practice *de minimis*). Supplies of fossil fuel also shift rightwards, because of technological advances, with supplies of biomass and timber dependent on the areas cropped of long-rotation (35 year [L_s] and existing commercial plantation land [L_p]) and short-rotation (L_b) plantations, with the split of joint product timber and bio-energy dependent on the relative price of timber and biomass as fuel (functions s_f, b_f, s_w and b_w). Long-rotation technology is treated as static but short-rotation productivity triples over the 70-year time horizon of FLAMES. The supply of land is fixed, with rents inversely proportional to the residual left to wilderness. Under these concepts, the equations of the economic aspects of the model are as follows:

A.1. Fuel market: (producers' price p, consumers' price $p+\tau=P$)

$$\begin{aligned}&(k_6 + k_7 p)\mathrm{e}^{k8t} + k_{34}\left(\frac{\mathrm{d}L_s}{\mathrm{d}t} - 35 + \frac{\mathrm{d}L_p}{\mathrm{d}t} - 35\right) S_f(s-P) + k_5 L_{b(\Sigma - Tb)} b_f(s-P)\\ &\quad = (k_{10} - k_{11}) e^{kFt} \frac{N}{N^0}(1-\alpha\tau)^{k12} \qquad \text{(A1)}\end{aligned}$$

non-biofuel supply + biofuel from long rotation + biofuel from short rotation = demand, a function of post-tax price, per capita demand shifts, population growth, and the macro impact of energy tax. Initial conditions are 2$/GJ, 300 EJ, neglecting traditional non-commercial bio-energy).

The rate of growth of per capita demand for fuel is implicitly less than the per capita growth of demand for energy because of improving end-use efficiency and increased use of non-fuel renewable energy. The exponential growth of emissions from fossil fuel (k21) is less than the growth of supply of fossil fuel because of switching to natural gas. The difference between reference scenarios noted in Table 2 in the paper is achieved through adjustments to k_8, K_f and k_{21} with the latter adjusted in a time-varying manner for f.f.e.s. as noted in footnote b.

A.2. Land Market: (price, r (i.e. rent))

$$L_p + L_s + L_b + 0.005t + (k_{15} - k_{16} r)\mathrm{e}^{kLt}\frac{N}{N^0}(1-\alpha\tau)^{k17} + (k_{13}/r)^{k14} = 6.5\ \text{bHa} \qquad \text{(A2)}$$

commercial forestry land + sequestration land + biofuel land + reference-case biofuel land + demand for farmland (a function of rent, per capita demand, etc.,) + wilderness = fixed supply of non-barren, non-forest land. Land left to wilderness inversely related to rent. L_s, L_b and L_p all functions of t with L_s and L_b selected by model user. L_p is depleted in proportion to population in reference case, modified by desequestration in policy cases. Initial conditions 1.9 bHa farmland, 0.7 bHa commercial forestry; 10/100$/Ha lo/hi rent cases.

A.3. Forest Product Market: (price s)

$$k_{34}\left(\frac{\mathrm{d}L_\mathrm{s}}{\mathrm{d}t}-35+\frac{\mathrm{d}L_\mathrm{p}}{\mathrm{d}t}-35\right)S_\mathrm{w}(s-P)+k_5L_{\mathrm{b}(\Sigma-Tb)}b_\mathrm{w}(s-P)$$

$$=(k_{31}-k_{32}S)\mathrm{e}^{kPt}\frac{N}{N^0}(1-\alpha\tau)^{k33} \qquad \text{(A3)}$$

long-rotation wood product + short-rotation wood product = demand for wood products, initially 1.3 bTonnes at 130$/tonne

A.4. Dedicated tax: τ

$$(r+k_4)L_\mathrm{b}+rL_\mathrm{s}+k_2\frac{\mathrm{d}Ls}{\mathrm{d}t}=pk_5L_\mathrm{b}+\tau(k_5L_\mathrm{b}+(k_6+k_7p)e^{k21t}) \qquad \text{(A4)}$$

rent + operating cost of biofuel land + rent and establishment cost of sequestration land = producer price on biofuel + tax on all carbon fuel (note, this is the equation for ECLAM; it is modified for FLAMES to include sales of wood product from policy land L_s and L_b as a cost offset, and with allocation of outputs to biofuel and wood products via b_f, s_f, b_w and s_w). Initial value 0 with zero initial policy-land.

Differential Eqs. A1–A4 are solved simultaneously using Matlab software and yield outputs that drive a very simple carbon balance equation. Further work will incorporate a more sophisticated carbon transport model, but preliminary work indicates that this will make rather small difference to the outcomes reported in Fig. 4 of the paper.

Additionally there is a Carbon Balance equation as follows:

$$\frac{\mathrm{d}M}{\mathrm{d}t}=\beta_\mathrm{f}(k_6+k_7p)e^{k21t}-k_1L_\mathrm{s}+\beta_\mathrm{b}\frac{\mathrm{d}L}{\mathrm{d}t}+\beta_\mathrm{s}\frac{\mathrm{d}L_\mathrm{s}}{\mathrm{d}t}+\beta_\mathrm{c}\frac{\mathrm{d}L_\mathrm{c}}{\mathrm{d}t}-\beta_n\left(\frac{M}{2}-280\right) \qquad \text{(E)}$$

Carbon to atmosphere = carbon fuel emissions - long-rotation absorption (with short- rotation absorption = short rotation emissions) + carbon from short-rotation land + carbon from long-rotation land + carbon from farmland (all relative to carbon in wilderness land)—absorption in ocean. Initial C_at = 760 Gt.

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