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Can radiative forcing be limited to 2.6 Wm^{-2} without negative emissions from bioenergy AND CO_2 capture and storage?

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Abstract Combining bioenergy and carbon dioxide (CO_2) capture and storage (CCS) technologies (BECCS) has the potential to remove CO_2 from the atmosphere while producing useful energy. BECCS has played a central role in scenarios that reduce climate forcing to low levels such as 2.6 Wm^{-2}. In this paper we consider whether BECCS is essential to limiting radiative forcing (RF) to 2.6 Wm^{-2} by 2100 using the Global Change Assessment Model, a closely coupled model of biogeophysical and human Earth systems. We show that BECCS can potentially reduce the cost of limiting RF to 2.6 Wm^{-2} by 2100 but that a variety of technology combinations that do not include BECCS can also achieve this goal, under appropriate emissions mitigation policies. We note that with appropriate supporting land-use policies terrestrial sequestration could deliver carbon storage ranging from 200 to 700 $PgCO_2$-equiavalent over the 21st century. We explore substantial delays in participation by some geopolitical regions. We find that the value of BECCS is substantially higher under delay and that delay results in higher transient RF and climate change. However, when major regions postponed mitigation indefinitely, it was impossible to return RF to 2.6 Wm^{-2} by 2100. Neither finite land resources nor finite potential geologic storage capacity represented a meaningful technical limit on the ability of BECCS to contribute to emissions mitigation in the numerical experiments reported in this paper.

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1 Introduction

The political process has set ambitious climate change goals. Numerous studies, including Van Vuuren et al. (2007, 2011), Rao et al. (2008), Calvin et al. (2009), Azar et al. (2010), Massui et al. (2011), Riahi et al. (2011), and Thomson et al. (2011), have shown that it is technically possible to limit radiative forcing (RF) to 2.6 Wm^{-2}, a level consistent with limiting long-term, steady-state, global mean surface temperature change (GMSTC) to less than 2 °C.[1] All of these studies have one thing in common, they all employed large-scale bioenergy (150–350EJ/yr primary energy toward the end of the century) in combination with carbon dioxide capture and storage (BECCS). BECCS has the potential to deliver energy (liquids, hydrogen and/or electricity) in combination with negative carbon emissions. The purpose of this paper is to explore the importance of BECCS in strategies to limit RF to 2.6 Wm^{-2} by 2100. Specifically we seek to test whether or not BECCS is necessary to returning RF to 2.6 Wm^{-2} by 2100 and secondarily we explore whether either potential geologic storage or land resources represent meaningful constraints on BECCS deployment.[2]

To this end, we employ the PNNL/JGCRI Global Change Assessment Model, Version 3.0 (GCAM 3.0), a closely coupled model of biogeophysical and human Earth systems. We consider different scenarios with alternative technology suites, including four without BECCS, and alternative international emissions mitigation participation regimes.

2 The GCAM

We employ GCAM 3.0 an integrated assessment model (IAM) of human and natural Earth system processes relevant to climate change to conduct our numerical experiments (Calvin et al. 2011). GCAM tracks emissions, atmospheric disposition, radiative and climate effects of 16 greenhouse gases, aerosols and short-lived species.[3] GCAM is a dynamic-recursive model, which links a global energy-economy-agriculture-land-use model with a climate model of intermediate complexity and is a direct descendent of the Edmonds-Reilly model (Edmonds and Reilly 1985). GCAM subdivides the world into 14 regions and operates from 2005 to 2095 in 5-year increments. The agriculture and terrestrial system (Wise and Calvin

[1] This assumes a climate sensitivity of 3.0 °C per doubling of atmospheric CO_2 (Ramaswany et al. 2001; Table 6.2, p. 358). While radiative forcing is roughly consistent with a change in long-term steady-state GMSTC of 2 °C relative to preindustrial levels, this is not the same as transient GMSTC. A fixed radiative forcing level of 2.6 Wm^{-2} will only slowly approach the steady-state change over centuries. In the experiments we report here, we consider overshoot emissions and radiative forcing pathways that spend time above the long-term steady-state level before returning to it. This transient excess in radiative forcing accelerates GMSTC. While scenarios examined in this paper are all characterized by radiative forcing of 2.6 Wm^{-2} by 2100, transient temperatures, like transient radiative forcing, will follow different paths with higher interim radiative forcing associated with higher transient temperatures. The magnitude of GMSTC will depend on the climate sensitivity (the change in steady-state GMSTC associated with a permanent doubling of the concentration of CO_2). Transient temperature in GCAM is computed using MAGICC (Wigley and Raper 1992, 2002) using an assumed climate sensitivity of 3.0 °C, though both higher and lower values are possible. For some scenarios transient GMSTC, relative to preindustrial, exceeds 2 °C before declining below that magnitude by 2100.

[2] Water is a third potential constraint on BECCS deployment, though we do not explicitly model the interaction between water, energy, agriculture, land-use and climate in this paper.

[3] This paper focuses primarily on CO_2 emissions and concentrations. This is due to a need for brevity. However, GCAM tracks all 16 species and radiative forcing calculations include the effects of emissions and concentrations from all emissions sources.

2011 and Kyle et al. 2011) further subdivides each of the GCAM's 14 geopolitical regions into as many as 18 sub-regions, based on the agro-ecological zones (AEZs).[4] The GCAM simultaneously determines a consistent set of market-clearing prices for all energy, agricultural and forest products. GCAM computes the supply and demand for primary energy forms (e.g., coal, natural gas, crude oil), secondary energy products (e.g., electricity, hydrogen, refined liquids), several agricultural products (e.g., corn, wheat, rice, beef, poultry, etc.) and three different types of bioenergy supply (purpose-grown bioenergy crops, crop residues, and municipal solid-waste)(Luckow et al. 2010). The GCAM model assumes global trade in fossil fuels and agricultural products, and tracks emissions of a full suite of gases and reactive substances from a variety of human activities. GCAM 3.0 was released in November 2011 and incorporates major revisions to the representation of agriculture, land-use, and terrestrial carbon cycle as well as introduced regionally specific graded geologic CO_2 storage capacity endowments as discussed below.

All of the scenarios modeled here share the same economic, demographic, natural resource and other critical assumptions described by Thomson et al. (2011). In particular, all scenarios assume a global population that grows until mid-century, peaks in 2065, and declines to approximately 9 billion between 2065 and 2100. Living standards continue to increase and technological improvements in the production of energy, energy-related services, and agricultural goods continue to occur throughout the century.

2.1 Carbon dioxide capture and storage in GCAM

GCAM employs a detailed representation of CO_2 capture and storage that includes capital and ongoing operational costs, energy consumption, capture efficiency, potential technological progress and other key aspects of different types of CO_2 capture systems. Specific technology representation and associated assumptions are reported in a series of papers including details on how GCAM models CO_2 capture applied to bio-electricity and biofuels (Luckow et al. 2010), coal-to-liquids and oil shale processing (Dooley et al. 2009), coal and natural gas fired power plants in competitive electricity markets (Wise and Dooley 2009; Wise et al. 2007), and in the refining and transportation sectors (Wise et al. 2010) among many others. Capture rates vary with application, technology and time range from as low as 82 % for a Phase 1 Coal-to-Liquids refinery to 98 % for the Phase 2 refinery CCS facility. See Table 5, http://wiki.umd.edu/gcam/index.php?title=The_Energy_System.

Over the past few years a significant development in the published literature on geologic CO_2 storage capacities has been the promulgation, widespread acceptance and use of more standardized terminology and methodologies for computing geologic storage capacity based upon the work of the Carbon Sequestration Leadership Forum (CSLF 2007), the IEAGHG (IEAGHG 2011) and others (Bachu et al. 2007; Bradshaw et al. 2007). Here we draw upon the dozens of published papers which utilize this standardized methodology for computing geologic storage capacity for different regions. Based upon this recent and more harmonized literature, Dooley (2012) presents revised global geologic CO_2 storage estimates that—depending on the stringency of criteria applied to calculate storage capacity—global geologic CO_2 storage capacity could be: 35,300 $PgCO_2$ of "theoretical" capacity; 13,500 $PgCO_2$ of "effective" capacity; 3,900 $PgCO_2$, of "practical" capacity; and 290 $PgCO_2$ of "matched" capacity for the few regions where this narrow definition of capacity has been calculated. In this paper we assume a maximum storage capacity of approximately 7,000 $PgCO_2$.

[4] See Monfreda et al. (2009).

Spatially detailed storage resources allow GCAM to more accurately reflect the growing understanding of the costs and challenges associated with CCS. The policy case explored here only uses a small fraction of the projected available resource in the "effective" case. In this analysis, we require that CO_2 be stored in the region in which it is captured, including deep saline formations underneath the ocean in each region's near shore waters.[5] That is, we allow no trade in CO_2 storage services, though such trade is technically feasible and has already occurred.

2.2 Land-use and bioenergy production in GCAM

Bioenergy supply is determined within a comprehensive land-use, terrestrial-carbon module closely coupled to the energy and economic representations within GCAM 3.0. A detailed discussion of the treatment of land-use and terrestrial carbon cycle can be found in Kyle et al. (2011) and Wise and Calvin (2011). Briefly, land is partitioned into 151 regions, each classified into one of 18 AEZs in which landowners allocate land to alternative uses based on its expected profitability in each application. Modern bioenergy[6] is treated as any other commercial crop and is produced only if its market price makes it competitive with other crops. Expected profitability for any given crop will vary across AEZs reflecting variation in yield potential. While the Earth's land area is fixed, the area under cultivation can either grow or shrink with offsetting changes in the extent of unmanaged ecosystems. Associated land-use-change emissions (or sequestration) are explicitly tracked. In the climate mitigation scenarios in this paper land-use change emissions are penalized (and afforestation rewarded) at the same rate as fossil fuel and industrial emissions, which limits and/or reverses deforestation. See Wise et al. (2009).

3 Experimental design

The main goal of our numerical experiments is test whether or not BECCS technologies are essential to limiting RF to 2.6 Wm^{-2} at 2100 and to explore the extent to which it remains possible to achieve such ambitious, low RF targets without deploying BECCS. To this end we consider a variety of alternative technology suites in combination with three alternative policy regimes. We pursue this line of investigation to see to what extent the climate policy environment affects the results obtained for the idealized mitigation policy setting.

3.1 Alternative policy settings

Radiative forcing levels are controlled by imposing a tax on carbon emissions. The carbon tax covers emissions from industrial activities and land-use change. That is, the policy is cost effective. It minimizes emissions mitigation costs at any point in time in the sense that it

[5] See Supporting Online Material, SOM Fig. 1, for the geographic distribution of potential carbon storage reservoirs.

[6] Bioenergy can be derived either from purpose grown crops such as switchgrasses, miscanthus, and woody crops like poplar, as well as from residues from agriculture and forestry residues. Some crops such as sugar cane, corn, or oil crops can be sold either into the agricultural or energy markets and in some instances, e.g. sugar cane, can be supplied to both as co-products. The determination of which crops are grown and the markets into which their outputs are sold depend on profitability in alternative applications. See, Kyle et al. (2011).

allows for emissions mitigation to take place wherever it is most cost effective across the entire economy.[7] The carbon price is assumed to rise at the rate of interest plus the average rate of removal of carbon by oceans, the Hotelling-Peck-Wan Path (Hotelling 1931; Peck and Wan 1996). It is important to note that we assume that agents that remove carbon from the atmosphere are rewarded at the same rate per ton as emitters are penalized. In other words, negative emissions receive a payment equal to the price on positive emissions. RF is returned to 2.6 Wm^{-2} at the end of the century via the tax mechanism, though no interim limit is imposed.

These three alternate policy settings differ as to when and how global participation in the emissions mitigation regime is accomplished. The first policy setting assumes an, idealized policy setting where all nations of the world take on emissions mitigation simultaneously in 2020. The second policy setting assumes that nations take on emissions obligations at different times: Western Europe, Eastern Europe, Japan immediately; Australia/NZ, Canada, China, Korea, USA in 2030; India, L. America, Other South & East Asia in 2050; and Africa, FSU, Middle East in 2070 as described in the Supporting Online Materials. Our third policy setting is identical to the second policy setting except that two regions, FSU and Middle East, never undertake emissions mitigations.

3.2 Alternative technology assumptions

We consider five alternative technology regimes, which are laid out in Table 1. The most comprehensive technology suite, which includes BECCS, is referred to as the reference (T1 Ref) technology assumption set. It is described in detail in Calvin et al. (2011). These reference technology assumptions embody significant technological progress, relative to the present, across the entire energy system from end-use (Kyle et al. 2010; Wise et al. 2010), to refining, to electricity production (Wise et al. 2010), to renewable energy (Kyle et al. 2009). However, we do not include an option to deploy direct air capture (DAC) of CO_2.[8]

Regimes T2–T4[9] explore implications of pursuing a limit to RF of 2.6 Wm^{-2} at 2100 assuming that CCS and/or bioenergy are unavailable.[10] Regime T5 represents a "low technology" future in which existing nuclear energy is phased out, no new nuclear plants are built and neither CCS nor commercial bioenergy are available for deployment.[11]

[7] Wise et al. (2009) showed that scenarios that ignore land-use while employing bioenergy run the risk of adverse indirect land-use change emissions, which can result in deforestation and higher costs of limiting greenhouse gas concentrations.

[8] The implications of DAC are discussed in other papers in this Special Issue.

[9] Note that removing technologies that use both bioenergy and CCS from the technology suite is insufficient to understand the implications of not having BECCS. If both bioenergy and CCS are separately available in the model, the model will find alternative transformation pathways to combine the technologies, e.g. bioenergy gasification introduced into the gas pipeline system and sold to power producers with gas generators and a CO_2 scrubber. Hence at a minimum either technology set T2 or T3 is the minimum requirement to study emissions mitigation in the absence of BECCS. T4 examines the combined effect of removing both bioenergy and CCS.

[10] For bioenergy, we assume that no commercially grown bioenergy can be used in the modern energy system, though traditional bioenergy continues to be used. For CCS, we assume that geologic storage is unavailable. For nuclear power, we assume that no new reactors are built and existing reactors are phased out as they retire.

[11] T5 examines the question of whether end-use technologies in combination with non-biomass renewables are sufficient to allow the achievement of 2.6 Wm^{-2} by the end of the century. For nuclear power, we assume that no new reactors are built and existing reactors are phased out as they retire.

Table 1 Alternative technology assumptions

Technology set	CCS	Bioenergy	Nuclear power	Other technology
T1 (Ref)	Yes	Yes	Ref	Ref
T2 (NoBio)	Yes	No	Ref	Ref
T3 (NoCCS)	No	Yes	Ref	Ref
T4 (NoBio & No CCS)	No	No	Ref	Ref
T5 (LowTech)	No	No	Phased out	Ref

4 Result of experiments

4.1 The radiative forcing and average global temperature change trajectories

RF and GMSTC pathways are shown in Fig. 1 for all of the five technology suites and two accession regimes. Solid lines indicate idealized scenarios with immediate global participation by all parties while dashed lines indicated scenarios in which participation by some regions was delayed as per SOM Table 1.

First we note that it was possible to limit RF to the target level by 2100 under our first two accession regimes and with all five technology suites. However, it was impossible to return RF levels to 2.6 Wm^{-2} by the end of the century under our third policy suite, even when all technologies, including BECCS, were available.

The delayed accession pathways all exhibit higher interim RF levels and GMSTC, Fig. 1. This is due to the obvious reason that non-participating regions not only continue to emit carbon, but there are additional carbon-leakage effects. Thus, despite the fact that regions mitigating in the early part of the regime have lower emissions than they do in the idealized scenarios, near-term global emissions are higher than in the idealized scenarios. All of these delayed accession pathways have RF levels that exceed 3.5 Wm^{-2} for 25–45 years during this century, with two of the scenarios having RF levels of nearly 4.0 Wm^{-2} for 20–25 years. In the cases where all regions simultaneously take on emissions mitigation, RF levels exceed 3.2 Wm^{-2} for 20 years in only the T1 scenario and just barely exceed 3.0 Wm^{-2} in the T2 scenario.

The idealized scenarios all follow trajectories with GMSTC relative to preindustrial less than two degrees centigrade (°C), assuming a climate sensitivity of 3 °C for a doubling of the CO_2 concentration. Delayed accessions scenarios, with major portions of the world's nations not participating, lead to much higher transient temperatures, though GMSTC relative to preindustrial remain below 2.5 °C throughout the century. Variation in transient climate change could affect both energy and agricultural systems, though we make no attempt to quantify such feedbacks in this paper.

Variation in technology availability affected the shape of the RF and GMSTC trajectories. We observe that scenarios with access to bioenergy (T1, T3) follow relatively higher RF pathways prior to 2100. This result follows from the fact that the goal is stated in terms of the year 2100 RF level and without regard to any interim states. In a real-world policy environment such dramatic over-shooting of the long-term goal might be undesirable. In fact, near-term policies and measures tend to be framed in terms of near-term limits on emissions, something that can be directly monitored and controlled, rather than a long-term objective to be achieved a century hence. These results should not be taken as a policy recommendation, but rather as numerical experiment results that shed light on the implications of long-term goals.

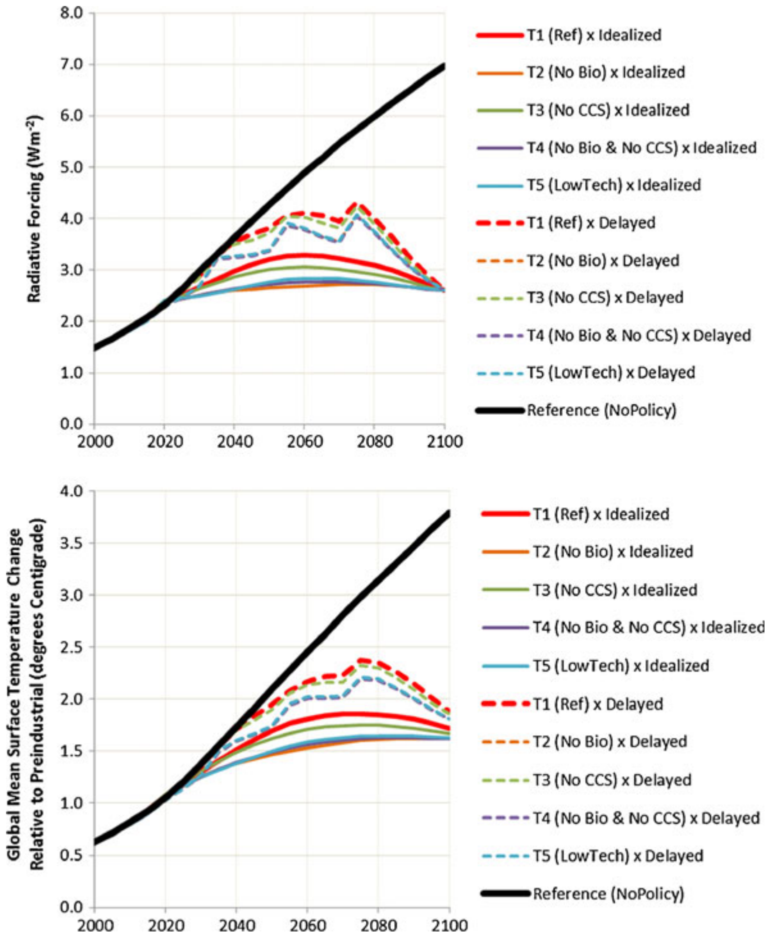

Fig. 1 RF trajectories for alternative technology regimes limiting forcing to 2.6 Wm^{-2} and associated transient GMSTC (climate sensitivity=3 °C)

Technology and energy choices are cost sensitive in GCAM, and are dependent on the value given to carbon in the energy (and land-use) system. As shown in Fig. 2, the carbon price required to achieve emissions reductions sufficient to limit RF to 2.6 Wm^{-2} by 2100 can be very high, though very high carbon prices are generally associated with very few agents actually paying a carbon price. Most agents substitute non-emitting technologies rather than pay high carbon prices. By the end of the century global emissions can be negative implying that the high carbon price is actually a source of income to the economy's agents.[12]

[12] In the idealized scenarios tax revenues, which are the product of the carbon tax and total carbon emissions, all reach a peak before the end of the century and decline thereafter. Tax revenues are negative in both T1 (RefJ) x Idealized and T3 (No CCS) x Idealized scenarios and represent net government payments rather than revenues on a scale of trillions of dollars per year by the end of the century. The delayed accession scenarios are all characterized by negative global emissions at the end of the century, but owing to the land-use leakage effects discussed later in this paper, are much larger is scale and have a more volatile temporal profile than in the idealized scenarios.

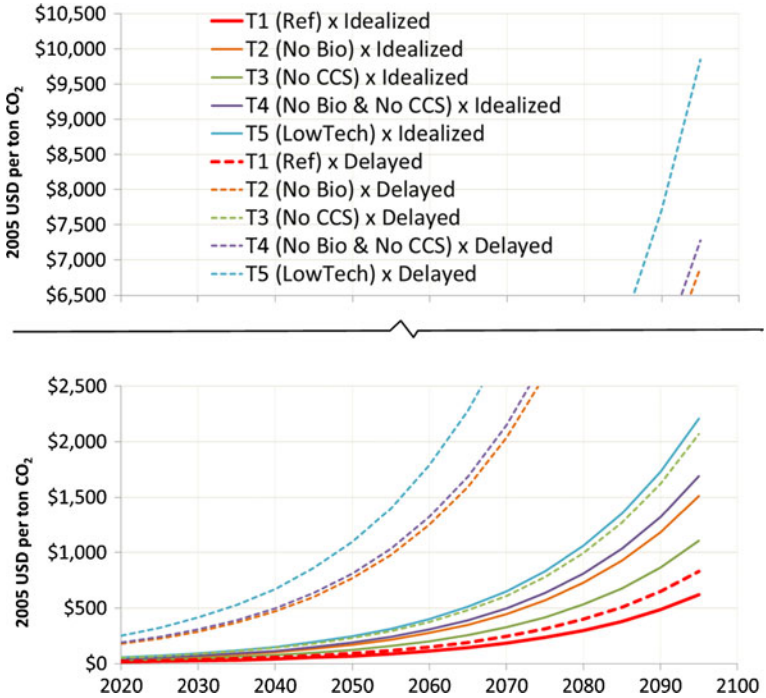

Fig. 2 Carbon price trajectories associated with limiting RF to 2.6 Wm^{-2} at the end of the 21st century

4.2 Carbon prices

Figure 2 shows the Hotelling-Peck-Wan (HPW) carbon price paths for all ten of the modeled scenarios. Carbon prices are applied to all carbon emissions in all mitigating regions. Once a region begins emissions mitigation, it transitions to the HPW carbon price. In any year the carbon price needed to limit RF to 2.6 Wm^{-2} at the end of the 21st century is lowest when all technology options are available (idealized mitigation regime), \$16/tCO_2 in 2020 rising to \$620/tCO_2[13] in 2095 for the T1(Ref). Even this case requires very substantial changes in the production and use of energy. In the T1 (Ref) delayed accession regime, the CO_2 price starts at \$21/tCO_2 in 2020 rising to \$830/tCO_2 in 2095. With all technologies are available, T1 (Ref), the cost of delayed accession is slightly more than one-third higher.

The availability of BECCS in addition to other technology options is always associated with the lowest carbon price for a given policy regime. The two BECCS (T1) scenarios are the two lowest cost pathways to limit RF to 2.6 Wm^{-2}. BECCS technology availability thus lowers mitigation costs. The required CO_2 price is 3 time higher in the T4 (No Bio & No CCS) idealized mitigation scenario, than it was when BECCS was available, T1 (Ref). With a delayed accession regime, costs rise even more without the availability of bioenergy and/or CCS, as participating regions must mitigate more of the emissions earlier in the century. The 2095 CO_2 price for the T4 (No Bio & No CCS) is almost 9 times greater than that in the corresponding T1 delayed accession case. We note however, that in the delayed accession

[13] All monetary data are in real 2005 US dollars

scenario removing bioenergy from the mix was far more costly than removing CCS. Without bioenergy it is costly to accomplish emissions mitigation in the transport sector.

High carbon prices are a potential political impediment to emissions limitation. In general, higher carbon prices will be associated with higher social costs. In other words they reflect the urgency with which resources are being called from other sectors to augment activities focused on reducing emissions.[14]

Energy prices are closely coupled to the carbon price. Higher carbon prices drive a wedge between the supply price of fossil fuels and the price consumers pay. As carbon prices rise the magnitude of that wedge grows. In cases where parts of the world apply a carbon price and other parts do not, the gap is greater in participating regions, because carbon prices are higher. Of course, there is no gap in non-mitigating regions, whose emissions increase as a result of the depressed fossil fuel supply prices, as discussed in Edmonds et al. (2008) and Clarke et al. (2009).

Note that the effect of technology availability operates on the carbon price in much the same way as delayed accession in that the coalition can achieve its goal with a lower carbon price when it has more members. Similarly, any carbon price delivers greater emissions mitigation with a wider array of technology options.

The delay in participation clearly saddles society with greater transient climate change, even when society is able to return RF to 2.6 Wm^{-2} by 2100. Our third international accession regime explores this effect further, by modifying the accession assumptions in SOM Table 1 to exclude both the Middle East and the FSU from the mitigating coalition during the 21st century. Without participation by these two regions, limiting RF to 2.6 Wm^{-2} **was not possible for any technology suite**. Emissions over the course of the century from those two regions alone meant that even with negative emissions from other regions, it was impossible to bring RF down to the target level. In particular, we observed a significant rise in land-use change emissions in these two regions, relative to both the immediate accession case and a no climate policy case, resulting from an incentive for these regions to produce bioenergy and food to meet the demands of the rest of the world. This experiment illustrates the importance of eventual participation in the mitigating coalition by all major emitters before 2100 and the limits to the ability of BECCS to reduce atmospheric CO_2 concentrations.

4.3 The fossil fuel emissions trajectory

Fossil fuel and industrial (FFI) CO_2 emissions are shown in Fig. 3. (Land-use change emissions are discussed below.) The FFI CO_2 emissions pathway is tightly coupled to the RF pathway. Since all paths are forced to have a RF level of 2.6 Wm^{-2}, all must have similar CO_2 concentrations by 2100 and hence similar cumulative emissions.

Delayed accession scenarios have higher peak fossil fuel and industrial (FFI) emissions than is the case with the idealized technology scenarios and peak later. Non-participating regions continue to emit and those emissions cannot be fully offset by accelerated reductions

[14] We make no attempt to define politically acceptable and unacceptable price regimes. Some studies, e.g. Clarke et al. (2009) defined scenarios for which the first-period carbon price exceeded \$1000/tCO2 as infeasible. Note that none of the scenarios reported in this study exceeded that value. In principle, the changes required here could be affected without an explicit carbon price, using for example regulatory policy instruments. Such tools can be less efficient than price-based instruments, but do not confront decision makers with explicit prices. On the other hand, many of the scenarios have very few carbon tax payers at very high prices and in some scenarios the net effect of the carbon price raises no revenue at all, but rather reflects a massive commitment on the part of governments to pay for the negative emissions.

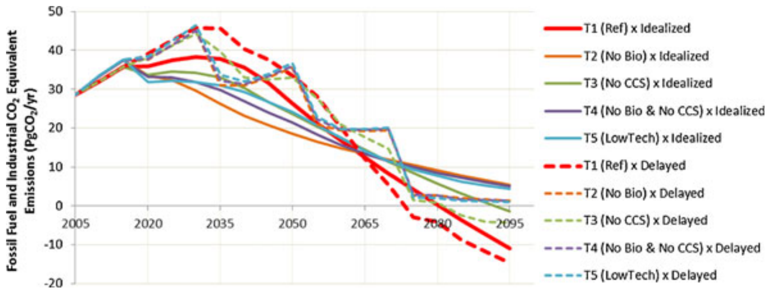

Fig. 3 Fossil fuel and industrial CO_2 emissions 2010–2095

in early mitigation regions. Delay is also associated with lower emissions in the final quarter of the 21st century. In contrast, for any technology set, the idealized scenario has lower transient emissions than its corresponding delayed-accession scenario in the first part of the century, but higher emissions late in the century.

Under both the idealized and delayed policy regimes BECCS technology availability allowed transient CO_2 emissions to increase in the early years because emissions could eventually be driven negative at the end of the century. On the other hand, if the emission path were fixed, then the effect of BECCS technology availability would be to lower the carbon price.

4.4 Land use, bioenergy production and food prices

The ability to produce bioenergy depends on the availability of cropland. In scenarios in which bioenergy is assumed to be available, production rises to as high as 300 EJ/y, comparable to the 200–400EJ cited in similar studies by Azar et al. (2010). This is possible for two reasons. First, crop yields for food products are assumed to improve sufficiently that the world population can be fed while still producing bioenergy (Wise et al. 2009; Thomson et al. 2010). Second, diets change because the application of carbon prices to land-use change emissions are incorporated into land rents and therefore food prices. Relative price shifts between high-carbon-intensity land products, e.g. beef, and low-carbon-intensity land products, e.g. grains, result in shifts in land use toward bioenergy and forests, as discussed in Wise et al. (2009). For example, beef and dairy production, which more than doubles between 1990 and 2095 in the Reference scenario grows by only 50 % in the T1 (Ref) x Idealized scenario. Reduced herd sizes free up 4.5 million km^2 of pastureland and 1.2 million km^2 of cropland in the T1 (Ref) x Idealized scenario relative to the Reference Scenario. This in turn enables expansion of unmanaged ecosystems by 3.2 million km^2 and bioenergy production by 2.5 million km^2.

Because GCAM 3.0 tracks all global land, all carbon in terrestrial systems, and the production of all food, fiber, and forestry products, the model captures key induced land use changes as well as associated secondary and tertiary impacts. We note that the application of a carbon price to land-use emissions results in a dramatic change in land use.[15] Deforestation shifts immediately to afforestation because carbon prices immediately create a strong market incentive to expand the stock of carbon held by land owners. We find that even in high bioenergy cases (up to 300 EJ/year) there is indeed sufficient land for food production for 9 billion people and for substantial net terrestrial carbon sequestration. On the other hand, the

[15] See Supporting Online Material Fig. 7.

incorporation of carbon value into terrestrial systems carries implications for food prices, as shown by Wise et al. (2009). While total food availability may be adequate, it can be associated with higher prices, which could carry potentially severe consequences for those at the lower end of the income distribution. The asset value of terrestrial carbon is also embedded in the price of bioenergy, which escalates steadily over time. This in turn sets the marginal cost of carbon removal using bioenergy with CCS in the T1 scenarios.[16]

Cumulative terrestrial carbon sequestration in both soils and above ground vegetation in response to the carbon price is significant, 200–700 $PgCO_2$-equivalent over the 21st century, Fig. 4, and is the only mechanism, other than storage in long-lived materials such as plastics, for removing and storing carbon when CCS is unavailable. The realization of this potential depends critically on valuing all carbon, fossil fuel and terrestrial, at the same price. Finding institutional mechanisms capable of delivering this potential is an important challenge.

This is not to say that there are not important interactions between the energy and agricultural sectors. Because all markets interact in the economic system, indirect land-use changes are an inevitable consequence. If all regions undertake emissions mitigation and value all carbon, indirect land-use change emissions are not observed. Just the opposite occurs in the delayed accession cases, Fig. 5. Note, however that the rate of net uptake declines with time as the forests mature and increasing food demands (due to both growing population through mid-century and rising per-capita incomes) limits the extent to which new forests are added over the century.[17]

Terrestrial carbon sequestration is smaller in the delayed accession cases, and it exhibits a delayed temporal pattern. Net carbon sequestration occurs only after most of the world's terrestrial systems are within the political boundaries of mitigating regions.

Indirect land-use change emissions are a significant source of inefficiency in the delayed participation scenarios through a process of "land-use leakage". As discussed in Calvin et al. (2009), afforestation efforts in regions undertaking emissions mitigation drive increased agricultural production costs in those regions leading to a shift in agricultural production toward non-mitigating regions, which expand agricultural production at the expense of their own forests. The deforestation in non-participating regions is associated with greater emissions release per hectare than carbon uptake in mitigating regions because the new forests in mitigating regions store carbon as they grow, but that growth occurs over time. In contrast deforestation releases the accumulated carbon from the entire growth history of the forest. As new regions join the mitigating coalition, they induce a spike in land-use change emissions followed by subsequent draw down of carbon by new forests in the mitigating regions.

4.5 Geologic CO_2 storage

There are four scenarios in which CCS technologies are utilized. In the T1 (Ref) x Idealized case about 1,380 $PgCO_2$ is stored in global reservoirs and in the delayed accession variant a cumulative total of about 1,450 $PgCO_2$ is stored. In the T2 (No Bio) x Idealized case, about 1,150 $PgCO_2$ is stored between 2020 and 2095 and about 600 PgCO2 in the delayed participation variant of T3 (no CCS). The much lower capture rates in T2 (No Bio) x delay scenario relative to the T2 (No Bio) x idealized scenario stems from the much higher carbon price in the former, which when applied to the non-captured emissions makes CCS relatively less attractive. Figure 4 showed the demand for geologic storage across these four cases. In

[16] See Supporting Online Material, Fig. 5

[17] This is discussed further in the SOM.

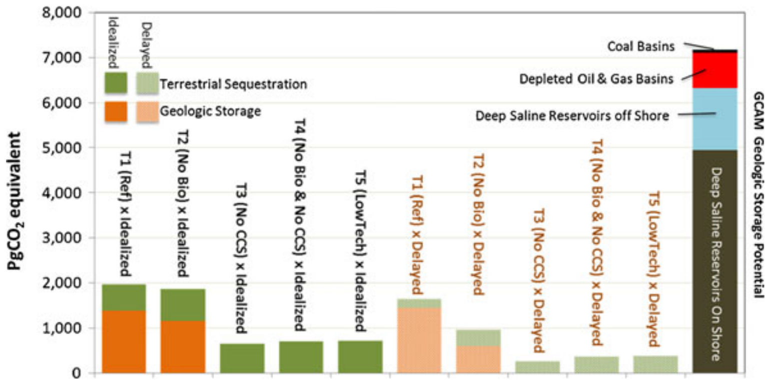

Fig. 4 Terrestrial sequestration, geologic storage, and potential geologic storage 2020–2095

T1, where BECCS is available, the fraction of CCS accounted for by bioenergy technologies rises steadily to more than half by the end of the century.[18]

Clearly potential geologic storage capacity greatly exceeds carbon being stored. At the regional scale however some regions bump up against limits to potential storage capacity. The result of these regional limits is a slightly higher carbon price than would have emerged if storage were not constrained, which provides the incentive for regions with large storage potential to expand utilization of CCS. In aggregate, however, less than 20 % of estimated practical storage capacity is utilized in any of the scenarios examined here.

5 Summary of findings

The joint utilization of bioenergy and CCS technologies could potentially provide net negative CO_2 emissions on local, regional and potentially global scales—given an appropriate policy environment. At sufficiently high carbon prices CCS technologies are utilized in combination with bioenergy in both the production of fuels and electricity. Deployment can grow to the point where net emissions of the global system are negative. This would be a dramatic turn of events and requires unprecedented cooperation on the part of the world's nations. Yet there is no technical reason why it could not come to pass.

We find that while a potentially valuable tool for limiting RF to 2.6 Wm^{-2} by 2100, an appropriate policy environment, BECCS is not essential. We showed that it is possible to meet that goal without utilizing BECCS technology. We found numerous technology combinations capable of limiting RF by 2100 to 2.6 Wm^{-2}, though all were associated with higher carbon prices than when both bioenergy and CCS were available.

Despite the scale at which BECCS deploys in emissions control regimes which limit RF to 2.6 Wm^{-2} by 2100, geologic storage did not represent a meaningful technical limit on technology deployment, though appropriate institutions would need to be developed to monitor, verify, and accredit geologic storage. Similarly, land did not represent a technological constraint, though land is fixed and significant land-use change, including change associated with dietary composition change was required.

[18] See Supporting Online Material Fig. 8.

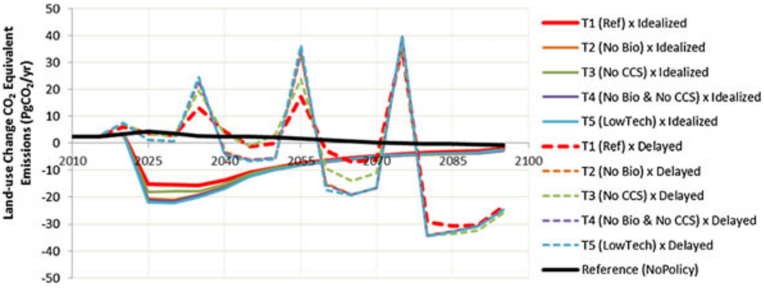

Fig. 5 Land-use change CO_2 emissions 2000–2095

In addition several other results emerged.

- We note that with appropriate supporting land-use policies terrestrial sequestration could deliver carbon storage ranging from 200 to 700 $PgCO_2$-equiavalent over the 21st century.
- In delayed international accession scenarios where eventually all of the world's major regions joined a coordinated emissions mitigation program, we observed that RF pathways were significantly higher, and that the value of having a full suite of technology options, including BECCS, was significantly higher than in idealized global emissions mitigation scenarios.
- When two regions were left out of the coalition throughout the 21st century, it proved impossible to return RF to 2.6 Wm^{-2} by 2100. Eventually all major emitting regions of the world need to engage in emissions mitigation.

Finally, we also found that land-use could play an important role in achieving that goal. However, this result depends critically on a supporting policy environment. Earlier research going back as far as Edmonds et al. (2003) has shown that an inefficient policy environment can cause land-use change to frustrate rather than support emissions mitigation efforts. We have not explored the degree to which the potential of terrestrial systems to sequester carbon can be realized in other policy environments nor have we explored the implications of mitigation policies beyond carbon taxation. An important direction for future research is the examination of imperfect regional and national policy environments.

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