

Agriculture, Land use, Carbon Cycle and Climate  
Stabilization with Incomplete International Participation  
Katherine Calvin, Jae Edmonds, Leon Clarke, Ben Bond-Lamberty, Sonny Kim, Page Kyle,  
Allison Thomson, Marshall Wise

**Abstract**

*The EMF 22 subgroup on Transition Scenarios explores the impact of imperfect cooperation on limiting climate change. This paper adds to that literature, focusing on the implications of delay on the terrestrial system. Delayed participation results in significant leakage in the terrestrial system, as crop and bioenergy production is outsourced to non-participating regions. Shifting production across regions results in an increase in total global cropland and a substantial increase in land-use change emissions. In addition, we explore the impact of delayed accession on global emissions mitigation, carbon taxes, and policy cost. Finally, we look at the quantity and deployment of bioenergy under different policies and technology suites.*

**1. Introduction**

The EMF22 Transition Scenario Subgroup (Clarke et al., 2009) explores the implications of delayed participation on the ability to limit climate change to prescribed levels. Most of the existing literature on emissions mitigation and climate stabilization has focused on first-best scenarios, where all regions of the world are assumed to act immediately (e.g., IPCC, 2007; Clarke et al., 2007). A limited number of papers (Richels et al., 2007; Edmonds et al., 2008) have explored delayed participation in climate coalitions. The EMF22 International Transition Scenario Subgroup broaden this literature with an inter-model comparison analyzing five different climate limits under both perfect and imperfect cooperation assumptions (Clarke et al., 2009). The MiniCAM model's previous submission to this subgroup focused on the feasibility of very low climate limits (Calvin et al., 2009a). The work presented in this paper expands on the results and analyses presented there, focusing in particular on the pressures for leakage in incomplete participation scenarios.

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Delayed accession creates a pressure for emissions leakage, where emissions in non-participating regions increase relative to their reference scenario. Typically, discussions of leakage focus on effects in the energy and industrial system (Felder and Rutherford, 1993; Bollen et al., 2000; Burniaux and Oliveira Martins, 2000; Paltsev, 2001; Kuik and Gerlagh, 2003; Babiker, 2005; and Reinaud, 2008). Emissions in non-participating regions increase due to either lower fuel prices or a shift in industrial production to these regions. These effects, however, are often small. For example, one EMF22 participant found that fossil & industrial emissions in non-participating regions increased by no more than 6% (relative to the reference scenario) in the 3.7 W/m<sup>2</sup> scenarios (Calvin et al., 2009b). In this paper, we focus on leakage within the terrestrial system. The shift in crop and bioenergy production under imperfect cooperation results in substantially more leakage in land-use change emissions than the effects on the energy system in the Calvin et al. (2009b) paper.

In addition, we look at the impact of delayed accession on global emissions mitigation, carbon taxes, and policy cost. We find that delayed accession shifts global emissions over time, such that more mitigation is undertaken in the second half of the century compared to the immediate accession scenarios. Thus, delay in participation results in a delay in global mitigation. Despite the delay in mitigation efforts at the global level, early participants still reduce emissions more than under delayed accession, resulting in higher carbon taxes under delay. Finally, we find that delayed accession increases the cost of reaching a particular climate target for all regions, including the delayed participants.

## **2. The MiniCAM Model**

The analysis in this paper uses the MiniCAM integrated assessment model. MiniCAM (Brenkert et al. 2003, Kim, et al. 2006) is a dynamic-recursive model, which links a global energy-

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economy-agricultural-land-use model with a suite of coupled gas-cycle, climate, and ice-melt models, integrated in the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC). MiniCAM tracks emissions and concentrations of greenhouse gases and short-lived species<sup>1</sup>. An important feature of the MiniCAM is that energy, agriculture, forestry, and land markets are integrated with the extent of unmanaged ecosystems and the terrestrial carbon cycle. The MiniCAM thus produces outputs that include not only emissions of 15 greenhouse gases and aerosols, but also agricultural prices, land use, and stocks of terrestrial carbon.

The MiniCAM is a descendent of a model developed by Edmonds and Reilly (1985). It has been used extensively for energy, climate, and other environmental analyses conducted for organizations that include the U.S. Department of Energy (DOE), the U.S. Environmental Protection Agency, the Intergovernmental Panel on Climate Change (IPCC), and other government, private and non-governmental organizations. Documentation for MiniCAM can be found at <http://www.globalchange.umd.edu/models/MiniCAM.pdf/>.

The MiniCAM energy system includes primary energy resources, production, energy transformation to final fuels, and the employment of final energy forms to deliver energy services such as passenger kilometers in transport or space conditioning for buildings. Energy supplied from depletable resources, namely fossil fuels and uranium, depends on the abundance and grade of available resources as well as available extraction technologies. Renewable resources like wind and solar are produced from graded renewable resource bases. Bioenergy

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<sup>1</sup> MiniCAM tracks emissions of 15 greenhouse related gases: CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, NO<sub>x</sub>, VOCs, CO, SO<sub>2</sub>, carbonaceous aerosols, HFCs, PFCs, and SF<sub>6</sub>. Each is associated with multiple human activities that are explicitly modeled in MiniCAM.

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availability depends on the availability and character of land resources, technology options for production, and competing land use options.

MiniCAM is a technology-rich model. It contains detailed representations of technology options in all of the economic components of the system. Technology choice is determined by market competition. Individual technologies compete for market share based on their technology characteristics (efficiency in the production of products from inputs), the cost of inputs, and the price of outputs. The market share captured by a technology increases as its costs decline, but MiniCAM uses a probabilistic model of market competition and not a “winner take all” model of cost competition.

The MiniCAM agriculture, land use, land cover, terrestrial carbon cycle module determines the demands for and production of products originating on the land, the prices of these products, the allocation of land to competing ends, the rental rate on land, and the carbon stocks and flows associated with land use. Land is allocated between alternative uses based on expected profitability, which in turn depends on the productivity of the land-based product (e.g. mass of harvestable product per ha), product price, the rental rate on land, and non-land costs of production (labor, fertilizer, etc.). The productivity of land-based products is subject to change over time based on future estimates of crop productivity change. A more complete description of the agriculture and land use component of MiniCAM can be found in Wise et al. (2009a).

The scenarios in this paper use the version of MiniCAM that participated in the U.S. Climate Change Technology Program’s (CCTP) analysis of technology scenarios (Clarke, et al., 2007).

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A full description of MiniCAM and the current demographic, economic, resource, and technology assumptions are provided in Clarke et al. (2008), accessible at <http://www.pnl.gov/science/pdf/PNNL18075.pdf>. In general, the technology assumptions for the results here are based on Reference Case assumptions in the Clarke et al report. However, in these scenarios, we do allow nuclear power to expand and CO<sub>2</sub> capture and storage (CCS) technologies to deploy when economic.

### **3. The Reference Scenario**

The reference scenario and the assumptions used in its construction are detailed in Clarke et al. (2007, 2008). Global population is characterized by a peak and decline future path, reaching a maximum in 2065 at more than 9 billion people. Global GDP grows by an order of magnitude over the coming century.

Global energy consumption increases to more than triple its 2005 value in 2095 (Figure 1, Panel A). Fossil fuels continue to dominate global energy consumption in the reference scenario, despite substantial growth in the consumption of renewable energy. Electric power generation grows by a factor of six between 2005 and 2095, from ~66 EJ per year to ~371 EJ per year (Figure 1, Panel B).

The MiniCAM model tracks global land allocation over the next century (Figure 1, Panel C). In the reference scenario, forest land declines over the century to accommodate increases in crop land and land for bioenergy. Crop land grows in the first half of the century due to increases in population and meat consumption. Post-2050, however, crop land stabilizes and begins to decline as a result of increased crop productivity and a decline in population. Land-use change

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emissions decline from a little more than 1,100 TgC/year in 2005 to approximately 300 to 400 TgC/year by the end of the century (Figure 1, Panel D). The decline in land-use change emissions is due to the increase in crop productivity, which results in less demand for land for food production. This result is dependent on the assumed rate of crop productivity increase.<sup>2</sup>

Fossil fuel and industrial emissions, which grow from approximately 8 PgC per year in 2005 to nearly 22 PgC/y, continue to dominate total anthropogenic emissions (Figure 1, Panel D). Note that the consumption of bioenergy is treated as having no net *direct* carbon emissions to the atmosphere (although there may be emissions from converting land to bioenergy crops from other uses).

### 4. Policy Scenarios

The EMF 22 subgroup asked participating modelers to explore 10 scenarios in which anthropogenic climate change was limited (Table 1). These scenarios limit radiative forcing from Kyoto gases<sup>3</sup> to three different levels: 4.5 W/m<sup>2</sup>, 3.7 W/m<sup>2</sup>, and 2.6 W/m<sup>2</sup>, which correspond to CO<sub>2</sub>-equivalent concentrations, with and without overshoot.<sup>4</sup>

| Table 1: Climate Change Limitation Scenarios |                                          |                          |                   |                        |                   |
|----------------------------------------------|------------------------------------------|--------------------------|-------------------|------------------------|-------------------|
| Radiative Forcing Limit                      | CO <sub>2</sub> Equivalent Concentration | Immediate Accession (S1) |                   | Delayed Accession (S2) |                   |
|                                              |                                          | Overshoot (OS)           | Not to Exceed (S) | Overshoot (OS)         | Not to Exceed (S) |
| 2.6 W/m <sup>2</sup>                         | 450 ppm-eq                               | S1_2p6_OS                | S1_2p6_S          | S2_2p6_OS              | S2_2p6_S*         |
| 3.7 W/m <sup>2</sup>                         | 550 ppm-eq                               | S1_3p7_OS                | S1_3p7_S          | S2_3p7_OS              | S2_3p7_S*         |

<sup>2</sup> Wise et al. (2009a,b) shows an increase of as much as 2 PgC/yr in land-use change emissions when crop productivity is held constant at 2005 values.

<sup>3</sup> The gases included are CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, SF<sub>6</sub>, C<sub>2</sub>F<sub>4</sub>, and HFCs. The radiative forcings calculated do not include the cooling effects of aerosols or the warming effects from the Montreal gases.

<sup>4</sup> For the 4.5 W/m<sup>2</sup> forcing target, only scenarios without overshoot are considered.

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|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------|--|----------|--|----------|
| 4.5 W/m <sup>2</sup>                                                                                                                                                                                                                                                                                       | 650 ppm-eq |  | S1_4p5_S |  | S2_4p5_S |
| <p>* It was not possible to delay participation in regions 2 and 3 as per Table 2 and keep radiative forcing from exceeding 2.6 W/m<sup>2</sup> or 3.7 W/m<sup>2</sup> during the 21<sup>st</sup> century. That is, scenarios S2_2p6_S and S2_3p7_S are not possible given the assumptions in MiniCAM.</p> |            |  |          |  |          |

Emissions mitigation in MiniCAM is achieved by the imposition of an economy-wide carbon tax. This tax is applied to all carbon emissions, including not only fossil fuel and industrial emissions, but also includes land-use change emissions. The “immediate accession” (S1) scenarios are characterized by perfect when and where flexibility. Thus, the carbon tax is assumed to be implemented to achieve the climate goal in a cost-effective manner, which requires the carbon tax to rise at the rate of interest plus the rate of ocean carbon uptake (Edmonds et al., 2008). In an “immediate accession” (S1) “overshoot” scenario, the initial carbon price is adjusted to ensure that the radiative forcing target is met in the specified year. Carbon prices in subsequent years are prescribed by the exponential rate of increase. Prescribing a carbon tax that rises at the interest rate ensures that the marginal cost of abatement is constant across time, and thus, exhausts all opportunities for arbitrage across time.

The carbon price path in an “immediate accession” (S1) “not-to-exceed” scenario is characterized by two parts: an initial rise to the radiative forcing limit, and maintenance of that limit thereafter. The initial price is set such that when the upper bound on radiative forcing is achieved, the carbon price stabilizes to maintain the radiative forcing target. Thus, the carbon price path is smooth throughout the century, rising exponentially in early years and roughly constant in later years.

In the delayed accession scenarios, we again place a carbon tax on all emissions, regardless of source. However, these scenarios do not assume immediate international cooperation and

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instead assume three different accession dates around the world. Group 1 (roughly Annex I less Russia) begins emissions mitigation immediately and impose carbon taxes that follow the same patterns as in the immediate accession scenarios. Group 2 begins emissions mitigation in 2036;<sup>5</sup> Group 3 starts to reduce emissions in 2051. Because the tax is rising exponentially, regions would suffer a carbon-price shock if they imposed the Group 1 price immediately (See Edmonds et al., 2008). Instead, we assume that when Group 2 and 3 enter the climate regime, their initial tax is less than the current prevailing Group 1 tax. Specifically, we assume that Group 2 and 3 impose the 2012 Group 1 price in their year of accession. Carbon prices then rise linearly over twenty years to meet the prevailing Group 1 price. Delayed accession assumptions are summarized in Table 2.

| Region  | MiniCAM regions                                          | Period of Policy Phase In |
|---------|----------------------------------------------------------|---------------------------|
| Group 1 | USA, Canada, W. Europe, E. Europe, Japan, Australia & NZ | 2012 to 2020              |
| Group 2 | The Former Soviet Union, India, China, Latin America     | 2036 to 2050              |
| Group 3 | Korea, South & East Asia, Middle East, Africa            | 2051 to 2065              |

### 5. Emissions Mitigation, Carbon Taxes, and Policy Cost

Figure 2 shows global total anthropogenic<sup>6</sup> carbon emissions for the reference scenario and each of the policy scenarios. Note that emissions are not provided for two of the scenarios: the delayed accession 3.7 W/m<sup>2</sup> not-to-exceed (S2\_3p7\_S) scenario and the delayed accession 2.6 W/m<sup>2</sup> not-to-exceed (S2\_2p6\_S) scenario. These two scenarios are not possible given the assumptions in MiniCAM. Radiative forcing from Kyoto gases was already 2.4 W/m<sup>2</sup> in 2005;

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<sup>5</sup> The EMF22 Specification calls for Group 2 to start emissions mitigation in 2031. However, MiniCAM's 15 year timestep requires mitigation to either begin in 2021 or 2036. To err on the side of caution, we have delayed their accession 5 years until 2036. Altering this assumption will have an impact on the achievability of low stabilization targets; the 3.7 W/m<sup>2</sup> not-to-exceed scenario is technically possible in MiniCAM if Group 2 enters the regime in 2021, but not if they delay until 2036.

<sup>6</sup> This figure includes fossil fuel and industrial emissions, as well as land-use change emissions.

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hence, the  $2.6 \text{ W/m}^2$  scenario requires substantial emissions reductions by 2020. With delayed accession, dramatic global emissions reductions of this kind are not possible because of the assumptions about growth in the non-participating regions and the pressures towards leakage (discussed later). In the  $3.7 \text{ W/m}^2$  scenario, 2050 is the critical period; limiting radiative forcing to  $3.7 \text{ W/m}^2$  prior to this date and after this date is possible. However, staying below  $3.7 \text{ W/m}^2$  in 2050 is not possible, again due to growth assumptions and emissions leakage.

The immediate and delayed accession scenarios both require limiting global emissions in order to meet a prescribed climate goal. Climate stabilization is essentially a zero-sum game; thus, emissions mitigation not undertaken by one region in one time must be undertaken by another region and time. This property has two implications for delayed accession. First, global emissions are shifted across time. The delayed accession scenarios all have higher global emissions in the early years than the immediate accession scenarios. However, emissions in the second half of the century must compensate for higher emissions in the early years. Thus, in the second half of the century, global emissions in a delayed accession regime are lower than under immediate accession. Delay in participation results in delay in global mitigation. This effect can be seen in Figure 2.

Secondly, Group 1 undertakes more emissions mitigation in the early years due to lack of participation in Groups 2 and 3. For example, in a  $3.7 \text{ W/m}^2$  overshoot scenario, Group 1 emissions under delay are 17% lower than Group 1 emissions in the delayed accession scenario. Thus, the carbon tax in Group 1 in the delayed accession scenarios must be larger than the tax in the immediate accession cases (Figure 3). The increase in taxes due to imperfect cooperation is

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more significant for lower climate targets. For the 3.7 W/m<sup>2</sup> overshoot scenario, the tax is 35% higher in the delayed accession case. In the 2.6 W/m<sup>2</sup> overshoot scenario, however, the tax increases by a factor of 2.5 due to imperfect cooperation.

Figure 3 also shows the differences in tax paths for overshoot versus not-to-exceed cases. In the immediate accession 2.6 W/m<sup>2</sup> scenarios, the not-to-exceed tax is five times larger in 2020 than the overshoot case. However, these tax paths cross during the century such that the overshoot tax is six times larger than the not-to-exceed tax in 2095. This illustrates the differences in the two problems. In a not-to-exceed scenario, the difficulty is in reducing emissions immediately so that radiative forcing stays below the prescribed target. In an overshoot scenario, the difficulty is in accelerating emissions reductions to “make up” for any excess radiative forcing that was allowed in the early part of the century.

Figure 4 shows the cost of each policy for the globe and each of the three regions. As expected, delayed accession increases the cost of limiting climate change for the world (Panel A) and the Group 1 nations (Panel B). Interestingly, delayed accession also increases cost in Groups 2 (Panel C) and 3 (Panel D). These regions experience a benefit from non-participation in the early part of the century when they are not undertaking any mitigation effort. However, the action that they undertake in the second half of the century to “catch up” more than compensates for this benefit. The result is higher costs under delayed accession for all regions. This finding is consistent with that of Calvin et al. (2009b) and Edmonds et al. (2008). Additionally, the increase in costs due to delayed accession increases for lower climate limits.

## 6. Bioenergy Implications

Bioenergy plays a substantial role in limiting radiative forcing in all of the scenarios considered. The distribution of bioenergy, and the amount of bioenergy consumed, is driven by assumptions about technology and policy. Figure 5 shows bioenergy consumption in the immediate accession 3.7 W/m<sup>2</sup> overshoot scenario under four different variations of MiniCAM. The top row (Panels A and B) assumes carbon emissions are taxed both in the energy system and the terrestrial system. The scenarios in the bottom row (Panels C and D), however, only tax fossil and industrial emissions, ignoring any land-use change emissions. The left column (Panels A and C) assume that bioenergy with carbon capture and storage (CCS) technologies are available.<sup>7</sup> The right column (Panels B and D) does not allow bioenergy with CCS. Bioenergy with CCS (bioCCS) technologies are capable of generating negative emissions and thus become very attractive under a climate policy. Thus, when bioCCS is available, it consumes most of bioenergy produced. Without CCS, however, biofuels consume the largest share of bioenergy.

Comparing the two rows of Figure 5, we see a noticeable difference in the total quantity of bioenergy consumed with and without a terrestrial carbon policy. The scenarios without pricing of land-use change emissions see as much as 25% more total bioenergy consumed than those with a tax on land-use change emissions. Most of the difference in bioenergy consumption is due to differences in purpose grown bioenergy.<sup>8</sup> Pricing land-use change emissions incentivizes afforestation practices. As a result, demand for bioenergy is tempered by a demand for forests. Without this tax on terrestrial emissions, bioenergy crops are free to expand into forest land

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<sup>7</sup> MiniCAM includes bioenergy technologies with carbon capture and storage for the production of electricity and hydrogen.

<sup>8</sup> MiniCAM also includes bioenergy from crop residues, waste streams from the pulp and paper industry, and municipal solid waste.

without consequence. This allows for substantial growth in land devoted to bioenergy crops (Figure 6, Panel A). However, as bioenergy land expands, it moves into more marginal land, decreasing the average yield. As a result, the increase in bioenergy land between the two policy regimes is substantially larger than the increase in purpose grown bioenergy production (Figure 6, Panel B). Thus, we conclude that technology is an important determinant of where bioenergy is consumed, and policy is an important determinant of how much bioenergy is consumed.

## 7. Land Use Implications

Bioenergy links the energy system to the terrestrial system. The amount of bioenergy consumed in the energy system is driven by total energy demand as well as the relative prices of the various fuels with which it competes (e.g., coal, gas, oil, nuclear, renewables). The amount of bioenergy produced is largely driven by land use.<sup>9</sup> The imposition of a carbon tax incentivizes the use of bioenergy in the energy system because it is assumed to have no direct carbon emissions. The increased use of bioenergy, however, is not without consequence. Purpose grown bioenergy competes for land with other uses (e.g., forests, crops, grassland, etc.). Meeting the increased demand for bioenergy may require the clearing of land. If the land cleared has a higher carbon content than bioenergy land, increasing bioenergy production will result in land-use change emissions. Thus, the use of bioenergy impacts both fossil and industrial emissions and land-use change emissions. Wise et al. (2009a,b) shows that when terrestrial carbon emissions are not taxed the increased demand for bioenergy results in a dramatic increase in land-use change emissions. We find the same result here. Figure 7 shows carbon emissions for the immediate accession 3.7 W/m<sup>2</sup> overshoot scenario, with and without terrestrial carbon pricing. From this

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<sup>9</sup> Purpose grown bioenergy and crop residues are dependent on the land dedicated to bioenergy and crop production. Bioenergy from municipal solid waste, however, is not linked to land-use or the terrestrial system.

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figure, we see that land-use change emissions (Figure 7, Panel A) spike in 2065 in the scenario without terrestrial carbon pricing. The spike in emissions is not insignificant: the difference is as much as 13 GtC/yr. As a result of the increase in land-use change emissions, more pressure is put on abatement in the energy and industrial sectors. To meet the same climate target, fossil and industrial emissions (Figure 7, Panel B) must be reduced an extra 6 GtC/yr in 2065 in the scenario without a price on terrestrial carbon emissions as compared to the scenario with a value on terrestrial emissions. This requires a nearly three-fold increase in carbon taxes, which is consistent with the findings in Wise et al. (2009a,b).<sup>10</sup>

For the policy scenarios considered in this paper, we assume that terrestrial carbon is valued at the same rate as energy and industrial emissions. However, this carbon price is only applied when a region is participating in the climate regime. As a result, delayed accession scenarios effectively combine both land-use policies in the early years. Group 1 nations value terrestrial carbon from 2012 onward. Group 2, however, does not impose a terrestrial policy until their accession date in 2036. Group 3 delays the land use policy until 2051. As a result, under delayed accession, participating regions have incentives for afforestation, while non-participating regions have no dis-incentives for deforestation. Additionally, the desire to decarbonize the energy system in the participating regions puts upward pressure on bioenergy demand and bioenergy prices. The net effect is leakage within the terrestrial system. Crop and bioenergy production shifts to non-participating regions. Participating regions can still use bioenergy and increase forests by importing bioenergy and crop production from the non-participating regions.

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<sup>10</sup> Note that Wise et al. (2009a,b) limit CO<sub>2</sub> only concentrations, while the analysis here limits CO<sub>2</sub>-equivalent concentrations. The effect of terrestrial carbon pricing, however, is virtually identical here as it is in Wise et al. (2009a,b).

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Figure 8 depicts land allocation, globally (Panel A) and for each of the three groups (Panels B-D) in the delayed accession  $3.7 \text{ W/m}^2$  overshoot scenario. From this figure, we see an expansion in forests in Group 1 (Panel B) in 2020 and 2035 due to the subsidy associated with holding carbon stocks. Group 2 (Panel C) increases crop land to compensate for the decrease in Group 1. When Group 2 enters the climate coalition in 2036, their incentives switch from growing high dollar crops and exporting to the Group 1 regions to planting trees for the carbon subsidy. As a result, Group 2 forests expand between 2036 and 2050. Group 3 (Panel D) increases crop land in those years to compensate for the decreased production in Group 2. After Group 3 enters the coalition in 2051, incentives across all world regions align and land allocation adjusts to patterns more similar to the 2005 land allocations (and the immediate accession land allocations).

The shift in cropland from one region to another is not a one-for-one substitution. While it may take one hectare of land to produce a given amount of corn in the USA, it may take more than one hectare of land to produce the same amount of corn elsewhere. The problem is exacerbated when cropland expands; the additional cropland is placed on more marginal land reducing the average yield of a region. The result is that by shifting cropland around the globe we increase the total cropland needed. Figure 9 shows the total cropland required in the  $3.7 \text{ W/m}^2$  overshoot scenarios (both immediate and delayed accession). Cropland under delayed accession is more than double cropland with immediate accession, despite only a 12% difference in beef consumption between the two scenarios.<sup>11</sup>

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<sup>11</sup> MiniCAM allows for consumers to shift away from meat consumption as prices increase. Due to the large amount of land and grain needed for meat production, valuing carbon in land puts upward pressure on meat prices inducing a shift toward a more vegetarian diet. It should be noted that the decline in beef consumption is relative to the reference scenario and not 2005. We assume that increases in income, particularly in the developing regions, drive increases in meat consumption relative to 2005.

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The effect of land-use leakage is an increase in land-use change emissions relative to both the reference scenario and the first-best (immediate accession) scenario. Figure 10 plots land-use change emissions under these three scenarios for the world and each of the three groups. Land-use change emissions in Group 1 (Figure 10, Panel B) are lower in the delayed accession case than either the reference or the immediate accession scenarios for the first half of the century. This is due to a combination of higher taxes under delayed accession and the ability to export food production to other regions of the world. These two effects allow Group 1 to convert more land to forests, reducing land-use change emissions. In the second half of the century, however, Group 1 is forced to convert some land back to crop production resulting in increased land-use change emissions from 2065 onward. Group 2 (Figure 10, Panel C) increases crop production in 2020 and 2035 at the expense of forest land; the result is a 65% increase in land-use change emissions relative to the reference scenario and a six-fold increase in emissions relative to the immediate accession scenario. The largest effect, however, is in Group 3 (Figure 10, Panel D). Group 3 is the primary food producer in the mid-century. Clearing land for this crop production results in a seven-fold increase in land-use change emissions relative to the reference scenario and a factor of twenty increase in land-use change emissions relative to the immediate accession scenario. The net effect of land leakage is almost a tripling of land-use change emissions globally (Figure 10, Panel A) in 2050 compared to the reference. This increase in emissions is significantly larger than the 7% increase in fossil and industrial emissions in the Calvin et al. (2009b) paper.

## 8. Discussion

Several lessons emerge from this analysis. First, delayed accession increases the taxes required to limit radiative forcing. Climate stabilization is essentially a zero-sum game. Thus, if some

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regions delay implementing a carbon policy, other regions are forced to undertake more emissions mitigation forcing a higher carbon tax.

Second, delayed accession increases the cost of limiting climate change globally, and in all regions. Delayed accession offers some near-term benefits for the non-participating regions. However, delay merely shifts mitigation and cost to the second half of the century. The increase in cost post-accession more than offsets any benefits from non-participation early in the century.

Without immediate accession, some radiative forcing targets are not possible. In a delayed accession case, we surpass the  $2.6 \text{ W/m}^2$  forcing threshold in 2020 due to high emissions from non-Annex I regions and leakage. As a result, any attempt to limit forcing to  $2.6 \text{ W/m}^2$  with delay will require overshoot. The  $3.7 \text{ W/m}^2$  not-to-exceed scenario is also not possible in MiniCAM due to a combination of growth in the developing world and leakage effects.

Technology and policy affect the quantity and deployment of bioenergy. The inclusion of technologies that combine bioenergy and carbon capture and storage results in the diversion of most bioenergy to the electric sector. Without CCS, most bioenergy is used in liquid fuels. Imposing a terrestrial carbon policy dampens the demand for bioenergy due to competition of land with forests.

Valuing terrestrial carbon allows us to increase fossil fuel and industrial emissions while still reaching the same radiative forcing limit. The imposition of a terrestrial carbon price reduces land-use change emissions. As a result, more fossil fuel and industrial emissions are allowed

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while still meeting the same forcing limit. The increases in fossil fuel and industrial emissions is often substantial, 6 GtC/yr in 2065 in the immediate accession 3.7 W/m<sup>2</sup> overshoot scenario.

Finally, the combination of delayed accession and valuing of terrestrial carbon results in a significant shift of crop production around the world. With each shift in production, more land is required to produce the same amount of food because production moves to lower yielding regions. Shifting production results in deforestation and a substantial increase in land-use change emissions, relative to the reference scenario.

### 9. References

Babiker, M.H. 2005. “Climate Change Policy, Market Structure, and Carbon Leakage.” *Journal of International Economics*, 65: 421-445.

Bollen, J. T. Manders, and H. Timmer. 2000. “Decomposing Carbon Leakage—An Analysis of the Kyoto Protocol.” Third Annual Conference on Global Economic Analysis, Melbourne, Australia.

Brenkert A, S Smith, S Kim, and H Pitcher. 2003. *Model Documentation for the MiniCAM*. PNNL-14337, Pacific Northwest National Laboratory, Richland, Washington.

Burniaux, J-M, J. Oliveira Martins. 2000. “Carbon Emission Leakage: A General Equilibrium View.” OECD Economics Department Working Paper No. 242, Paris.

## DRAFT—COMMENTS WELCOME

Calvin, Katherine, Jae Edmonds, Ben Bond-Lamberty, Leon Clarke, Page Kyle, Steve Smith, Allison Thomson, Marshall Wise (2009a). “2.6: Limiting Climate Change to 450 ppm CO<sub>2</sub> Equivalent in the 21st Century,” Submitted to *Energy Economics*.

Calvin, Katherine, Pralit Patel, Allen Fawcett, Leon Clarke, Karen Fisher-Vanden, Jae Edmonds, Sonny Kim, Ron Sands, Marshall Wise (2009b). “The Distribution and Magnitude of Emissions Mitigation Costs in Climate Stabilization under less than Perfect International Cooperation: SGM Results.” Submitted to *Energy Economics*.

Clarke, L., J. Edmonds, H. Jacoby, H. Pitcher, J. Reilly, and R. Richels. 2007. *CCSP Synthesis and Assessment Product 2.1, Part A: Scenarios of Greenhouse Gas Emissions and Atmospheric Concentrations*. U.S. Government Printing Office, Washington DC.

Clarke, L., M.A. Wise, J.A. Edmonds, M. Placet, P. Kyle, K. Calvin, S. Kim, S. Smith. 2008. *CO<sub>2</sub> Emissions Mitigation and Technological Advance: An Updated Analysis of Advanced Technology Scenarios (Scenarios Updated January 2009)*. PNNL-18075 (December, 2008). 82 pages.

Clarke L, Edmonds J, Krey V, Richels R, Tavoni M, Rose S. EMF22 International Scenarios Overview. *Energy Economics* 2009; forthcoming

Edmonds, J., L. Clarke, J. Lurz and M. Wise. 2008. “Stabilizing CO<sub>2</sub> Concentrations with Incomplete International Cooperation,” *Climate Policy*, 8:355–376. [PNNL-SA-16932].

## DRAFT—COMMENTS WELCOME

Edmonds, J. and J. Reilly. 1985. *Global Energy: Assessing the Future*, Oxford University Press, New York. 1985.

Felder, S. and T.F. Rutherford. 1993. “Unilateral CO2 Reductions and Carbon Leakage: The Consequences of International Trade in Oil and Basic Materials.” *Journal of Environmental Economics and Management*, 25: 162-176.

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate Change 2007: Mitigation of Climate Change. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA., 851 pp.

Kim, Son H., Jae Edmonds, Josh Lurz, Steven J. Smith, and Marshall Wise. 2006. “The Object-oriented Energy Climate Technology Systems (ObjECTS) Framework and Hybrid Modeling of Transportation in the MiniCAM Long-Term, Global Integrated Assessment Model,” *The Energy Journal*, *Special Issue: Hybrid Modeling of Energy-Environment Policies: Reconciling Bottom-up and Top-down*, pp.63-91. [PNWD-SA-7256].

Kuik, O. and R. Gerlagh. 2003. “Trade Liberalization and Carbon Leakage.” *The Energy Journal*, 24(3): 97-119.

## DRAFT—COMMENTS WELCOME

Paltsev, S.V. 2001. “The Kyoto Protocol: Regional and Sectoral Contributions to the Carbon Leakage.” *The Energy Journal*, 22(4):53-79.

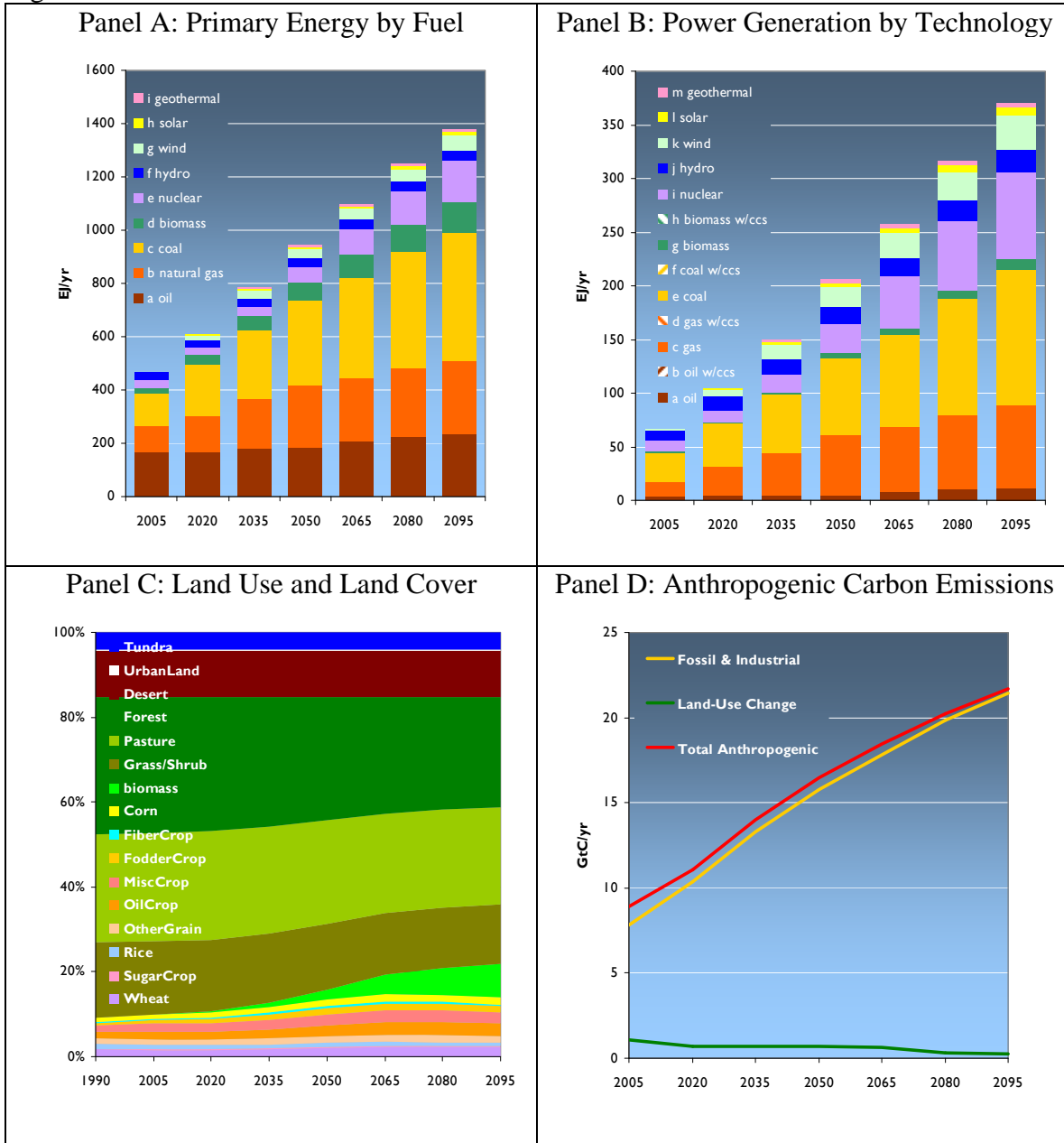
Reinaud, J. 2008. “Climate Policy and Carbon Leakage—Impacts of the European Emissions Trading Scheme on Aluminium.” OECD/International Energy Agency. October.

Richels, R., T. Rutherford, G. Blanford, and L. Clarke. 2008. “Managing the transition to climate stabilization,” *Climate Policy*, 7(5):409-428.

Marshall A. Wise, Katherine V. Calvin, Allison M. Thomson, Leon E. Clarke, Benjamin Bond-Lamberty, Ronald D. Sands, Steven J Smith, Anthony C. Janetos, James A. Edmonds. 2009a. “The Implications of Limiting CO<sub>2</sub> Concentrations for Agriculture, Land Use, Land-use Change Emissions and Bioenergy” Pacific Northwest National Laboratory. PNNL-18341.  
[http://www.pnl.gov/gtsp/publications/2009/200902\\_co2\\_landuse.pdf](http://www.pnl.gov/gtsp/publications/2009/200902_co2_landuse.pdf).

Wise, MA, KV Calvin, AM Thomson, LE Clarke, B Bond-Lamberty, RD Sands, SJ Smith, AC Janetos, JA Edmonds. 2009b. Implications of Limiting CO<sub>2</sub> Concentrations for Land Use and Energy. *Science*. 324:1183-1186. May 29, 2009.

Figure 1: The Reference Scenario



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Figure 2: Global Total Anthropogenic Carbon Emissions

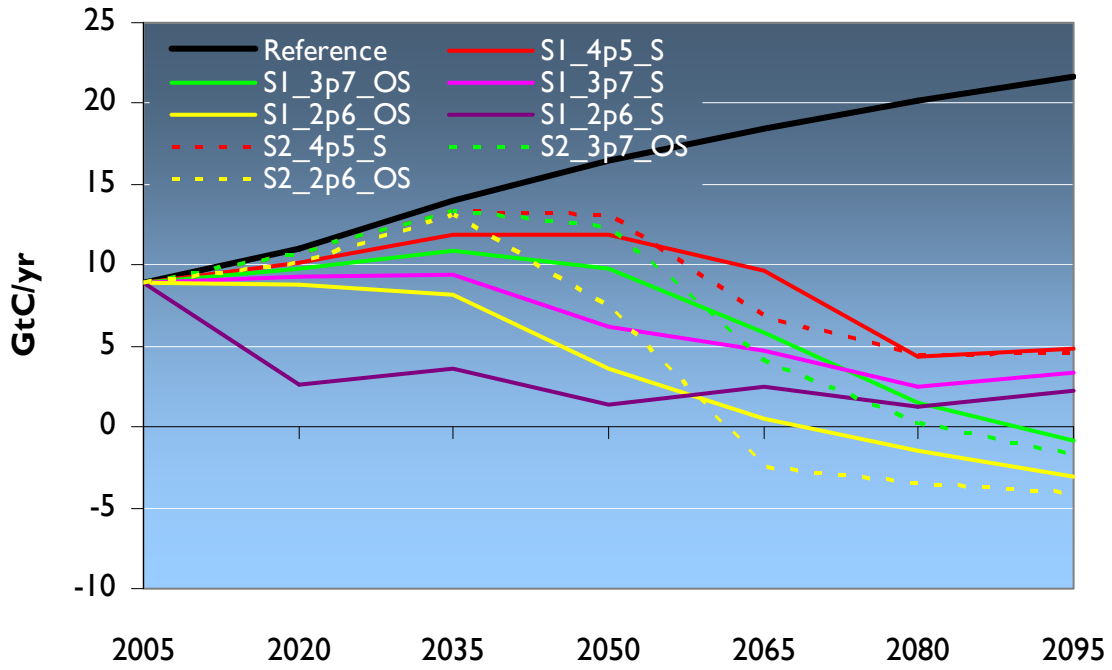


Figure 3: Carbon Taxes

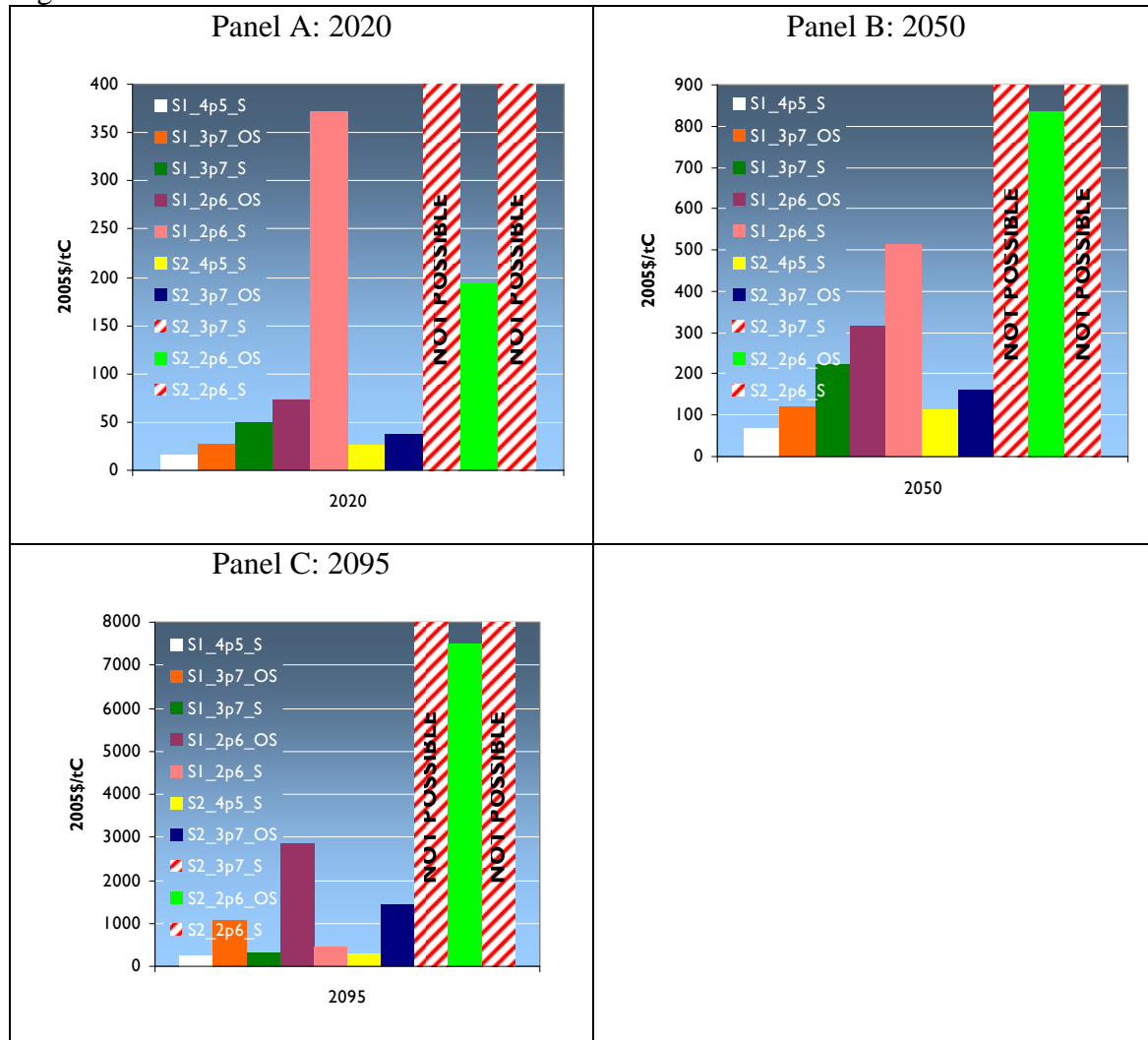


Figure 4: Total Discounted Policy Costs

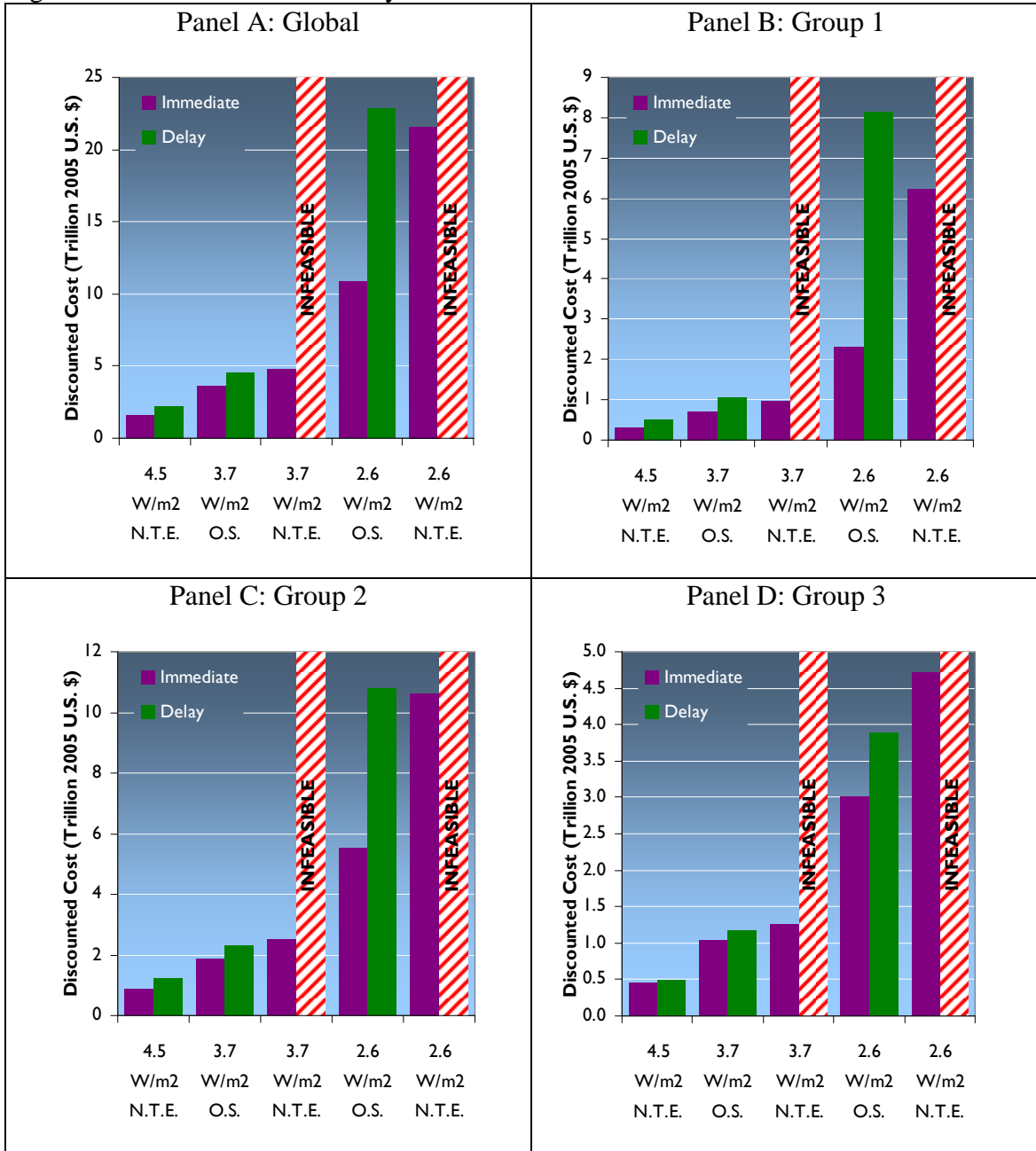
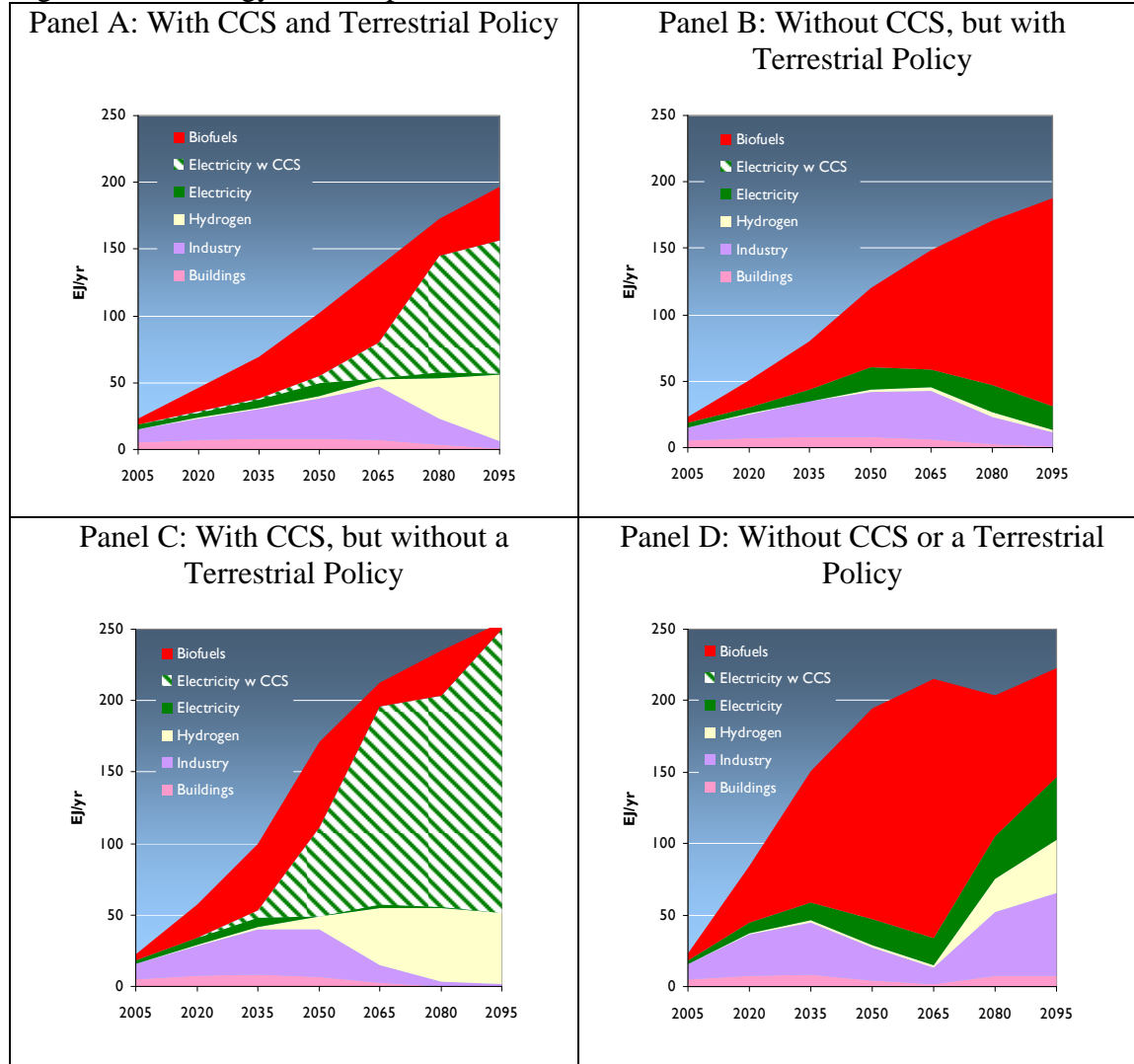


Figure 5: Bioenergy Consumption in the Immediate Accession 3.7 W/m<sup>2</sup> Overshoot Scenario



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Figure 6: Purpose Grown Bioenergy Land and Production in the Immediate Accession 3.7 W/m<sup>2</sup> Overshoot Scenario

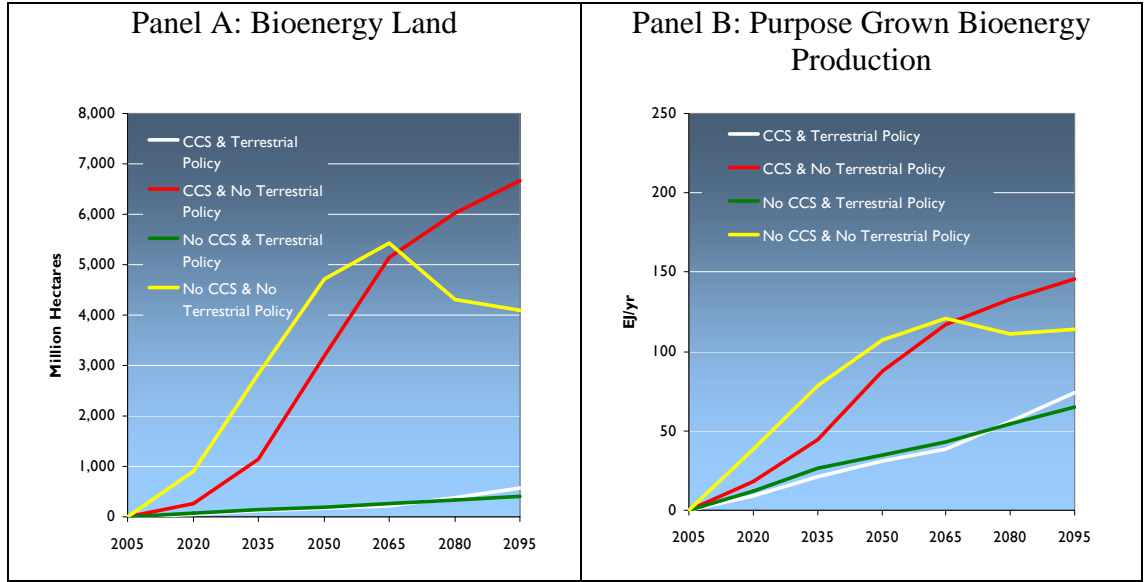


Figure 7: Emissions in the Immediate Accession 3.7 W/m<sup>2</sup> Overshoot Scenario

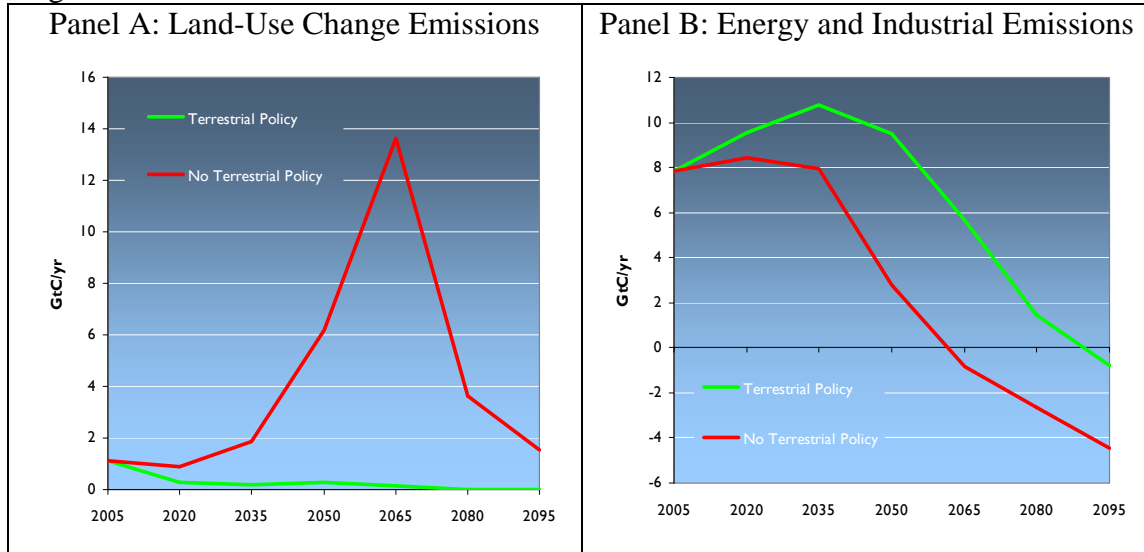


Figure 8: Land Allocation in the Delayed Accession 3.7 W/m<sup>2</sup> Overshoot Scenario

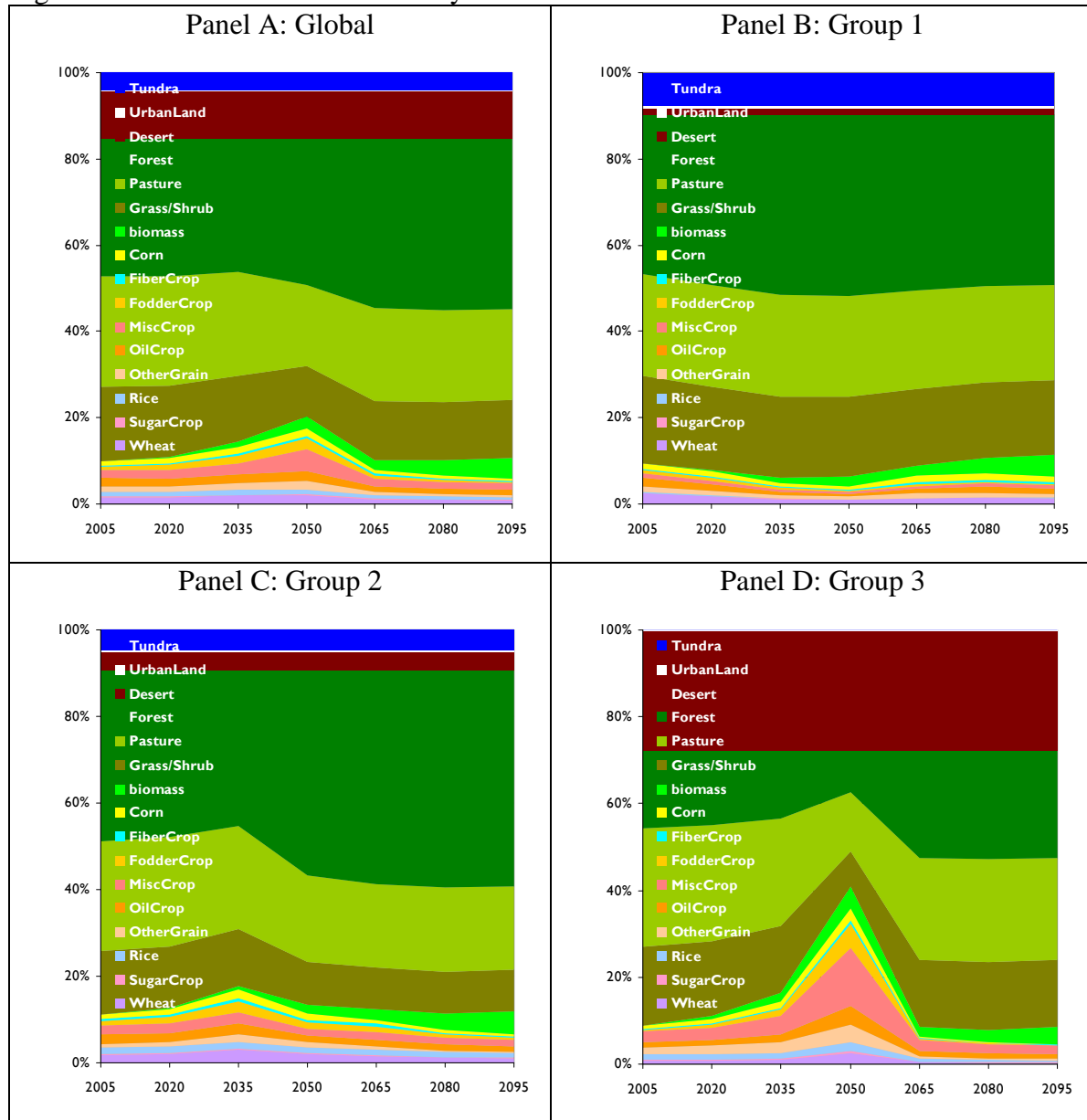
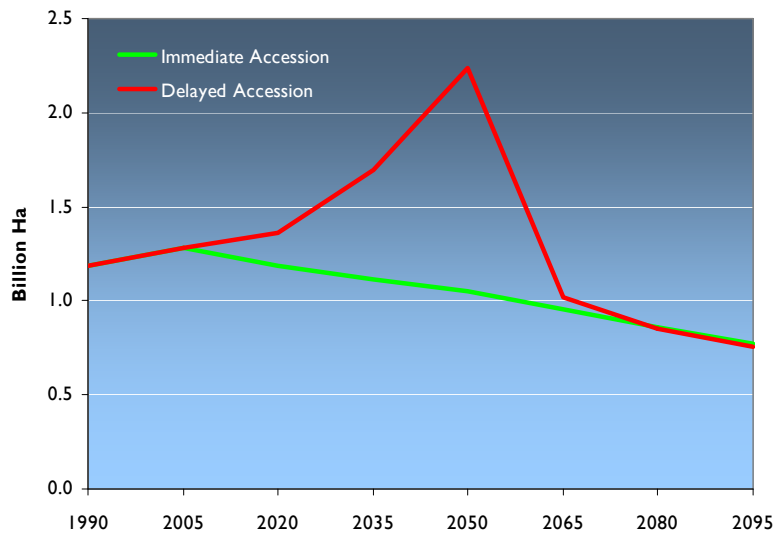


Figure 9: Global Cropland in the 3.7 W/m<sup>2</sup> Overshoot Scenarios



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Figure 10: Land-Use Change Emissions in a Reference and two 3.7 W/m<sup>2</sup> Overshoot Scenarios

