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The Implications of Limiting CO_2 Concentrations for Agriculture, Land Use, Land-use Change Emissions and Bioenergy

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February 2009

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Abstract

Limiting atmospheric CO_2 concentrations carries implications for agriculture, land use, unmanaged ecosystems, “second-generation” bioenergy, and the global energy system. Using PNNL’s integrated assessment modeling system, MiniCAM, we find that improving conventional crop productivity has the potential to reduce land-use change emissions by hundreds of billions of tons of carbon over the 21st century. The importance of the potential role of crop productivity specifically as a means of climate change mitigation has gone largely unrecognized. We further find that limiting the concentration of greenhouse gases in the atmosphere carries implications for land use that are unavoidable and independent of the production of bioenergy crops. Land is a scarce resource and the carbon associated with unmanaged ecosystems provides a carbon storage service that, if valued, becomes increasingly valuable with time. This in turn means that relative to a reference scenario, a larger stock of unmanaged ecosystems and managed forests is desirable, which in turn raises land rents, raises crop prices, decreases crop production and the land that is used to produce crops. We find that crop and forest product waste streams are a potentially important source of bioenergy with or without a carbon price. We find very little dedicated bioenergy crop production before 2035 and therefore no noticeable effect on crop prices until after the middle of the century (absence non-climate-related subsidies). Failure to take into account the value of terrestrial carbon storage services by unmanaged ecosystems and managed forests could have dramatic consequences for unmanaged ecosystems if CO_2 concentrations are limited. When terrestrial carbon is valued and both waste-derived and purpose-grown bioenergy technologies are available, the cost of limiting the concentration of CO_2 is reduced in some scenarios by half. When carbon is valued the dominant use of bioenergy is power generation with CO_2 capture and storage (CCS), not transportation fuels. We find that net global carbon emissions eventually become negative when CO_2 concentration limits are set below 550 ppm in 2095 and both bioenergy and CCS technologies are jointly employed.

1. Introduction

It is well known that limiting the concentration of atmospheric CO_2 carries implications for the global energy and land-use systems. A great deal of attention has been focused on energy and energy technologies over the years and more recently terrestrial systems have received increased attention. Bioenergy, which is a member of both the global energy and land-use systems, has been a focal point. Bioenergy has long been considered a potentially important technology, which could deploy extensively in a climate-constrained world, (IPCC AR4 2007; Clarke et al., 2007; Edmonds, et al 2007; Pacala and Socolow 2003; Hoffert et al., 2002). Bioenergy is of interest because, like fossil fuels, it is a hydrocarbon but, unlike fossil fuels, it obtained its CO_2 from the atmosphere relatively recently and the return of that carbon to the atmosphere upon oxidation leaves the net atmospheric CO_2 concentration largely unaffected. But, this accounting considers only the direct effects of bioenergy on the carbon cycle. Recent papers have raised questions about indirect effects on the larger energy-agriculture system (Tilman, Hill, and Lehman, 2006; Edmonds et al., 2003; McCarl and Schneider, 2001; Yamamoto, et al., 2001). Others have worried about the interaction between bioenergy production and food prices (Runge and Senauer, 2007; Gurgel, Reilly, and Paltsev, 2008; Gillingham et al., 2008; Edmonds, et al., 2003). And, more recently studies have begun to consider the implications of indirect carbon emissions associated with land-use change (Fargione et al., 2008; Searchinger, et al., 2008; Schmer, et al., 2008; Gillingham et al., 2008; Edmonds et al. 2003)[2]. These recent papers point to the interconnectedness of the global energy and land-use systems and present an ideal subject for investigation by integrated assessment models.[3]

In this paper we explore the implications of limiting CO_2 concentrations for agriculture, land use, unmanaged ecosystems, "second-generation" bioenergy, and the global energy system using PNNL's MiniCAM integrated assessment modeling system[4]. In that context we address several important questions, including the impact of bioenergy on crop prices, land use, land cover, and land-use change emissions. We examine the potential role of purpose-grown bioenergy in addressing climate change and its interactions with other energy technologies, with particular focus on CO_2 capture and storage (CCS)[5]. Finally, we consider the sensitivity of our results to assumed future rates of crop productivity growth and the policy environment.

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[2] In addition, there are dynamic effects associated with land-use change emissions. For example, a change of crop land to unmanaged forests would imply a commitment to carbon uptake that persists long after the initial change in land use.

[3] Other issues have also been raised. For example, Crutzen (2008) questioned the indirect effects on non-CO_2 greenhouse gas emissions such as N_2O of producing bioenergy. The question of non-CO_2 greenhouse gas emissions is not addressed in this paper. However, is the subject of future work.

[4] We therefore do not consider bioenergy forms, such as corn, whose production and use are subsidized. Our scope is limited to those energy crops that could be produced and consumed in a market-driven environment.

[5] This builds on earlier work described in Smith et al. (2006).

2. Model Description and Methods

2.1 The MiniCAM Integrated Assessment Model

MiniCAM is a long-term, integrated assessment model (Kim et al., 2006, Clarke, et al., 2007b, Brenkert et al. 2003). It combines representations of the global economy, energy systems, agriculture and land use, with representation of terrestrial and ocean carbon cycles, a suite of coupled gas-cycle, climate, and ice-melt models (Figure 1). MiniCAM tracks emissions and concentrations of greenhouse gases and short-lives species[6]. The energy-economy-agriculture-land-use model is a direct descendent of the model developed by Edmonds and Reilly (1985). The MiniCAM physical atmosphere and climate are represented by the Model for the Assessment of Greenhouse-Gas Induced Climate Change (MAGICC; Wigley and Raper 1992, 2002; Raper *et al.*, 1996). Documentation for MiniCAM can be found at http://www.globalchange.umd.edu/models/MiniCAM.pdf/.

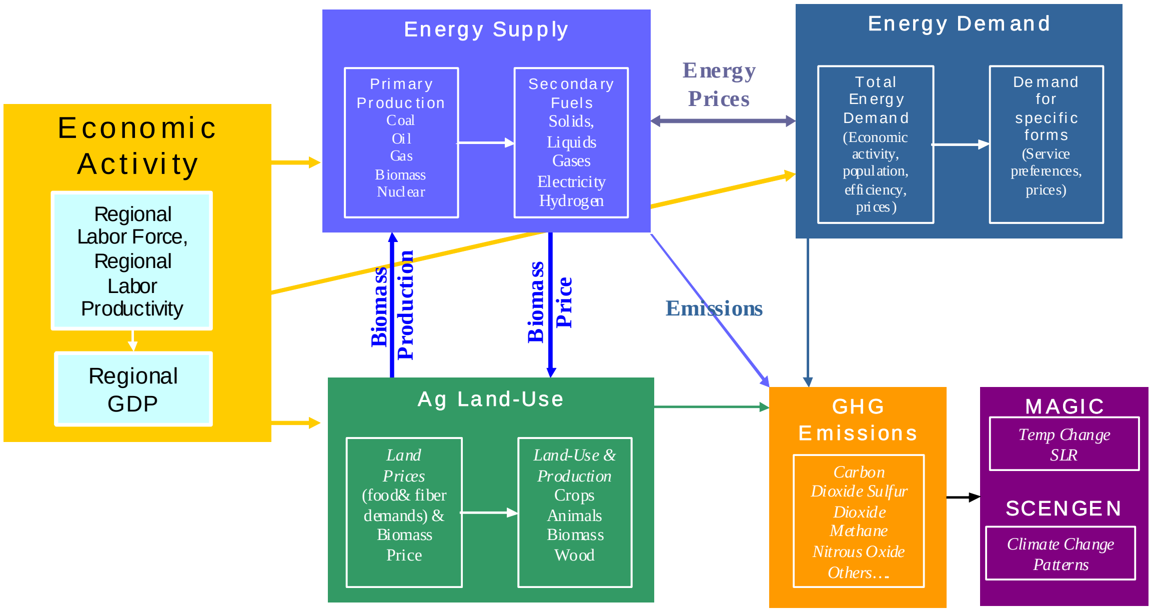

Figure 1. Elements of the MiniCAM Integrated Assessment Modeling Framework

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[6] MiniCAM tracks emissions of 15 greenhouse related gases: CO_2, CH_4, N_2O, NO_x, VOCs, CO, SO_2, carbonaceous aerosols, HFCs, PFCs, and SF_6. Each is associated with multiple human activities that are tracked in MiniCAM.

The MiniCAM energy-economy-land-use-land-cover representation is a dynamic recursive economic model. It is driven by assumptions about population size, age and gender, and labor productivity that determine potential gross domestic product in each of 14 regions[7] (Figure 2). MiniCAM is solved on a 15-year time step and is used to assess potential future developments over the period 1990 to 2095. MiniCAM establishes market-clearing prices for all energy, agriculture and land markets such that supplies and demands for all markets balance simultaneously. That is, there are no excess supplies or demands for land, agricultural products, primary energy, final energy, or energy services.

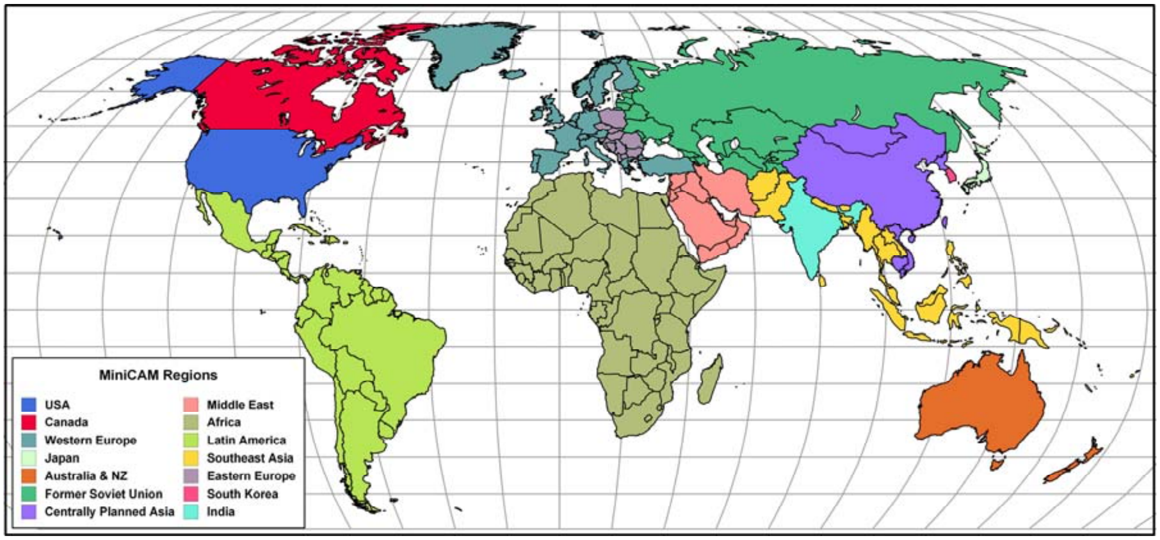

Figure 2. The Fourteen Geopolitical Regions of the MiniCAM Energy, Economy, Agriculture, Land Use, and Land Cover Module

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 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 extractive technologies. As fossil fuel and uranium resources are depletable they exhibit increasing costs. As more attractive resources are consumed, less attractive resources are exploited and *ceteris paribus*, costs rise. Renewable resources like wind and solar are produced

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[7] The United States, Canada, Latin America, Western Europe, Eastern Europe, the Former Soviet Union, the Mideast, Africa, India, China, Other South and East Asia, Australia and New Zealand, Japan and Korea.

from graded renewable resource bases. As discussed below, bioenergy availability depends on the availability and character of land resources, technology options for production, and competing land use options.

Primary energy forms include: liquids, gases, coal, bioenergy, uranium, hydropower, and solar energy. Primary energy forms are refined and transformed into end-use energy forms. End-use energy forms are: refined liquids, refined gas, coal, commercial solid bioenergy, hydrogen, and electricity. Final energy forms are used in the buildings, industry, and transport sectors. Technologies for producing, transforming and utilizing energy are assumed to evolve over time.

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), and cost of inputs and 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 contains an agriculture-land-use-land-cover-terrestrial-carbon-cycle module. Bioenergy production is represented in this portion of the MiniCAM. 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.

These estimates generally assume higher potential for increased productivity in developing countries, relative to developed regions, over the next 30 years, followed by convergence to the lower rate of productivity improvements anticipated for agriculture in developed countries (Bruinsma, 2003). Projected productivity estimates are only available until 2030, and therefore in later MiniCAM periods crop productivity change is adjusted on the assumption that it will continue to improve over time but converges to an assumption of 0.25 percent per year for all crops in the second half of the century. This assumption is based on a conservative slowing of growth from the available projections of the first decades, but is highly uncertain. In recent years, declines in crop productivity growth in some regions have led to concern that crop productivity growth may plateau or stagnate. Conversely, new research in crop management, crop breeding programs and genetic modification of crops has the potential to greatly increase crop productivity in the future (Tilman et al., 2002). Crop productivity change assumptions have a powerful effect on model results reported here, and therefore we report the implications of alternative assumptions about the future path of productivity.

The boundary between managed and unmanaged ecosystems is assumed to be elastic in the MiniCAM. The area of land under cultivation expands and contracts with the land rental rate. Thus, increased demands for land result in higher rental rates and expansion into unmanaged ecosystems and vice versa.

Historical land use from 1700 to 2005 is aggregated to the 14 MiniCAM regions from global maps of historical crop and pasture land (Klein Goldewijk, 2001; Klein Goldewijk et al., 2007), and from global maps of potential vegetation (Ramankutty and Foley, 1999). Historical agricultural production and harvested cropland area are taken from the FAOSTAT database for 1990 and 2005 (http://www.faostat.fao.org, accessed November, 2007). Cropping systems are divided into nine categories (rice, wheat, corn, other grains, oil crops, fiber crops, fodder crops, sugar crops, and miscellaneous crops) and animal production is represented by five categories (beef, dairy, pork, poultry, and other ruminants). Feed for animal production is split into pastured and mixed production systems following the methodology of Bouwman et al. (2005). Under this categorization, animal feed is supplied both by pasture land and by grain and fodder crops and thus future demand for animal products impacts land allocation in MiniCAM.

Carbon is distributed among fifteen reservoir types: unmanaged forests, other unmanaged land, managed forests, nine food and fiber crop types, bioenergy crops, pasture, and non-arable land. Stocks of terrestrial carbon (both above-ground and below ground) have been adapted from the IPCC (2001) and area weighted to the MiniCAM regions using GTAP data (Monfreda et al., 2009). Fluxes of carbon result from changes in land-use between model simulation periods. Thus, an increase in cropland may cause a reduction in forest land. As the carbon stock of initial use (forest) is greater than that of the resulting use (cropland) a pulse of carbon is emitted to the atmosphere from the land-use change.

2.2 Bioenergy

There are three types of bioenergy in the MiniCAM: traditional bioenergy production and use, bioenergy from waste products, and purpose-grown bioenergy. Traditional bioenergy consists of straw, dung, fuel wood and other energy forms that are utilized in an unrefined state in the traditional sector of an economy. Traditional bioenergy use, although significant in developing nations, is a relatively small component of global energy. We model traditional biomass as becoming less economically competitive as regional incomes increase over the century.

Bioenergy from waste products are fuels that are consumed in the modern sectors of the economy, but which are byproducts of another activity, for example black liquor in the pulp and paper industry or crop residues in agriculture. The availability of byproduct energy feedstocks is determined by the underlying production of primary products and the cost of collection. The total potential waste available is calculated as the total mass of the crop less the portion that is harvested for food, grains, and fibers, and the amount of biomass needed to prevent soil erosion and nutrient loss and sustain the land productivity. The amount of potential waste that is converted to bioenergy is based on the price of bioenergy. However, the bioenergy price does not affect production of the crop from which the waste is derived. For example, an increase in the price of bioenergy would increase the share of the wheat crop collected for use as bioenergy, but the higher bioenergy price would not affect the total production of wheat. Instead, the higher bioenergy price would result in higher purpose-grown energy crops, discussed next.

The third category of bioenergy is purpose-grown energy crops. Purpose-grown bioenergy refers to crops, whose primary purpose is the provision of energy. These would include for example, switchgrass and woody poplar. As noted earlier, we consider only “second generation” cellulosic bioenergy crops. Non-cellulosic crops, e.g. oils and sugars, are not included as potential purpose-grown bioenergy feedstocks in this analysis.

The profitability of purpose-grown, “second-generation” bioenergy depends on the expected profitability of raising and selling that crop relative to other land-use options in MiniCAM. This in turn depends on numerous other model factors including: bioenergy crop productivity (which in turn depends on the character of available land as well as crop type and technology), the rental rate on land, non-energy costs of crop production, cost and efficiency of transformation of purpose-grown bioenergy crops to final energy forms (including liquids, gases, solids, electricity, and hydrogen), cost of transportation to the refinery, and the price of final energy forms. The price of final energy forms is determined endogenously as a consequence of competition between alternative energy resources, transformation technologies, and technologies to deliver end-use energy services. In other words, prices are determined so as to match demand and supplies in all energy markets.

A variety of crops could potentially be grown as bioenergy feedstocks. The productivity of those crops will depend on where they are grown—which soils they are grown in, climate characteristics and their variability, whether or not they are fertilized or irrigated, the availability of nitrogen and other minerals, ambient CO_2 concentrations, and their latitude. In this analysis we assume that a generic bioenergy crop, based on switchgrass, can be grown in any region. Productivity is based on region-specific climate and soil characterizes and varies by a factor of three across the MiniCAM regions.[8]

In this paper we consider the possibility that bioenergy could be used in the production of electric power and in combination with technologies to provide CO_2 emissions captured and stored in geological reservoirs (CCS). This particular technology combination is of interest because bioenergy obtains its carbon from the atmosphere and if that carbon were to be captured and isolated permanently from the atmosphere the net effect of the two technologies would be to produce energy with negative CO_2 emissions.

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[8] In MiniCAM crop yields exhibit diminishing returns as production of any crop expands to less suitable land; we do not model a fixed yield. In this paper we have assumed that for a given soil and climate bioenergy crop yields increase at the generic rate of 0.25 percent per year.

We assume that CCS technology is available for application to large, point-source emissions facilities. These include electric power generation, hydrogen production, cement manufacture, and large industrial facilities. Complete documentation of our modeling of CCS technologies, as well as our modeling of all of the technologies in the energy system, is provided in Clarke et al., 2007b.

2.3 The Reference World and Assumed Policies to Limit CO_2 Concentrations

In the analysis presented here, we consider a reference world, which is a hypothetical construct in which it is assumed that the world evolves over time in an internally consistent manner that addresses an evolving menu of societal concerns, including local and regional environmental quality, but without any explicit intervention to limit greenhouse gas emissions. This clearly unrealistic construct serves a diagnostic purpose. It sets the context against which to understand the implications of explicitly considering policies that limit greenhouse gas emissions.

We limit greenhouse gas emissions, and limit the concentration of atmospheric CO_2 by charging a tax for the emission of CO_2 to the atmosphere. In this analysis, we make the simple assumption that the same price of carbon is charged everywhere in the world for all emissions. This is obviously an unrealistic assumption, whose relaxation has important implications for cost and effectiveness, particularly for limitation of CO_2 concentrations to low levels (Edmonds, et al., 2008; Richels, et al., 2008, Keppo and Rao, 2006). Nonetheless, it provides a useful starting point for analysis. We choose an arbitrary carbon price path following an exponential rate of increase. This price path is consistent with a cost effective CO_2 stabilization trajectory (Edmonds et al. 2008).

We consider two alternative applications of the carbon tax:

1. FFICT (Fossil Fuel and Industrial Carbon Tax): The carbon tax is applied only to fossil fuel and industrial CO_2 emissions without any accompanying land-use climate policy and
2. UCT (Universal Carbon Tax): The tax is applied to **all** carbon—fossil fuel, industrial, and land-use change carbon emissions.

2.4 Setting the Price of Carbon in Terrestrial Systems under the UCT Regime

The price of carbon is zero for terrestrial carbon in the FFICT regime, so terrestrial carbon pricing is not an issue. In the UCT regime carbon emissions from the terrestrial sphere are assumed to be valued equally with carbon emitted by fossil fuel and industrial sources.[9]

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[9] A change in atmospheric CO_2 concentration has the same impact on climate change no matter what the source. Thus, to a first approximation land-use emissions have the same impact as fossil emissions. But, there are important differences. Land-use emissions do not have the same impact on atmospheric concentrations as fossil emissions because land-use emissions also imply changes in the future behavior of

Carbon in terrestrial systems can be priced using either a flow or a stock approach. The flow approach is analogous to the pricing generally discussed for emissions in the energy sector: landowners would receive either a tax or a subsidy based on the *net flow* of carbon in or out of their land. If they cut down forest to grow bioenergy crops, then they would pay a tax on the CO_2 emissions from the deforestation. In contrast, the stock approach applies a tax or subsidy to landowners based on the *carbon content* of their land. If the carbon content of the land changes, for example, by cutting forests to grow bioenergy crops, then the tax or subsidy that the landowner receives is adjusted to represent the new carbon stock in the land. The stock approach can be viewed as applying a "carbon" rental rate on the carbon in land. Both approaches have strengths and weaknesses. Real-world approaches may not be explicitly one or the other.[10]

3. Results

3.1 The Reference Scenario

The assumptions employed to construct the reference scenario are described in detail in Clarke et al. (2007a and 2007b). These assumptions have been updated to reflect more recent energy data and to reflect recent trends in economic growth, particularly in South and East Asia. While significant increases in the use of non-emitting energy forms—wind, solar, nuclear and other renewables—occur in the reference scenario, the use of fossil fuels continues to grow (Figure 3). Bioenergy production grows to more than 100 EJ per year by 2095, but is dominated by energy derived from waste streams associated with other crops. Purpose-grown bioenergy is an insignificant energy source until after 2035 (Figure 4). Fossil fuel and industrial emissions, which grow from approximately 6 PgC per year in 1990 to more than 22 PgC/y are plotted in Figure 5. 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).

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the carbon-cycle. A tonne of carbon emitted due to deforestation, for example, is associated with a decrease in forest that might act as a carbon sink in the future. The theoretically proper approach to setting the price or rental rate for terrestrial carbon is discussed in the appendix to this paper.

[10] For example, Norway recently pledged $24 million in aid to Brazil to protect its rainforests (AP, 2007).

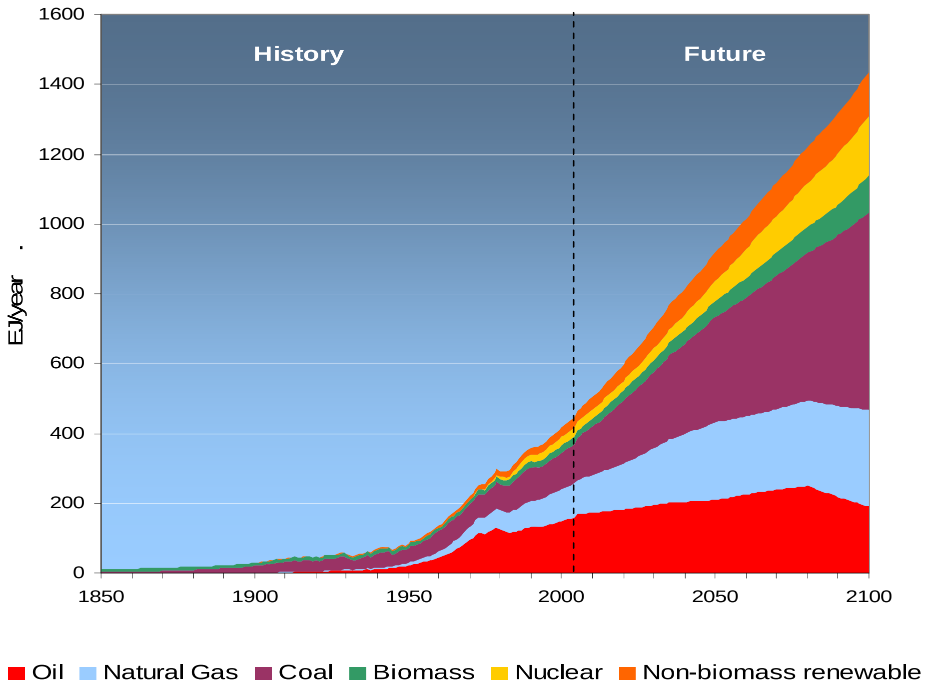


Figure 3. Reference Scenario Energy Consumption, 1850 to 2100

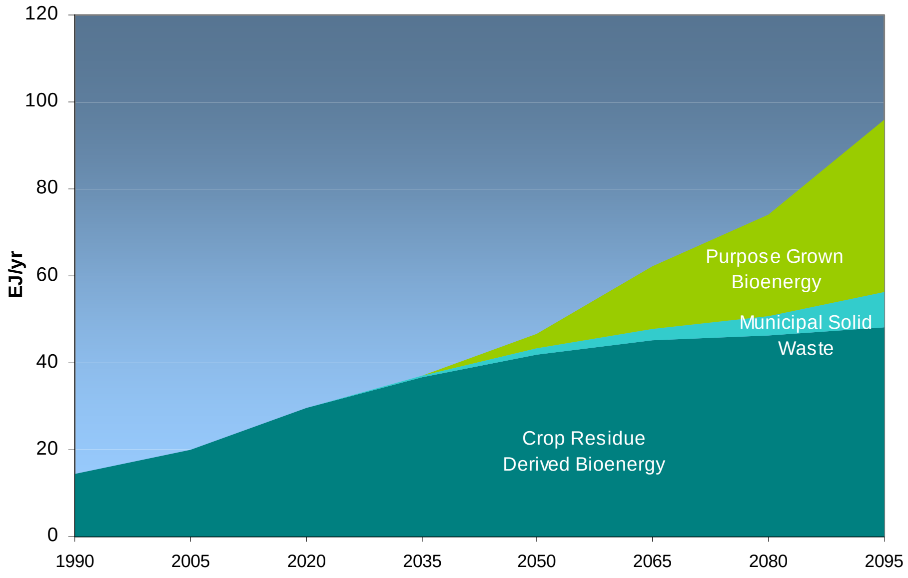


Figure 4. Reference Scenario Bioenergy Production by Source, 2005 to 2095

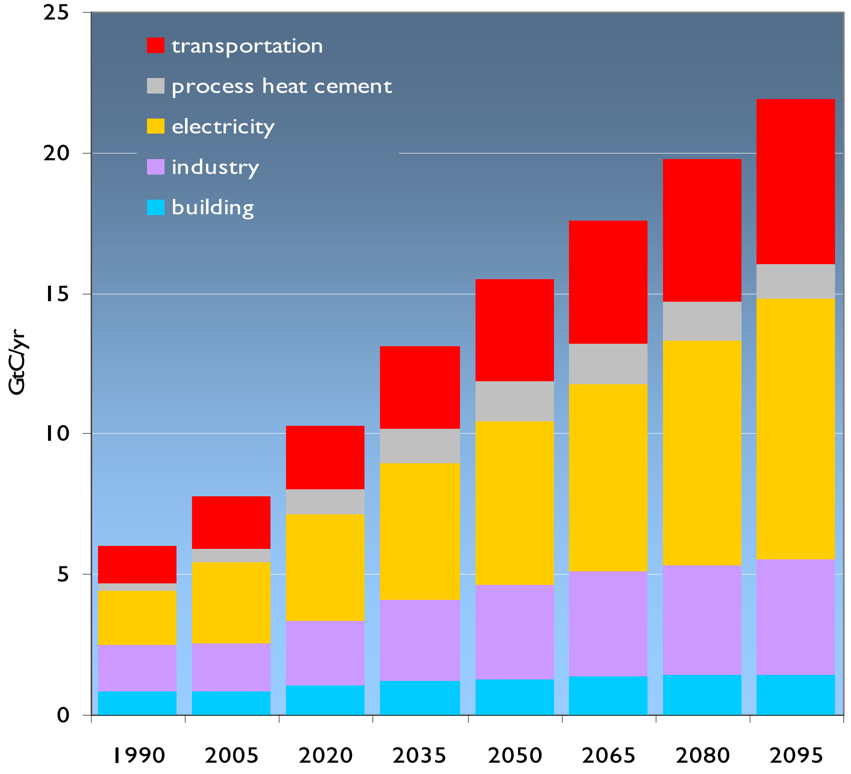


Figure 5. Reference Scenario Fossil Fuel and Industrial CO_2 Emissions by Sector, 2005 to 2095

The distribution of land is plotted in Figure 6. In the reference scenario total land area in forests declines slightly over the century while total land associated with agriculture, pastures and crop lands increases, primarily due to expansion of pasture lands. Land-use change 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 7). The decline in land-use change emissions is the consequence of our assumed increases in crop productivity around the world and results are sensitive to the assumed rate of crop productivity increase.

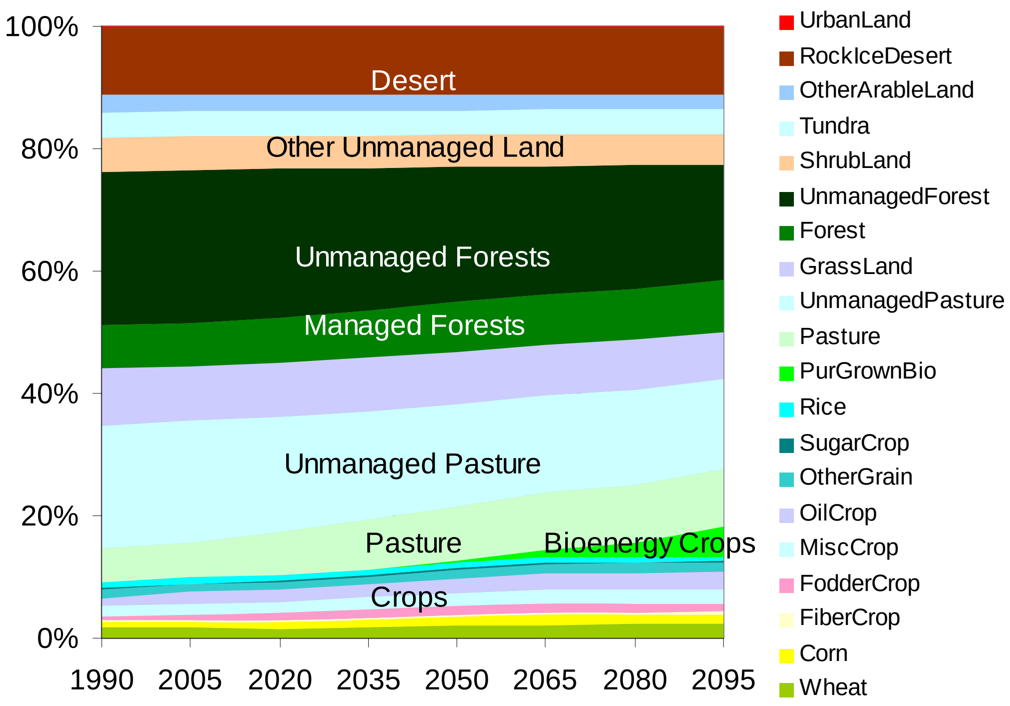


Figure 6. The Reference Scenario Distribution of Land, 2005 to 2095

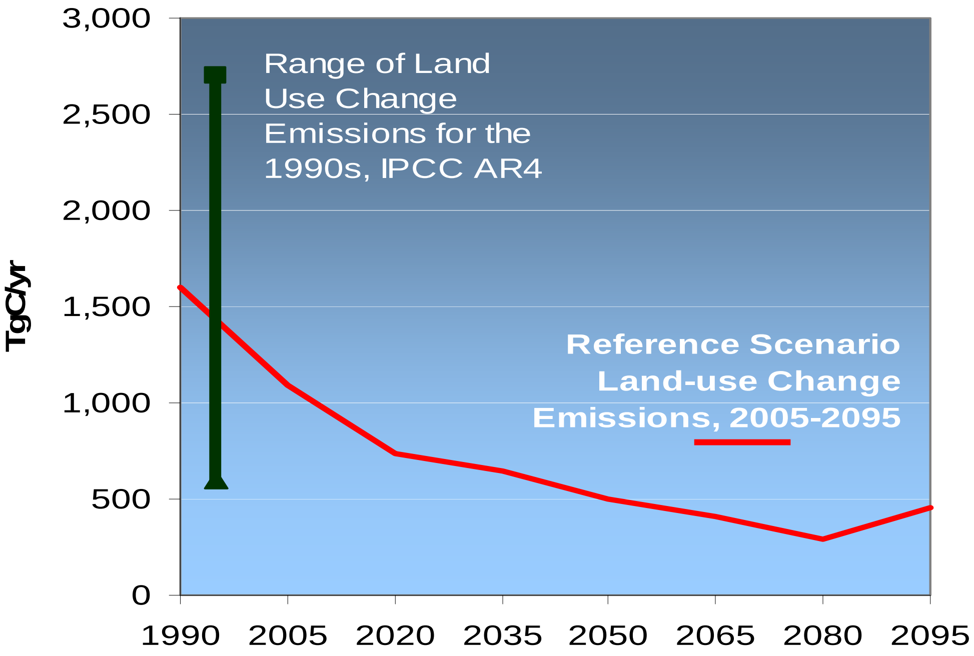


Figure 7. Reference Scenario Land Use Change Emissions, 2005 to 2095 and Range of Estimates for the 1990s

Crop prices decline in the reference scenario, due to increasing crop productivity, which enables crop production to keep pace with increasing crop demands by increasingly affluent economies in the reference scenario. In contrast, increasing energy prices exert upward pressure on the price of bioenergy (Figure 8).

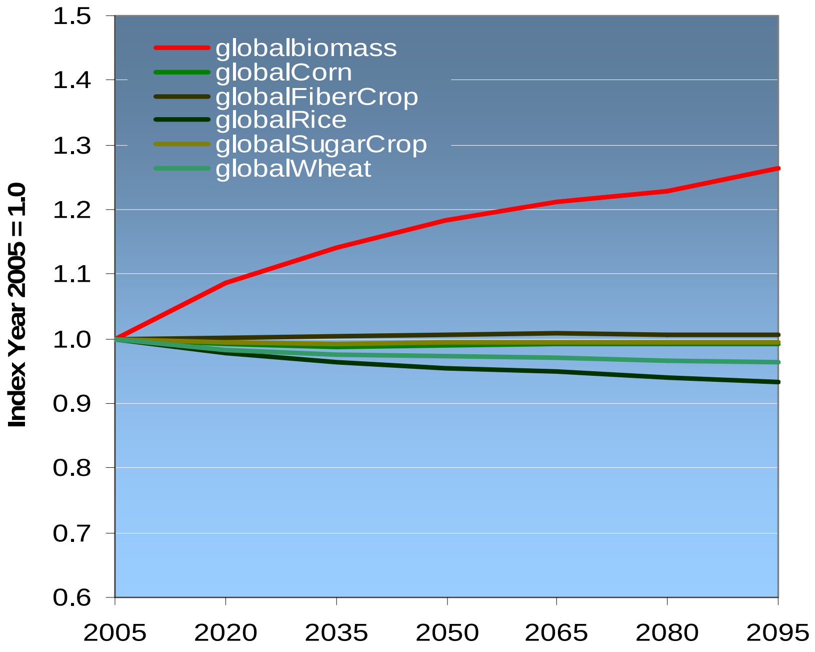


Figure 8. Reference Scenario Crop Prices, 2005 to 2095

3.2 Sensitivity to Crop Productivity Growth Rate Assumptions

Reference scenario results for agricultural prices, land use and land use change emissions are sensitive to the rate of crop productivity growth. We test the sensitivity of model results to this assumption by setting the rate of crop productivity improvement to zero after 2005.

Increases in regional GDP continue to drive increasing demands for agricultural products in our reference scenario. When crop productivity is constant, increasing demands can only be met if the area in crops increases. This in turn implies higher crop prices (Figure 9). Since bioenergy prices are largely determined by competition in the energy market, increases in energy prices are tempered relative to increases in crop prices. Expanding demand for food—livestock, grains and other food crops—leads to the expansion of crop lands into unmanaged ecosystems and net deforestation. It also eliminates the production of purpose-grown bioenergy.

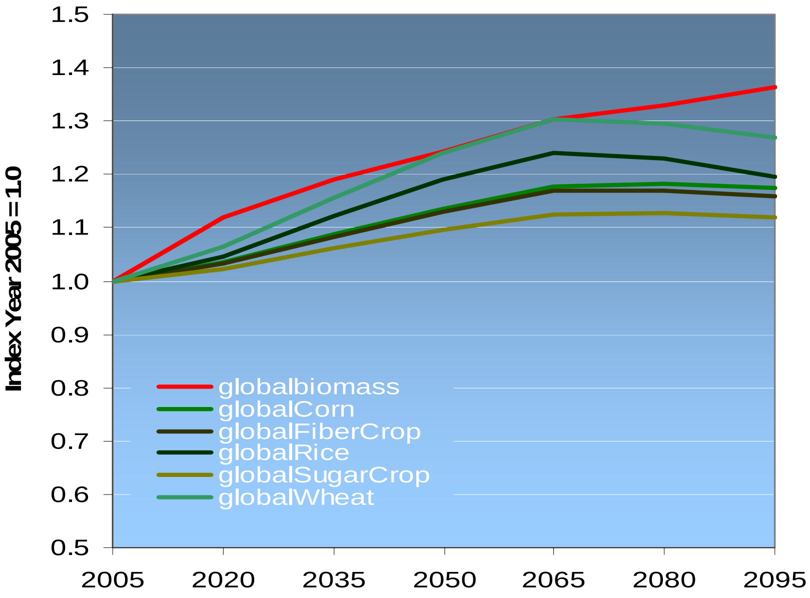


Figure 9. Sensitivity of Crop Prices to the Assumption of Frozen Crop Productivity, Reference Scenario, 2005 to 2095

Fixed agricultural crop productivity leads to the expansion of agricultural activities into unmanaged ecosystems and land-use change emissions. Land-use change emissions are plotted in Figure 10 under reference scenario assumptions and an alternative frozen crop productivity sensitivity reference scenario. Annual emissions of CO_2 peak at 2.4 PgC/year in 2035 and then decline to almost zero by the end of the century only because virtually all unmanaged ecosystems have been converted to a managed regime.

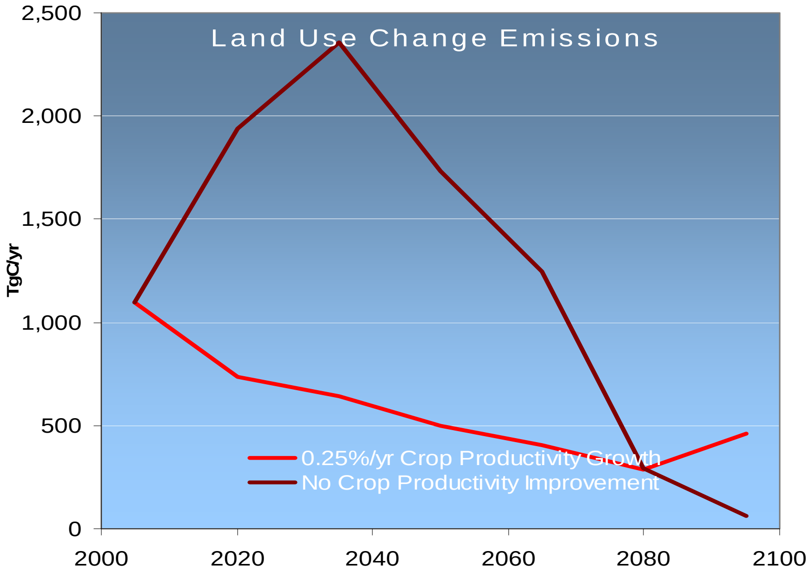


Figure 10. Sensitivity of Land Use Change Emissions to the Assumption of Frozen Crop Productivity, Reference Scenario, 2005 to 2095

Cumulative net carbon emissions from land use change increase by more than 70 PgC over the period 2005 to 2095 when crop productivity growth is set to zero. For comparison, global CO_2 capture and storage over this same period was 150 PgC when CO_2 concentrations were stabilized at 550 ppm (Edmonds et al., 2007). The conclusion here is that land-use change emissions are sensitive to crop productivity growth assumptions.

3.3 Limiting CO_2 Concentrations in the FFICT Regime

The FFICT regime explicitly penalizes CO_2 emissions from fossil fuel and industrial emissions, but values carbon emissions and storage services in the terrestrial system at zero (i.e., the regime does not subsidize carbon stocks or penalize carbon emissions from land use). Carbon price paths that limit 2095 CO_2 concentrations to prescribed values are shown in Figure 11, denominated in 2005 USD. They range from $33/tC in the year 2020 for the 550 ppm CO_2 2095 target to $90/tC for the 450 ppm CO_2 limit. Carbon prices escalate systematically for the remainder of the century so as to leave CO_2 concentrations at target levels in the year 2095 (Figure 12). These prices would be higher if it were not for the assumption that all nations of the world impose a common price on all fossil fuel and industrial carbon emissions beginning in the year 2012. The effect of delayed accession on prices in mitigating regions depends both on the length of delay in accession and on the stringency of the ultimate climate goal (Edmonds et al. 2008; Richels et al. 2008). The lower the CO_2 concentration limit, the higher near term carbon prices in mitigating regions. The effect on near-term prices is highly non-linear.

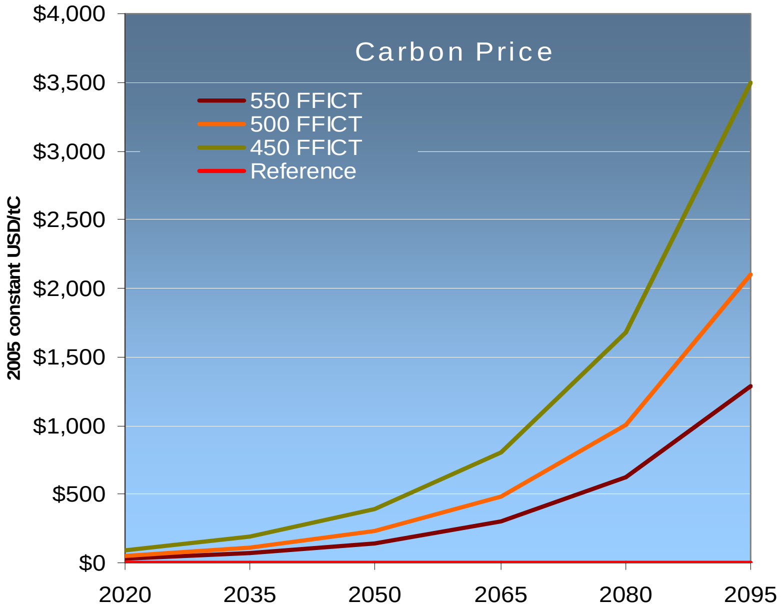
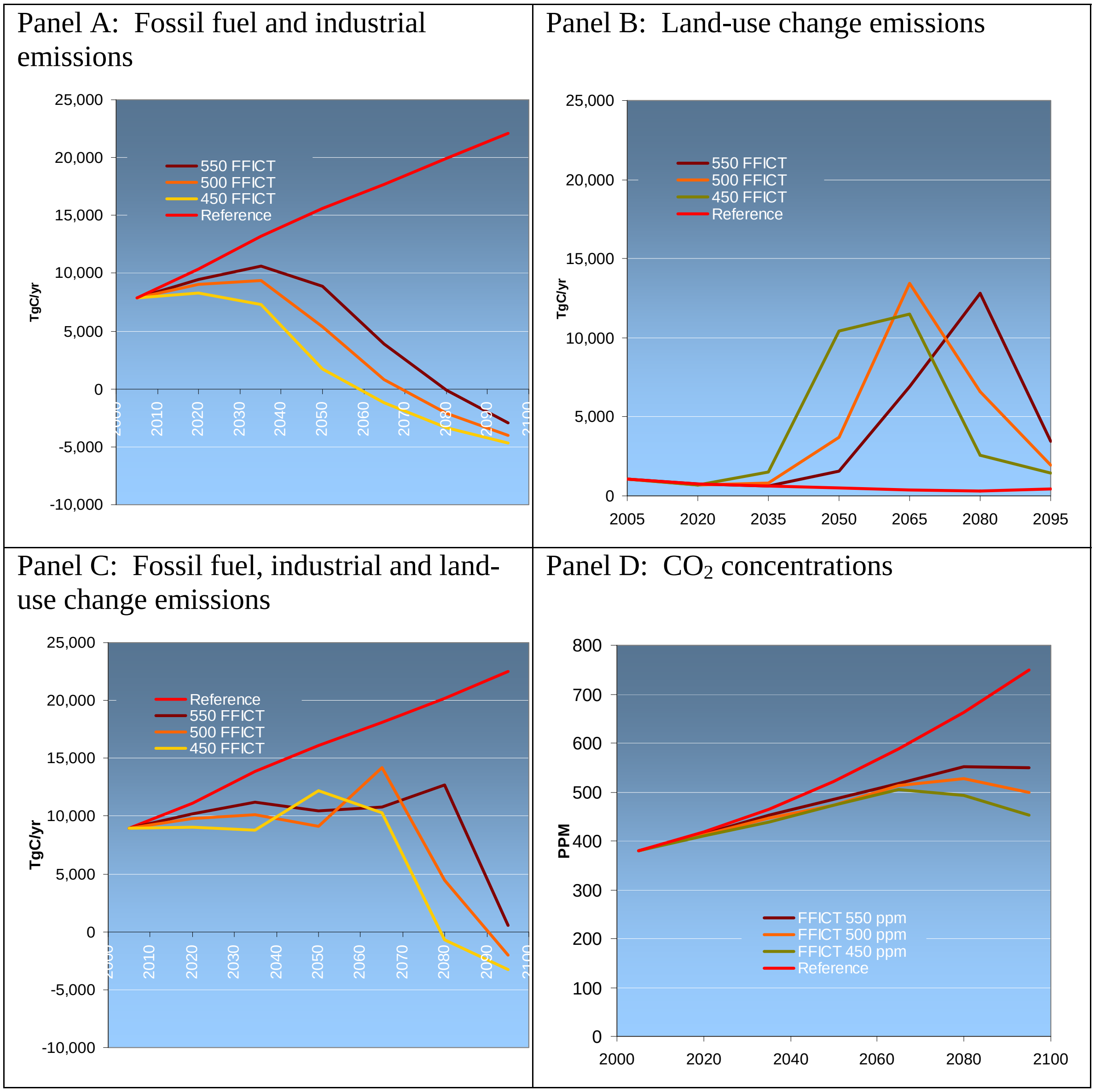


Figure 11. Carbon Price along Three Alternative CO_2 Concentration-Target Pathways with the FFICT Regime



Panel A: Fossil fuel and industrial emissions

Panel B: Land-use change emissions

Panel C: Fossil fuel, industrial and land-use change emissions

Panel D: CO_2 concentrations

Figure 12. CO_2 Emissions and Concentrations along the Reference and Three Alternative CO_2 Concentration-Target Pathways with the FFICT Regime

Several points are worth noting about these emissions trajectories. First, CO_2 concentrations along the 450 ppm, 500 ppm, and 550 ppm trajectories have maximum values greater than the target concentrations for the year 2095, and are thus called "overshoot" trajectories. We can characterize a scenario by three values: target CO_2 concentration, maximum CO_2 concentration, and cumulative concentrations (ppm) in excess of the target. The overshoot is very minor for the 550 ppm scenario where the maximum concentration of 552 ppm is reached in 2080 and the total time above the 500 ppm level is approximately 15-20 years. The sum of concentrations (ppm) in excess of the target is 11 ppm-years. The 550 ppm target scenario would thus be a 550ppm target /552ppm maximum /11 ppm-yr concentration overshoot case.

The deviation is much more significant in the 450 ppm scenario. The maximum CO_2 concentration in the 450 ppm target scenario over 50 ppm above the 2095 target and the CO_2 concentration exceeds the 2095 target level throughout the second half of the century. The 450 ppm scenario might be characterized as a 450ppm target /504ppm maximum /1766ppm-yr concentration overshoot case.

Overshoot scenarios are not the subject of this paper, so we leave the investigation of this class of scenarios to future work. Nevertheless, we note that there is no reason for society to commit to maintain a maximum concentration once it has been established and further, all low CO_2 concentrations, e.g. any concentration below 380 ppm, necessarily involve overshoot trajectories.

Second, we observe that in this analysis at least, annual global CO_2 emissions are negative in 2095 in the 450 and 500 ppm target scenarios. Negative net global emissions are the result of extensive production of bioenergy and their use in combination with CCS technology (BioCCS). BioCCS is a technology that does not deploy at low carbon prices and it does not become a significant use for bioenergy until carbon prices exceed approximately $140/tC (2005 constant USD).

The production of bioenergy is shown in Figure 13. Panel A shows the production of bioenergy from waste streams while Panel B shown the production of bioenergy from purpose-grown bioenergy plantations. We note that waste-derived bioenergy is a significant fraction of total bioenergy, and that even in scenarios in which CO_2 concentrations are limited, waste-derived bioenergy remains a significant fraction of total bioenergy production. Purpose-grown bioenergy begins to be produced in significant quantities in 2035 and production grows throughout the century. For more stringent CO_2 limits, deployment of purpose-grown bioenergy is much more aggressive in the middle of the century, even though production is similar in all scenarios by the end of the century.

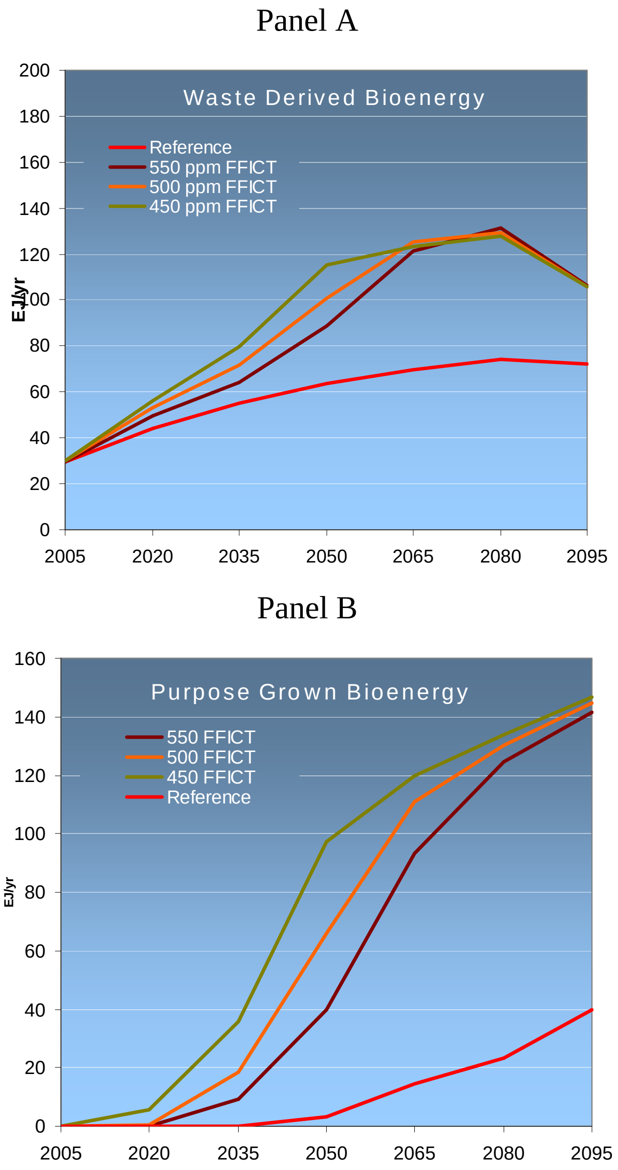


Figure 13. Waste Derived (Panel A) and Purpose Grown Bioenergy (Panel B) Production along the Reference and Three Alternative CO_2 Concentration-Target Pathways with the FFICT Regime

The amount of bioenergy used by different applications is given in Figure 14 for the Reference and three alternative CO_2 concentration target scenarios. At low carbon prices most bioenergy remains in its traditional markets in industry, power and buildings. Almost none is used in conjunction with CCS technology. As prices rise, BioCCS technologies expand dramatically. Further, by the end of the century most of the natural gas, including that derived from biological sources, is also being used in conjunction with CCS technology.[11]

Limiting climate policy to fossil fuels without consideration for terrestrial carbon value profoundly changes land use, particularly in the second half of the 21st century (Figure 15). In each of three CO_2 concentration limitation scenarios land engaged in the production of purpose-grown bioenergy eventually expands to become greater than land used for all other crops. Since potentially arable land is limited, unmanaged ecosystems are consumed in the process. This in turn results in land-use change carbon emissions that rise to a maximum of more than 10 PgC/year, with the more stringent scenarios reaching this emission rate earlier (Figure 12).

We find that in the FFICT regime most of the bioenergy is being produced at the expense of unmanaged ecosystems (forests and grasslands) and pasture. Gurgel et al. (2008) examined similar scenarios. Several features of the Gurgel et al. work differ from that presented here. First, bioenergy plays a larger role in the global energy system in their reference scenario than here. By 2100 Gurgel et al. produce more than 200 EJ/year of bioenergy in the reference scenario, while this reference scenario produces only 40 EJ/year from purpose-grown bioenergy sources and less than 60 EJ/y from organic waste streams. In the 550 ppm scenario reported here total bioenergy production grows to about 248 EJ/year, which is larger in magnitude than that reported in Gurgel et al., however only 140 to 150 EJ/year in this study's CO_2 concentration limitation scenarios are derived from purpose-grown bioenergy plantations. By 2100 similar amounts of land are also deployed in bioenergy production in both this study and Gurgel et al. One major difference between these two studies is that in this study's 550 ppm CO_2 concentration limit scenario much more land use change occurs, and particularly intrusion into unmanaged ecosystems. Land use change in Gurgel et al. is both smaller relative to their reference scenario and drawn relatively more evenly from pasture and unmanaged ecosystem land uses. Both studies show relatively smaller changes in land allocated to cropping because the demand for food crops is relatively inelastic in both studies. We note the expansion of cropland in this scenario is associated with the overall expansion of land under cultivation and the consequent diminution of marginal crop productivity as crop lands expand into less productive soils.

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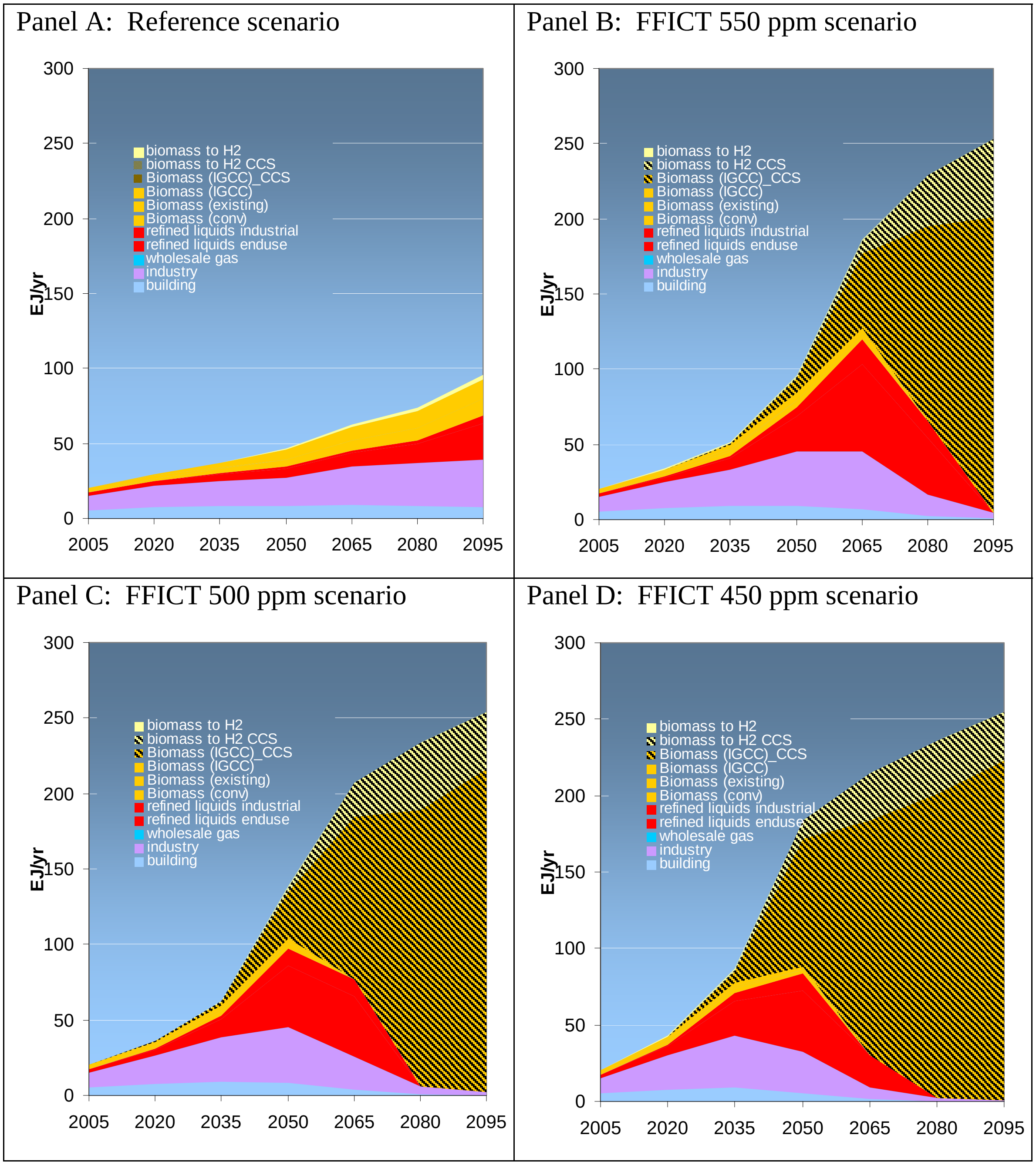
[11] We note the growth of bioenergy used to produce liquid fuels that is associated with a spike in the price of liquids accompanying the exhaustion of conventional oil resources. This occurs earlier and is more pronounced in CO_2 limitation scenarios than in the reference scenario because coal-to-liquids and unconventional liquids from shales and oil sands, which are economic in the reference scenario, are uneconomic at the CO_2 prices observed in the three CO_2 limitation scenarios. The use of bioenergy to produce liquid fuels declines as the long-term CO_2 limit tightens.

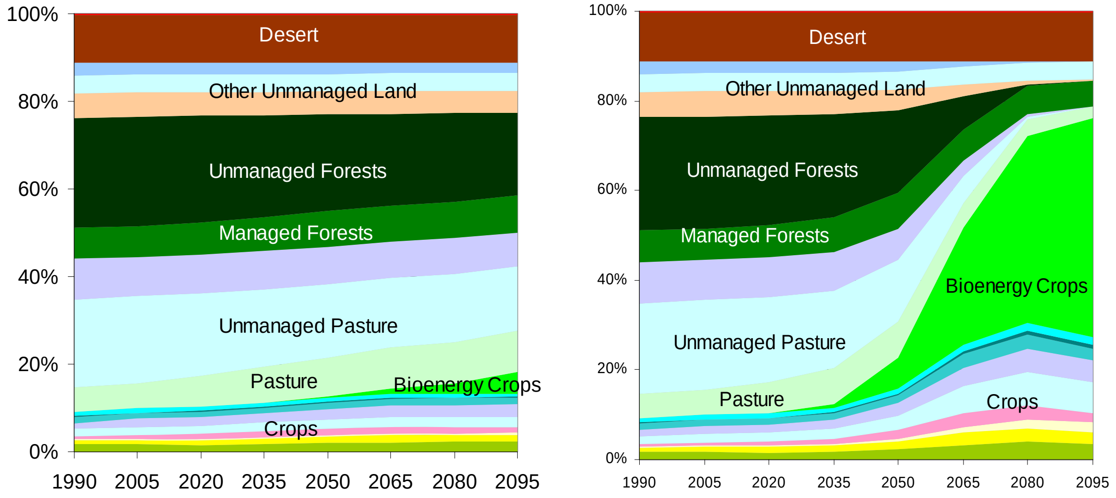

Panel A: Reference scenario

Panel B: FFICT 550 ppm scenario

Panel C: FFICT 500 ppm scenario

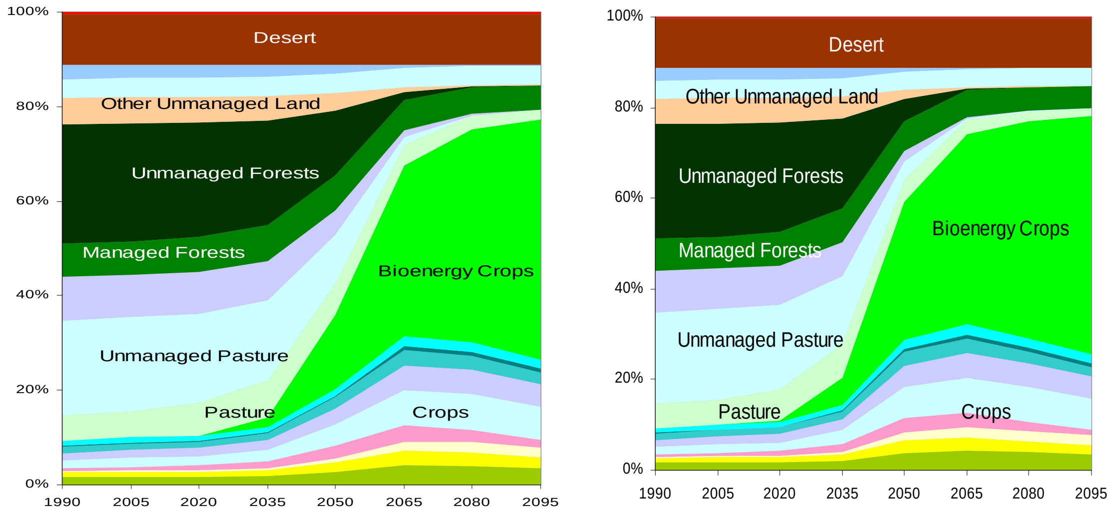
Panel D: FFICT 450 ppm scenario

Figure 14. Use of Bioenergy along the Reference and Three Alternative CO_2 Concentration-Target Pathways with the FFICT Regime



Panel A: Reference Scenario

Panel B. FFICT 550 ppm Scenario



Panel C. FFICT 500 ppm Scenario

Panel D. FFICT 450 ppm Scenario

Figure 15. Land Use along the Reference and Three Alternative CO_2 Concentration-Target Pathways with the FFICT Regime

The expansion of bioenergy production in our CO_2 concentration limit scenarios increases the overall demand for land, raises land rental rates, and thereby raises the crop prices relative to the reference scenario. The price of the wheat crop is given in Figure 16. Even in the 450 ppm CO_2 scenario the price of wheat does not rise substantially until mid century. At that point the expanding demand for land for bioenergy plantations drives rental rates upward to the point at which wheat prices begin to rise. The year 2100 price of wheat is four times the 2005 level in the 550 ppm CO_2 scenario and more than ten times that level in the 450 ppm CO_2 scenario.

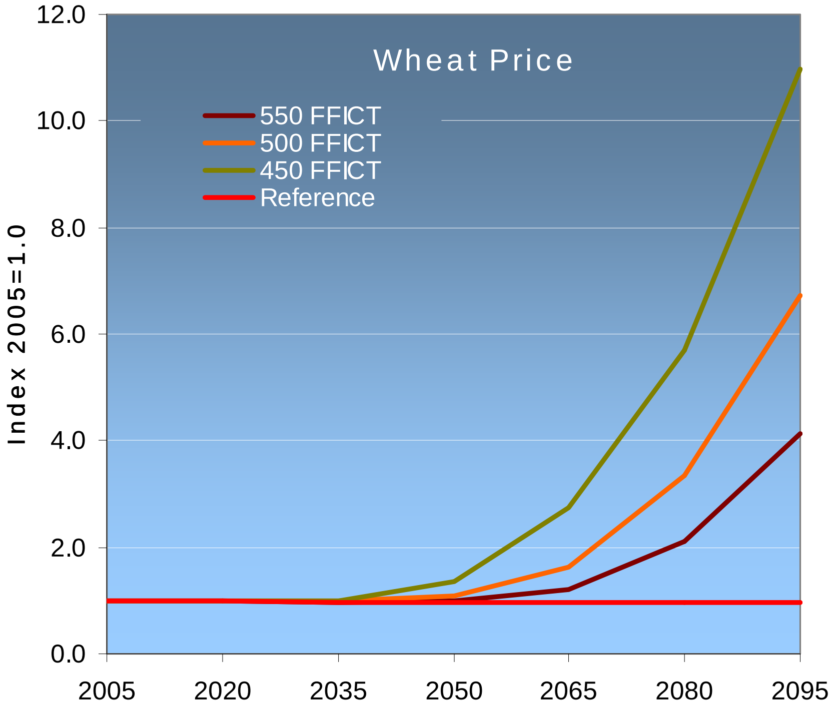


Figure 16. The Price of Wheat in the Reference and Three Alternative CO_2 Concentration-Target Pathways with the FFICT Regime

3.4 The UCT Regime, Limiting CO_2 Concentrations While Valuing Terrestrial Carbon

Terrestrial ecosystems provide a wide variety of economic services including recreation, water purification, flood and drought damage mitigation, soil preservation and renewal, detoxification and decomposition of wastes, pollination of crops and natural vegetation, dispersion of seeds, cycling and movement of nutrients, control of pests, and stock of potentially useful chemical compounds[12]. In a climate-constrained world unmanaged ecosystems would provide another service, carbon storage. The addition of the service of carbon storage implies that the unmanaged ecosystems will increase in value with the value of carbon. If a ton of carbon is worth $100, then the approximately 2000 PgC estimated to be in the terrestrial biosphere (Cao and Woodward, 1998) would have a stock value of $200 trillion. At a 5 percent rate of return, that stock of carbon would produce a value of $10 trillion/year in services. This is a value comparable to the United States GDP.

In this section of our paper we report the result of limiting CO_2 concentrations as before, but valuing all carbon equally—including the carbon in the terrestrial biosphere. As discussed earlier, this set of numerical experiments, the UCT regime, apply a common value to all carbon emissions regardless of whether the emissions originate from

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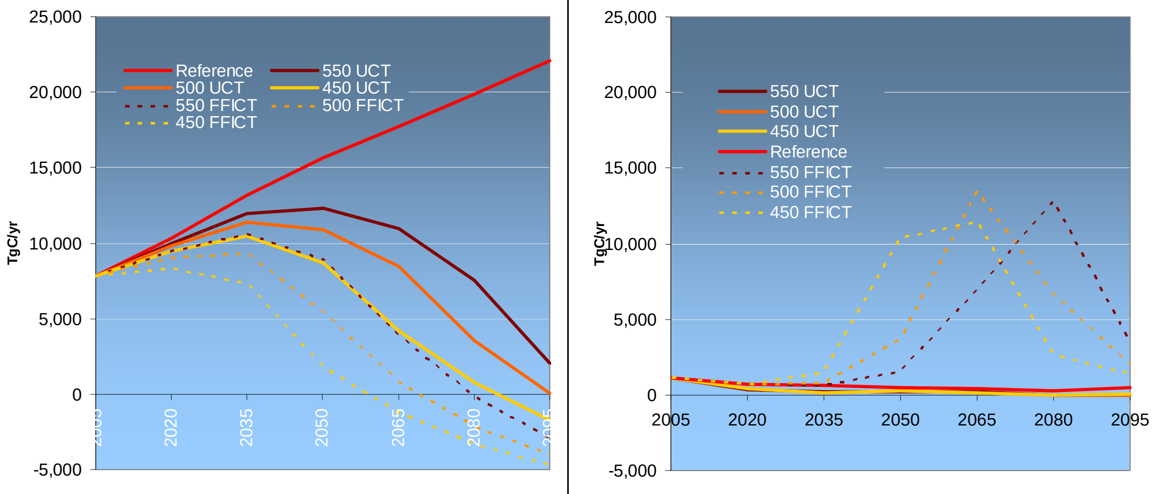
[12] See Daley (1997) and Boyd and Banzhaf (2007).

industrial processes, fossil fuel use, or land-use change. Figure 17 shows the emissions from fossil fuel use and industrial activities (Panel A), land use change emissions (Panel B), total anthropogenic emissions (Panel C), and the resulting concentration pathway for the UCT scenarios.

Panel A: Fossil fuel and industrial CO_2 emissions

Panel B: Land-use change CO_2 emissions



Panel C: Fossil fuel, industrial , and land-use change CO_2 emissions

Panel D: Atmospheric CO_2 concentration

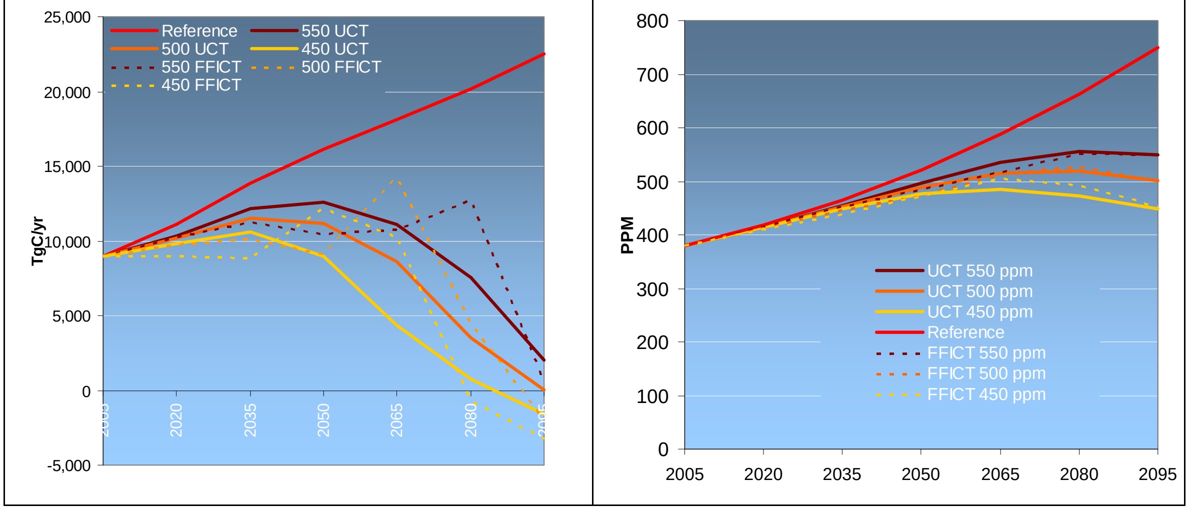
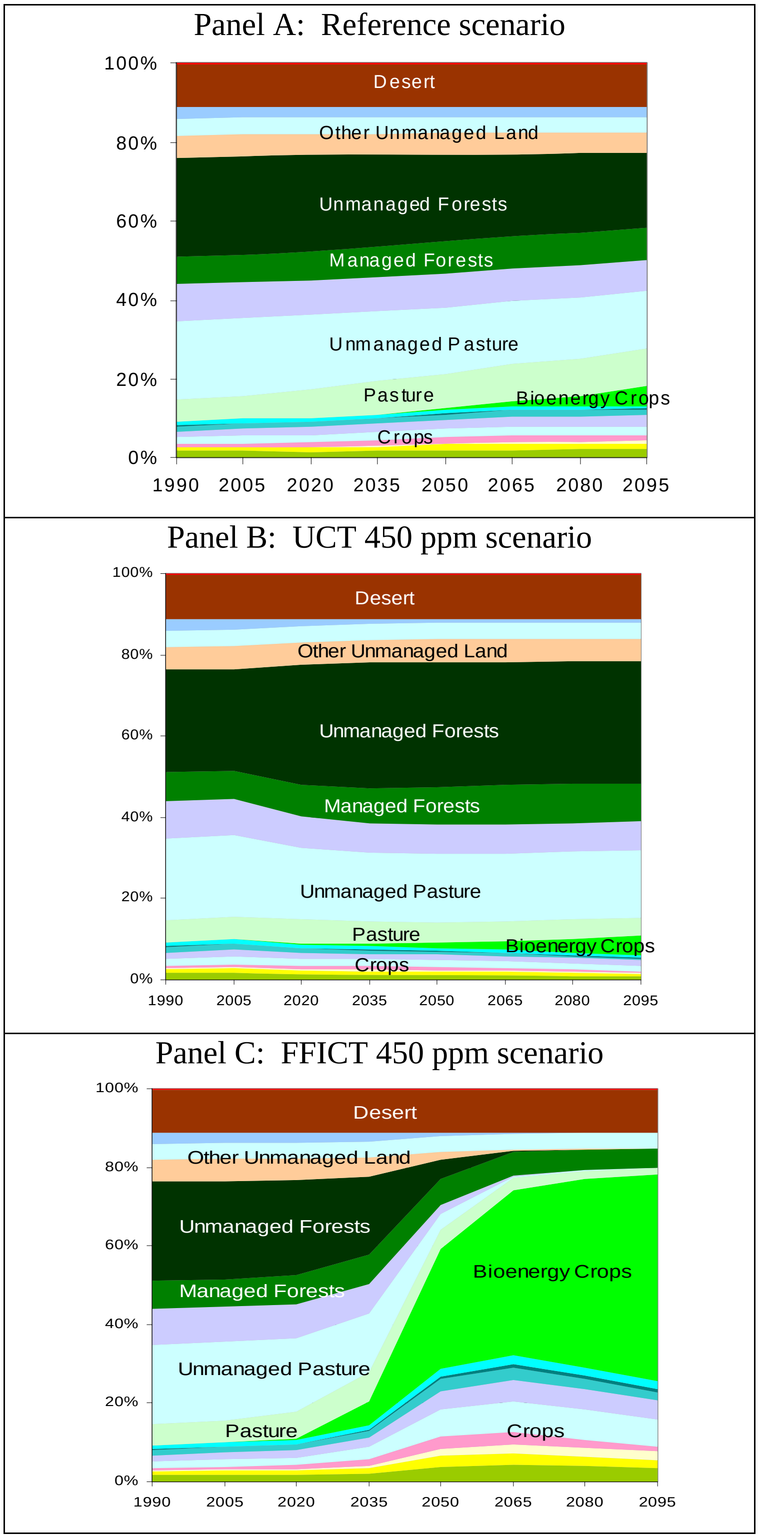


Figure 17. CO_2 Emissions and Concentrations along the Reference and Three Alternative UCT CO_2 Concentration-Target Pathways: a Comparison of UCT and FFICT Regimes

From Figure 17, we observe that valuing all carbon emissions equally along a path that leads to the same concentration in 2095 allows higher fossil fuel and industrial emissions over the entire century relative to the FFICT regime, because land-use change emissions are replaced by conservation and expansion of unmanaged ecosystems and managed forests (Panel B). Establishing a positive value for carbon, results in an immediate increase in the optimal stock of terrestrial carbon and that terrestrial carbon stock is maintained throughout the century.

The distribution of land use is shown in Figure 18 for the reference scenario and two scenarios that limit the concentration of CO_2 in 2095 to 450 ppm. In the CO_2 control scenario, the extent of forested ecosystems expands relative to the reference scenario (Figure 18, Panels A and B). The area employed as cropland and pasture decrease in the 450 ppm UCT control scenario, while the area of land employed to produce bioenergy expands relative to the reference scenario. The contrast between land use in Panels B and C is stark. When terrestrial carbon emissions are valued at the same rate as fossil fuel and industrial carbon emissions, the UCT regime, the extent of land use change is dramatically different. In the UCT 450 ppm CO_2 target scenario cumulative land use change emissions are decreased from the reference case to approximately 24 PgC over the century. In contrast, when only fossil fuel and industrial emissions were valued, the FFICT regime, land use change accounted for more than 419 PgC in cumulative emissions. The cumulative difference, 395 PgC, over the period 2005 to 2095, is approximately 45 percent of total emissions mitigation in the 450 ppm limitation scenario.



Panel A: Reference scenario

Panel B: UCT 450 ppm scenario

Panel C: FFICT 450 ppm scenario

Figure 18. Land Use along the Reference Pathway (Panel A), a UCT Pathway Defined To Achieve a CO_2 Concentration Target of 450 ppm (Panel B), and a Comparison to the Corresponding FFICT Scenarios (Panel C)

The price of carbon needed to meet the target CO_2 concentration in the year 2095 under the UCT regime is reduced by between sixty percent (550 ppm target) and seventy percent (450 ppm target) in all years relative to the FFICT regime, Figure 19. Those price reductions are a direct reflection of the value of including terrestrial carbon in the emissions mitigation strategy. Those price reductions are also roughly proportional to the reduction in total cost that might be expected to achieve a CO_2 concentration target.

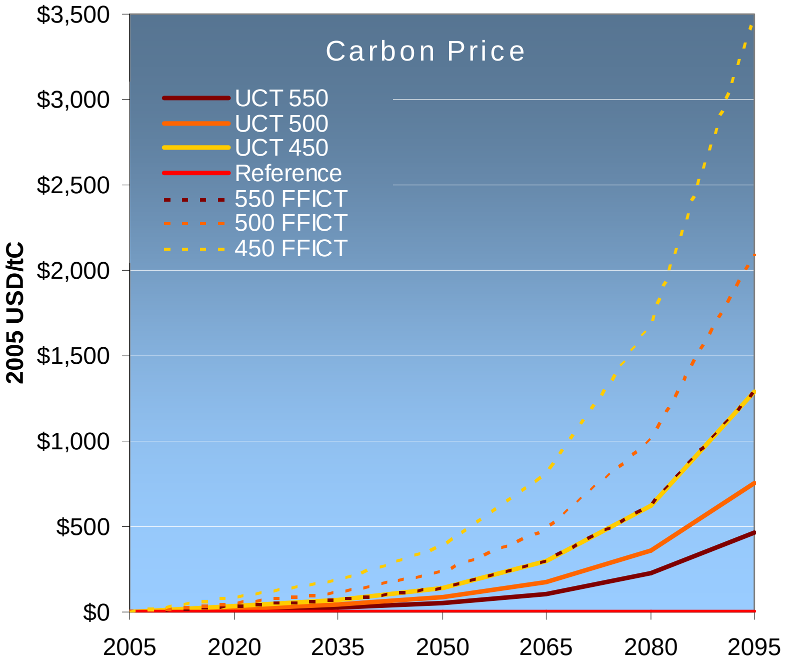
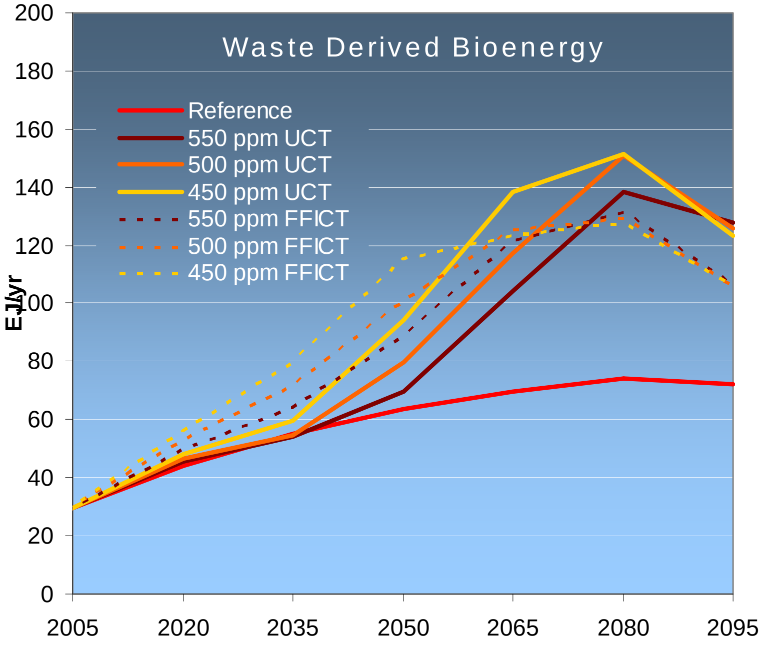


Figure 19. Carbon Price along Three Alternative UCT CO_2 Concentration-Target Pathways: a Comparison of UCT and FFICT Regimes

Bioenergy production is reduced under the UCT regime relative to the FFICT regime (Figure 20). Bioenergy prices are also significantly lower (Figure 21). The reduction in price is more pronounced for lower CO_2 concentration targets. The price of bioenergy was half its level in 2095 in the UCT scenario when compared to the FFICT scenario for the 2095 450 ppm CO_2 limit.

Panel A



Panel B

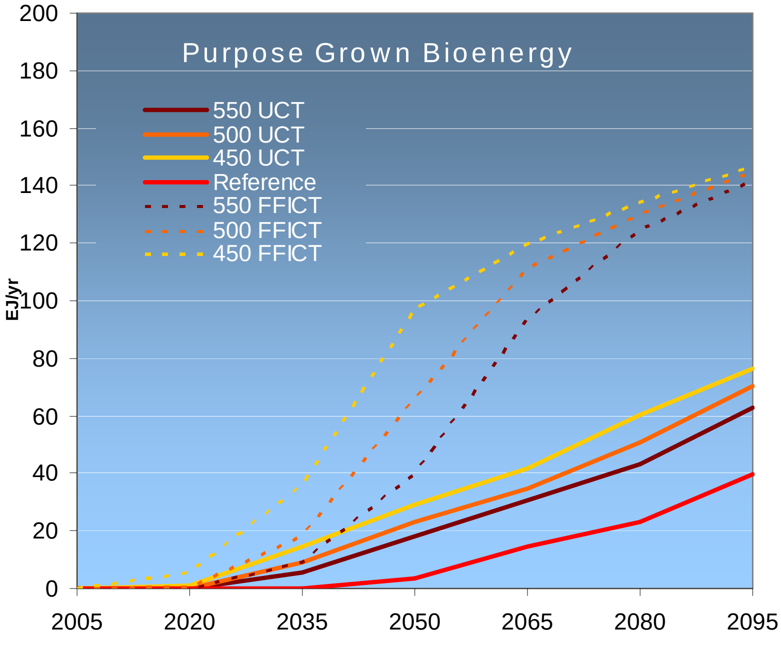
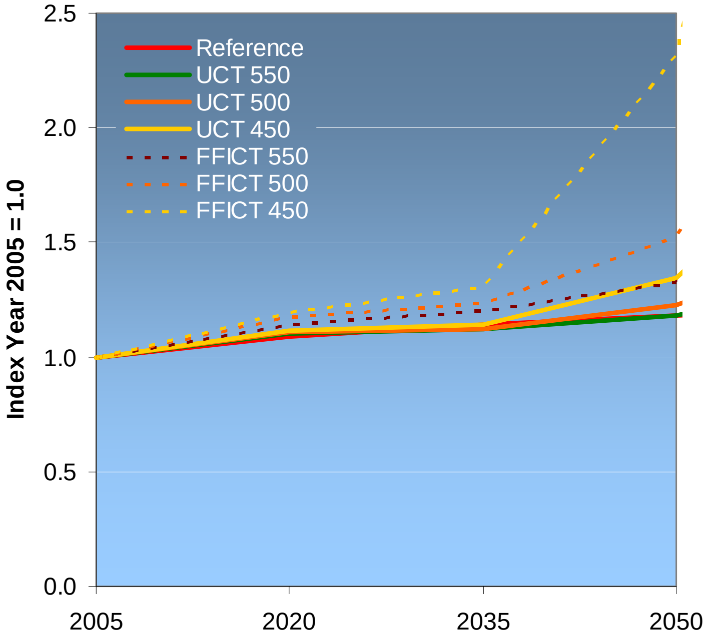


Figure 20. Waste Derived (Panel A) and Purpose Grown Bioenergy (Panel B) Production along Three Alternative UCT CO_2 Concentration-Target Pathways: a Comparison of UCT and FFICT Regimes

The growth over time in the bioenergy prices in Figure 21, along with the range of prices across cases, highlights a key economic insight from this analysis, namely that the market price of bioenergy is increased by the carbon price. As noted, we have assumed no net direct carbon emissions from consuming bioenergy, and therefore the carbon price is **not** added to the price of bioenergy as it would be for fossil fuels. However, the presence of a CCS technology option does add an opportunity cost to consuming bioenergy in applications, such as transportation fuels, where carbon emissions are not captured. This opportunity cost is reflected directly in the bioenergy market price, and the increase and differences in bioenergy prices follows to a large extent the increase and differences in carbon prices among the cases (compare Figure 21 with Figure 19). Applications with CCS are willing to pay this bioenergy market price since they are credited with the value of carbon emissions captured and stored. The CCS option means that bioenergy applications without CCS become less competitive at higher carbon prices, and it means that bioenergy growers will realize large increases in prices received.

Panel A: Present to 2050



Panel B: Present to 2095

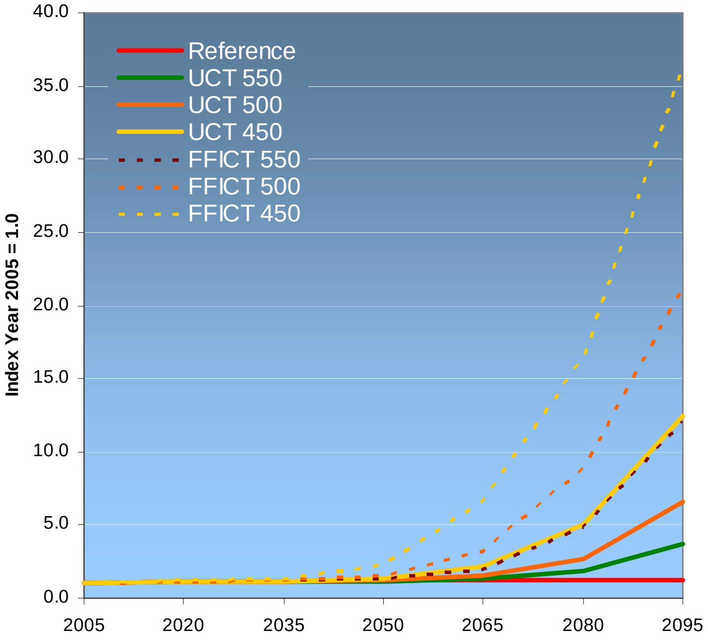
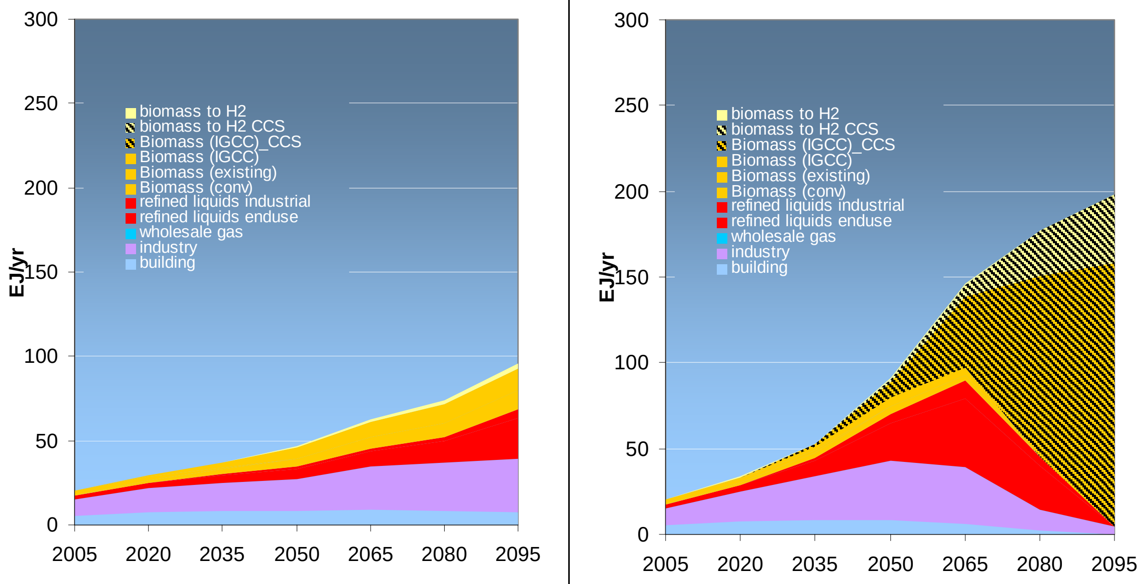


Figure 21. Bioenergy Prices along Three Alternative UCT CO_2 Concentration-Target Pathways: a Comparison of UCT and FFICT Regimes

Figure 22 plots the pattern of bioenergy use in the references scenario (Panel A), a UCT 450 ppm 2095 CO_2 concentration limit associated with a carbon price applied to all carbon emissions—terrestrial land-use change CO_2 emissions as well as fossil fuel and industrial emissions (Panel B), and a FFICT 450 ppm 2095 CO_2 concentration limit associated with a carbon price applied only to fossil fuel and industrial emissions (Panel C). Panels B and C differ in the magnitude of bioenergy production but not in the pattern of bioenergy use. When all carbon is valued, the UCT scenario, direct use of bioenergy in buildings and industry reaches a peak and then declines throughout the second half of the century. The dominant use of bioenergy shifts to central station power generation with CCS technology in the UCT regime. Under the FFICT regime there is a similar, but accelerated shift from traditional bioenergy markets to BioCCS (Figure 22, Panel C). By the end of the 21st century in the UCT scenarios bioenergy is used almost exclusively with CCS technology when all carbon emissions—terrestrial and fossil fuel and industrial—are priced equally. Furthermore, less bioenergy is used in conjunction with CCS technology in Figure 22 Panel B than in Panel C. The reason is that bioenergy carried with it a charge for the carbon that could have been stored on that land if that land were returned to an unmanaged state. Under a UCT regime it is simply not profitable to use bioenergy to produce liquids and gases. Only when bioenergy receives a payment for the net carbon removal via CCS in addition to its energy content does the technology look attractive at high carbon prices under a UCT regime. (The carbon price in the 450 ppm CO_2 concentration limit in 2095 exceeds $1400/tC.)

Panel A: Reference scenario.

Panel B: UCT 450 ppm scenario—all carbon emissions controlled.



Panel C: FFICT 450 ppm scenario—only fossil fuel and industrial emissions controlled.

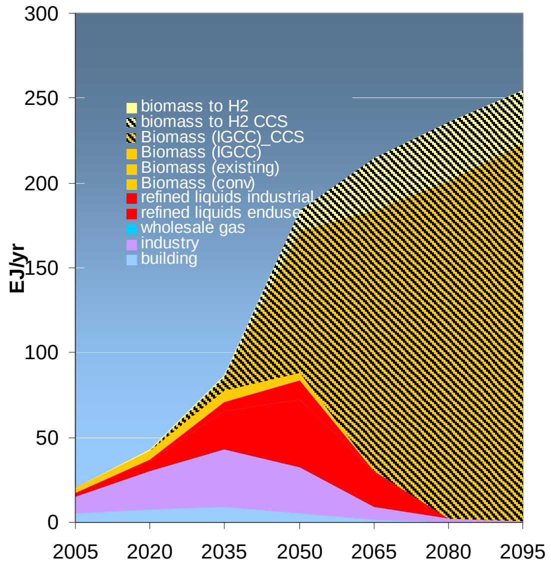


Figure 22. Use of Bioenergy along the Reference Pathway (Panel A), a UCT Pathway to 450 ppm (Panel B), and a Comparison to the Corresponding FFICT 450 ppm Scenario (Panel C)

The effect of valuing carbon in the terrestrial system as well as valuing fossil fuel and industrial emissions, the UCT regimes, is to

1. Expand land held as unmanaged ecosystems and managed forests, relative to the reference scenario,
2. Expand bioenergy production, and especially the production of purpose-grown bioenergy relative to the reference scenario, but to reduce the production of bioenergy and particularly late-century purpose-grown bioenergy relative to the FFICT scenarios with the same CO_2 concentration target but applying a carbon price only to fossil fuel and industrial emissions, and
3. Increase the price of crops relative to both the reference scenario and a scenario with a common CO_2 concentration target where the carbon price applies only to fossil fuel and industrial emissions, as seen in Figure 23.

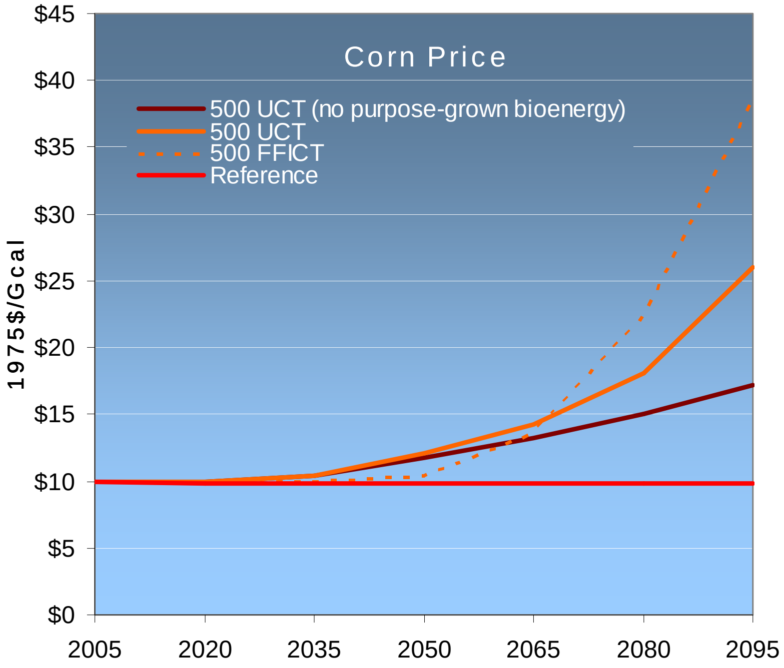


Figure 23. The Price of Corn along Reference and Alternative Scenario Pathways, including a UCT 500 ppm 2095 CO_2 Concentration Limit in which Purpose-grown Bioenergy is not Available

The impact on crop prices is the consequence of both valuing unmanaged ecosystem services of carbon storage and increased demand for land associated with expanded purpose-grown bioenergy production under UCT regimes. To isolate the consequence of valuing carbon, we limit CO_2 concentrations to 500 ppm in 2095 but allow no purpose-grown bioenergy production and observe the effect on crop prices. Valuing terrestrial carbon expands the demand for land in unmanaged ecosystems and managed forests.

This expansion puts upward pressure on land rents and raises crop prices both relative to the reference scenario and in absolute terms (Figure 23).

The reference scenario includes purpose-grown bioenergy production. Removing purpose-grown bioenergy production from the scenario has virtually no effect on crop prices in the reference scenario.

We observe that, until after 2050, simply valuing terrestrial carbon produces a higher price of corn in the 500 ppm target scenario without purpose-grown bioenergy than meeting the same target with purpose grown bioenergy as an option, but without valuing terrestrial carbon until. That is, the price paths cross in 2065. The effect on corn prices of purpose-grown bioenergy is modest until after 2050 (Figure 23). The combined effect of valuing carbon and the production of purpose-grown bioenergy crops is to put upward pressure on crop prices.

The demand for food crops for human consumption is relatively inelastic and therefore crop production is largely unaffected by carbon policy. Figure 24 shows wheat production along a reference pathway and pathways to limit the concentration of CO_2 in 2095. Note that in all instances wheat production peaks by midcentury and then begins to decline. This pattern reflects the consequences of increased per capita incomes. Production grows with income until such time as incomes are sufficiently high that animal protein begins to supplant calories from grains. When the target CO_2 concentration is 450 ppm and all carbon is valued, the most stringent UCT regime considered here, wheat production is 15 percent higher in 2050 and only 2 percent higher in 2095 than in 2005.

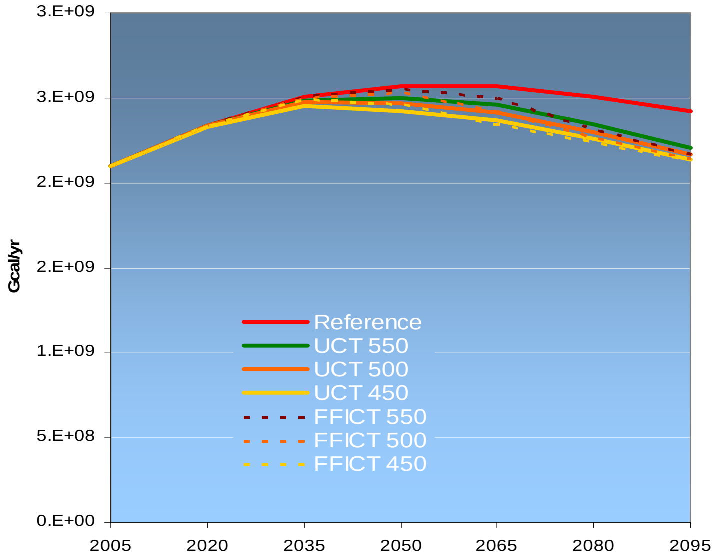


Figure 24. Annual Wheat Production along Reference and Alternative Scenario Pathways

There is a larger impact on total expenditures, which are, to a first approximation, proportional to prices. Total revenues from wheat sales approximately triple over the course of the century in the 450 ppm scenario with all carbon valued (terrestrial as well as fossil fuel and industrial, the UCT regime). In comparison, revenues from wheat production actually decline after 2035 in the reference scenario. Of course, there are two sides to every economic transaction and higher agricultural prices imply higher agricultural incomes.

For comparison, incomes in market exchange rates in the presently developed, OECD, regions grow by approximately a factor of 3 between 2005 and 2095. Global per capita incomes at market exchange rates rise by a factor of more than 7. Developing regions' per capita income increases by a factor of more than 15 at market exchange rates, though absolute levels of per capita income may not have reached levels achieved in some OECD regions in 2005.

The effect of carbon values on livestock consumption of grains and for crops that are used to feed livestock is more pronounced than for crops that are predominantly consumed by humans. Livestock herd size declines in the carbon emissions limitation scenarios. Figure 25 shows the effect on livestock production of limiting CO_2 concentrations in 2095.

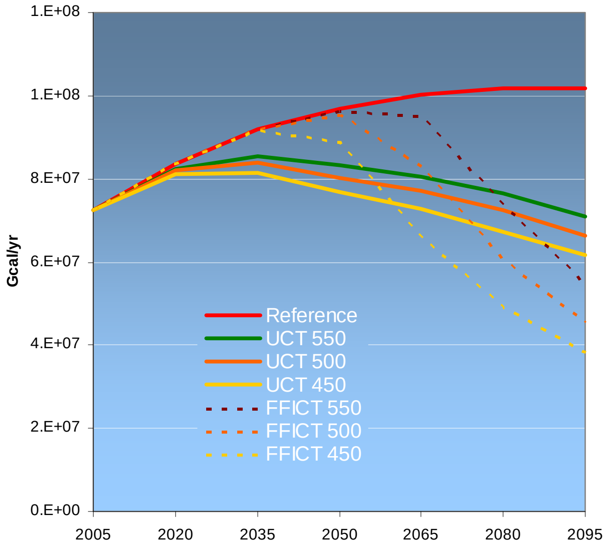


Figure 25. Beef Production along the Reference and Alternative Stabilization Pathways

Production of crops that are used to feed humans and livestock, such as corn, show changes in output that lie somewhere between those reported for wheat and livestock.

4. Limitations and Work Remaining

The work presented here advances previous work, Edmonds et al. (2003) and Smith et al. (2008). Yet it is also incomplete. Work remains in at two different categories, technical and policy analysis. In the technical domain, full accounting of all greenhouse emissions needs to be developed. Beyond that, account needs to be taken of changing CO_2 and other gas concentrations, and changing climate. Uncertainties surround both. While numerous experiments have been undertaken to understand the consequence of CO_2 concentrations for a wide range of ecosystems, uncertainties in both the science and representation of the effects in modeling remain (Ainsworth and Long, 2005). Cross-effects with other atmospheric constituents, such as N, remain to be taken into effect. Those effects in turn need to be reconciled with dynamic soil and vegetation. These in turn must be reconciled with a changing climate. While the mechanics of such reconciliation are daunting, the effect on results could be great. Present knowledge of climate sensitivity is limited to a range of approximately 2^oC to 5^oC. Knowledge of the spatial pattern of temperature change, including seasonal and diurnal patterns, is even less will known. Knowledge of the spatial patterns of changes in precipitation is frequently uncertain with regard to sign. The work here employed highly aggregated representations of land use and land cover. Variation in land characteristics was represented through statistical distributions rather than by discrete geographically disaggregated data. Future work will move toward increasingly discrete land characterizations.

Perhaps the most important direction for future work is the explicit representation of water. It is implicitly assumed that present water availability and use will continue indefinitely. Development of an explicit model of water supply and availability including soil moisture, surface water, ground water, and desalinization, along with models of water uses including consumption (e.g. irrigation), transient (e.g. drinking water) and stock (e.g. recreational use of reservoir water), for the wide variety of competing human uses will enhance understanding of the issues addressed in this paper. This in turn implies explicit interaction with climate models with all the attendant uncertainty noted above.

The suite of policy analysis issues to be explored is equally as broad and challenging as the technical issues. Many important questions remain to be examined. This analysis assumes a globally common carbon price that evolves in an economically efficient manner. Heterogeneous policy environments have been shown to yield higher costs and degraded policy effectiveness, (Richels et al., 2007; Keppo and Rao, 2007; and Edmonds et al., 2008). Work needs to go forward to explore the implication of heterogeneous international emissions mitigation environments for land-use and land cover, terrestrial carbon cycle, and bioenergy. Work is also needed to explore the implication of imperfect domestic policy environments. The ability of societies to control land use may be limited. In the scenarios we explored, we assumed that land-use change emissions were either not controlled at all or were controlled through the application of a common price of carbon. The real world may be somewhere between these two extremes and may utilize regulatory rather than price mechanisms. Further work will help illuminate the implications of alternative policy architectures.

5. Conclusions

We explored the implications of limiting CO_2 concentrations for agriculture, land use, unmanaged ecosystems bioenergy, and the global energy system using PNNL's MiniCAM integrated assessment modeling system. Based on that research we make the following observations:

1. We find that improving conventional crop productivity has the potential to reduce land-use change emissions by hundreds of billions of tons of carbon over the 21st century. This potential role in climate change mitigation has gone largely unrecognized. The difference between present technology and continued improvement in crop productivity consistent with historical rates provides carbon emissions mitigation comparable in magnitude with any major energy technology. Enhancing crop productivity growth should be added to any technology strategy to limit greenhouse gas concentrations.

2. Limiting the concentration of greenhouse gases in the atmosphere carries implications for land use that are unavoidable. Land is a scarce resource and the carbon associated with unmanaged ecosystems provides a service that, if valued, implies that the carbon storage service becomes increasingly valuable with time. This in turn means that relative to a reference scenario, a larger stock of unmanaged ecosystems and managed forests is desirable, which in turn raises land rents, decreases the land that is used to produce crops and raises crop prices. Importantly, this effect is independent of whether or not bioenergy is a competing crop.

3. We find that crop and forest product waste streams are a potentially important source of bioenergy with or without a carbon price. We observed little purpose-grown bioenergy production in our reference scenario.

4. Purpose-grown bioenergy production has no significant effect on crop prices until after the middle of the century in the absence of subsidies. Only when CO_2 concentration limits engender a rising carbon price does purpose-grown bioenergy have a significant impact—independent of the impact of the increasing value of carbon storage services by unmanaged ecosystems and managed forests—on energy and agricultural markets.

5. Failure to take into account the value of terrestrial carbon storage services by unmanaged ecosystems and managed forests could have disastrous consequences for unmanaged ecosystems.

6. When terrestrial carbon is valued and both waste-derived and purpose-grown bioenergy technologies are available, the cost of limiting the concentration of CO_2 is reduced. When carbon is valued the dominant use of bioenergy is power

generation with CO_2 capture and storage, not transportation fuels. We find that net global carbon emissions eventually become negative when CO_2 concentration limits are below 550 ppm in 2095 and both bioenergy and CO_2 capture and storage technologies are jointly employed.

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