III. Commercial viability of second generation biofuel technology[27]

The previous chapters focused on first generation biofuels. In this chapter we focus on second generation biofuels, specifically biofuels derived from cellulosic or lignocellulosic conversion. Advocates for the development of cellulosic conversion believe that second generation technology avoids many of the adverse consequences of first generation biofuels: it does not directly compete for food (since it is based on crops such as switchgrass or waste like maize stover), it causes less environmental impact than row crop agriculture, and the energy yield per hectare (ha) is generally higher (it has the potential to be five times higher than that of maize, since the entire plant can be converted to fuel).

Yet second generation biofuels are currently not competitive and expectations about future costs and energy output per unit of land vary. Taking those variations into account and using MIT's Emissions Prediction and Policy Analysis (EPPA) model, we estimate the potential role of biomass as an energy supplier until 2100. We construct four scenarios in which second generation biofuels could develop: with and without climate policy, and with and without trade restrictions on biofuels. We provide global results and specific results for the United States. Our aim is to provide insights into the following issues:

(a) What is the potential size of a cellulosic biofuels industry?

(b) What are the limitations of biofuels production in terms of land availability?

(c) How would the development of the industry affect land cover and food and land prices?

(d) If this technology matures, where and when will biomass production occur?

We estimate that second generation biomass has the potential to generate 30–40 EJ/year (exajoules per year) by 2050 and 180–260 EJ/year by 2100. As a comparison, global bioenergy[28] production in 2005 was less that 1 EJ and global oil consumption in 2005 was 190 EJ.

Under a scenario with climate policy in place, global prices for food, agriculture and forestry products would increase by 5 to 10 per cent. This relatively small price increase seems to suggest that it is possible to introduce a large cellulosic biofuels industry without dramatically disturbing agricultural markets.

If unrestricted bioenergy trade is allowed, we project that the main biofuels producers would be Africa, Latin America and the United States. Conversely, if trade restrictions are set up, China, Europe and India also become relevant producers. In this scenario, the level of global bioenergy production is lower by 3–6 EJ/year in 2050 and by 70–110 EJ/year in 2100 in comparison to the unrestricted trade scenario.

The chapter is organized as follows: the next section provides estimates of cost and yield energy output for second generation biofuels. Subsequently, we present four scenarios for bioenergy production, where the level of climate stabilization and the trade regime are taken into account. Finally, we discuss land-use implications and impacts on agricultural and land prices.

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[27] This chapter was prepared by Sergey Paltsev, John Reilly and Angelo Gurgel, Joint Programme on the Science and Policy of Global Change, Massachusetts Institute of Technology, Cambridge, United States.

[28] We use the terms "bioenergy", "biomass energy" and "biofuels" interchangeably in this chapter. Unless specified otherwise, we measure them in terms of energy in liquid biofuels.

A. Cost and energy yield estimates

In order to understand the potential of second generation biofuels we provide an overview of their cost and energy output. We consider early estimates of global resource potential and economics (Edmonds and Reilly, 1985) and more recent reviews (Moreira, 2004), as well as the economics of liquid fuels (Hamelinck et al., 2005) and bioelectricity (International Energy Agency, 1997).

Hamelinck et al. (2005) estimate costs of €9–13/Gigajoule (GJ) for lignocellulosic conversion of ethanol, compared with €8–12/GJ and eventually €5–7/GJ for methanol production from biomass. Before tax, costs of gasoline production are €4–6/GJ. The IMF (2007) reports that the current cost of ethanol from cellulosic waste is $0.71 per litre, which is 2.1 times higher than the cost for gasoline production.[29] The International Energy Agency (IEA, 2006) estimates that lignocellulosic production costs for ethanol could fall to $0.40 per litre of gasoline equivalent, and for biodiesel to $0.70–$0.80 per litre using the Fischer-Tropsch synthesis.[30]

Regarding energy yield estimates, different biomass sources must be considered. Vegetable oil crops have a relatively low energy yield (40–80 GJ/ha/year) compared with crops containing cellulose or starch/sugar (200–300 GJ/ha/year). According to the Intergovernmental Panel on Climate Change (IPCC, 2001), high yielding short rotation forest crops or C4 plants (e.g., sugar cane or sorghum) can give stored energy equivalent of over 400 GJ/ha/year.

Woody crops are another alternative. The IPCC (2001) reports a commercial plot in Sweden with a yield of 4.2 oven-dry tons[31] (odt)/ha/year, and anticipates that with better technologies, management and experience, the yield can be up to 10 odt/ha/year. Using a higher heating value (20 GJ/odt)[32] similar to that used by Smeets and Faaij (2007) in their study of bioenergy potential from forestry, we estimate a potential of 84–200 GJ/ha/year yield for woody biomass.

Hybrid poplar, willow and bamboo are some of the quick growing trees and grasses that may serve as fuel source for a biomass power plant. They contain high amounts of lignin, a glue-like binder that is largely composed of cellulose. These so-called “lignocellulose” biomass sources can potentially be converted into ethanol via fermentation or into a liquid fuel via a high temperature process.

Table 3.1 provides a summary of recent estimates of energy output per unit of land, of energy content of dry biomass and conversion efficiency of dry biomass into liquid fuels. Current energy output per unit of land varies from 6.5 oven-dry ton/hectare (odt/ha) for corn to 30 odt/ha for sugar cane. The most optimistic estimates about the future potential energy output per hectare of land double the amount to around 60 odt/ha for sugar cane. Expected efficiency of converting biomass into liquid fuels also varies, with most estimates ranging around 30–45 per cent.

Table 3.1 also reports the corresponding numbers for 2020, 2050 and 2100 for second generation biomass, following the analysis from MIT’s Emissions Prediction and Policy Analysis

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[29] Different studies report costs in different units. An important metric is cost of biofuels production relative to gasoline production.

[30] The Fischer-Tropsch synthesis is a catalyzed chemical reaction in which synthesis gas (syngas), a mixture of carbon monoxide and hydrogen, is converted into liquid hydrocarbons of various forms.

[31] One oven-dry ton (odt) is the amount of wood that weighs one ton at 0 per cent moisture content.

[32] Higher heating value (HHV) of a fuel is defined as the amount of heat released by a specified quantity (initially at 25° C) once it is combusted and the products have returned to a temperature of 25° C.

(EPPA) model. The EPPA model is less optimistic than the maximum potential numbers as it represents an average for land of different quality in different regions.[33]

Table 3.1. Estimates of the potential for energy from biomass

Biomass source	*Odt/ha*	*GJ/odt*	*Dry biomass energy yield (GJ/ha)*	*Conversion efficiency*	*Liquid biomass energy yield (GJ/ha)*
Grain corn(a)	6.5	21	136.5	16%	21.8
Grain corn *(future)*	6.5(a)	21	136.5	45%(b)	61.4
Sugar cane(c)	30	21.5	650	40%	260
Sugar cane *(future)*	63	21.5	1350(c)	45%(d)	607.5
Eucalyptus(c)	23	20	450	43%(f)	193.5
Eucalyptus *(future)*	50	20	1000(c)	68%(g)	680
Poplar	20(h)	20	400	51%(e)	204
Switch-grass fuel pellets(a)	10	18.5	185	88%	162.8
Switch-grass			430(c)	51%(e)	219.3
EPPA Model estimates (2020)(i)	6 – 16	20	120 – 320	40%	48 – 128
EPPA Model estimates (2050)(i)	11 – 18	20	210 – 360	40%	84 – 144
EPPA Model estimates (2100)(i)	18 – 30	20	358 – 600	40%	144 – 240

(a) Samson et al. (2000). (b) Novem/ADL (1999), cited by Fulton and Howes (2004). (c) Moreira (2006). (d) Assumption based on Moreira (2006) considering all solid biomass primary energy will be converted into final energy through cogeneration plants and 40 per cent of the sugar cane residues are left in the field to protect the soil. (e) Assumption based on Novem/ADL (1999), cited by Fulton and Howes (2004) for ethanol production from poplar through enzymatic hydrolysis. (f) Assumption based on Novem/ADL (1999), cited by Fulton and Howes (2004) for diesel production from gasification / Fischer-Tropsch. (g) Assumption based on Novem/ADL (1999), cited by Fulton and Howes (2004) for diesel production from hydrothermal upgrading (HTU) biocrude. (h) Luger (2007). (i) Values are region-specific.

Despite all the advantages of second generation biofuels with respect to the current technology, some of the shortcomings of the latter remain valid even for second generation biofuels. Box 4.1 below summarizes this point.

B. Land area and potential for energy from biomass

Land needed to grow energy crops competes with land used for food and wood production. For example, Smeets and Faaij (2007) estimate a global theoretical potential of biomass from forestry in 2050 at 112 EJ/year. This number is reduced to 71 EJ/year after considering demand for wood production for other uses. And the number is further decreased to 15 EJ/year when economic considerations, such as profitability, are taken into account.

In a study about biodiesel use in Europe, Frondel and Peters (2007) found that 11.2 million hectares (Mha) of land would be required to meet the EU target for biofuels (5.75 per cent of transport fuels from renewable sources by 2010). This represents 13.6 per cent of total arable land in the EU-25. Similarly, an IEA (2004) study estimates that replacing 10 per cent of fossil fuels by bioenergy in 2020 would require 38 per cent of the total acreage in the EU-15. These analyses, while providing useful benchmarks, take market conditions as given and do not consider future changes in prices and markets. These will depend, for example, on the existence of greenhouse gas mitigation policies that could create additional incentives for biofuels production, as discussed in chapters I and II.

Table 3.2 provides estimates of the global potential for energy from biomass based on the world land area.[34] IPCC (2001) estimates an average energy yield of 300 GJ/ha/year from biomass by 2050. The area not suitable for cultivation is about half of the total Earth land area of

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[33] Second generation biomass technology in the EPPA model is not crop-specific as it can use sugar cane, switchgrass, corn stover, willow, bamboo, etc. as a source. For more information on the model and cost estimates used, see Reilly and Paltsev (2007) and Gurgel et al. (2007).

[34] This table refers to productivity of second generation biomass, but sugar cane presents similar productivity.

15.12 Gha and includes tropical savannas, deserts and semi-deserts, tundra and wetlands. Converting area in hectares into energy yield, we estimate the global potential for biomass at around 2100 EJ/year. This estimate could increase/decrease if different land types are included/excluded from the calculation. Assuming a conversion efficiency of 40 per cent from biomass to the final liquid energy product, we estimate a potential of 840 EJ/year of liquid energy product from biomass.

Table 3.2. World land area and potential for energy from biomass

	Area (Gha)	*max dry bioenergy (EJ)*	*max liquid bioenergy (EJ)*
Tropical Forests	1.76	528	211
Temperate Forests	1.04	312	125
Boreal forests	1.37	411	164
Tropical Savannas	2.25	0	0
Temperate grassland	1.25	375	150
Deserts and Semideserts	4.55	0	0
Tundra	0.95	0	0
Wetlands	0.35	0	0
Croplands	1.6	480	192
Total	**15.12**	**2106**	**842**

Source: area (IPCC, 2000); assumptions about area to energy conversion: 15 odt/ha/year and 20 GJ/odt (IPCC, 2001); assumption for conversion efficiency from biomass to liquid energy product: 40 per cent.

Table 3.3 presents similar calculations for the United States, where potential for dry bioenergy is 200 EJ/year and for liquid fuel from biomass is 80 EJ/year. Note that these are maximum potential estimates that assume that all land that currently is used for food, livestock and wood production would be used for biomass production.

Table 3.3. United States land area and potential for energy from biomass

	Area (Gha)	*max dry bioenergy (EJ)*	*max liquid bioenergy (EJ)*
Cropland	0.177	53	21.2
Grassland	0.235	70.4	28.2
Forest	0.26	78.1	31.2
Parks, etc	0.119	0	0
Urban	0.024	0	0
Deserts, Wetland, etc	0.091	0	0
Total	**0.906**	**201.6**	**80.6**

Source: area (United States Department of Agriculture, 2006); assumptions about area to energy conversion: 15 odt/ha/year and 20 GJ/odt (IPCC, 2001); assumption for conversion efficiency from biomass to liquid energy product: 40 per cent.

A recent study by the United States Government (CCSP, 2007) estimates an increase in the global energy use from 400 EJ/year in 2000 to 700–1000 EJ/year in 2050 and to 1275–1500 EJ/year in 2100. The corresponding numbers for the United States are 100 EJ/year in 2000, 120–170 EJ/year in 2050 and 110–220 EJ/year in 2100. These numbers indicate that energy from biomass alone will not be able to satisfy global needs even if all land is used for biomass production, unless a major breakthrough in technology occurs.

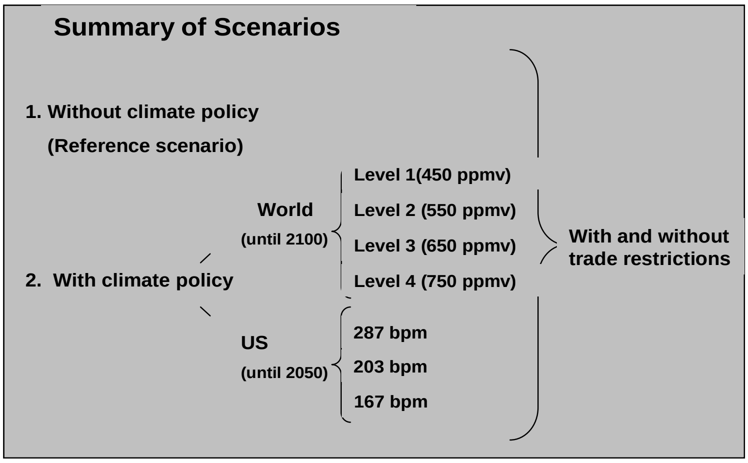
Indeed, a recent cost/benefit study (Hill et al., 2006) found that even if all American production of maize and soybean were dedicated to biofuels production, this supply would meet only 12 per cent and 6 per cent of the United States' demand for gasoline and diesel, respectively.

Another study shows that the climate benefit of biofuels (using current production techniques) is limited because of the fossil fuel used in the production of the crop and processing of biomass (Brinkman et al., 2006). However, advanced synfuel hydrocarbons or cellulosic ethanol produced from biomass could provide greater supplies of fuel and environmental benefits compared to current technologies. In this chapter we consider a second generation biofuel with production costs based on a "cellulosic" or "lingocellulosic" conversion. Examples are grasses and fast-growing trees, which are widespread and abundant.[35]

To illustrate the potential role of biomass as an energy supplier, we draw on recent applications of the Emissions Prediction and Policy Analysis (EPPA) model developed by the Massachusetts Institute of Technology's Joint Programme on the Science and Policy of Global Change (Paltsev et al., 2005).

The first of these applications involves scenarios of atmospheric stabilization of greenhouse gases. The second study involves investigation of GHG mitigation policies in the United States that have been proposed in recent Congressional legislation (for an assessment of the Congressional proposals, see Paltsev et al., 2007) and additional assumptions about developed countries' reduction of greenhouse gases, by 2050, from present levels to 50 per cent below 1990 levels. These applications allow us to focus both on the global bioenergy potential and on specific issues related to the United States.

We present below different scenarios: a reference scenario that assumes no climate policy and a scenario with a climate policy. It is expected that, in the latter case, biofuels production will develop earlier and faster. Under each of these two scenarios, two other options are presented, one based on restricted trade in biofuels and the other on unrestricted trade.



C. Scenarios for climate policy

1. Reference scenario: no climate policy

The reference scenario is one in which no climate policy is introduced. It allows us to compare the economic costs and performance of the biomass industry when a climate policy is in place, as opposed to a situation without climate policy. Obviously, the world is already

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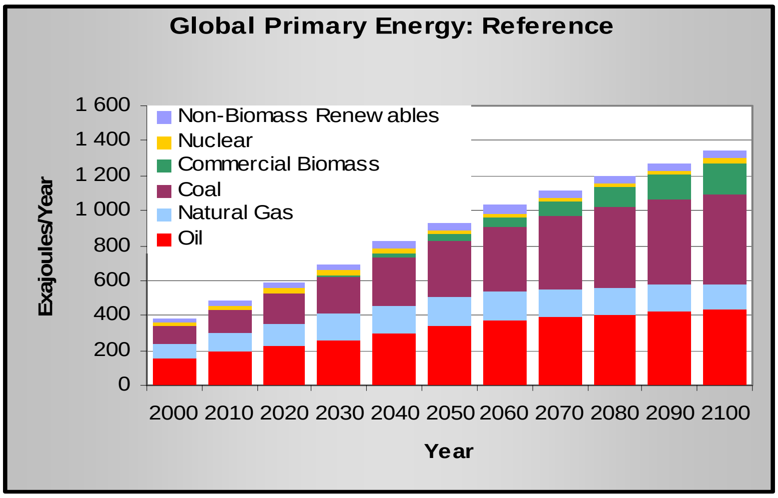
[35] Some analysts also consider that genetically modified micro-organisms could be an efficient way to produce biofuels. While this is an important topic for future research, we do not attempt to include in our current analysis considerations on possible consumer reaction against genetically modified products and trade restrictions that may affect the expansion of the biofuels industry.

committed to climate-related actions through instruments such as the Kyoto Protocol or the EU Emissions Trading Scheme, as discussed in chapter II. However, we expect those commitments to have broader coverage in terms of participating countries and the degree of emissions reduction.

Figure 3.1 shows the composition of global primary energy in the reference scenario as developed for the recent United States Climate Change Science Programme study (CCSP, 2007). The reference scenario exhibits a growing production of biofuels from the year 2020 on. Deployment is driven primarily by a 2100 world oil price that is over 4.5 times the price in 2000. Dwindling supplies of high grade crude oil drive up the oil price to make cellulosic ethanol competitive.

Figure 3.1. Global primary energy consumption in the reference scenario



Source: CCSP (2007).

By 2040, the total global biofuels production (in terms of liquid fuel output) reaches 30 EJ/year, which is a drastic increase compared with the 2005 output of 0.8 EJ/year. By 2100 bioenergy production reaches 180 EJ/year,[36] which is approximately the same amount of energy related to global oil consumption in 2000. Even with these substantial increases in bioenergy production, it would still account for only 5 per cent of global primary energy use in 2040 and 15 per cent in 2100. This result is mainly driven by the absence of climate policies that encourage or mandate the use of renewable fuel sources.

2. Scenario with climate policy: atmospheric stabilization of greenhouse gases

We illustrate how bioenergy technologies perform when climate-related constraints are introduced by using four stabilization scenarios employed in the CCSP study (CCSP, 2007). The stabilization levels are defined in terms of the total long-term effect of GHGs on the Earth's heat balance. The stabilization scenarios are defined in terms of associated CO_2 concentrations; nevertheless, the study formulates the targets as radiative forcing levels that allow for the increase in other greenhouse gases as well. Box 3.1 below discusses the measurement of atmospheric stabilization and defines radiative forcing.

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[36] A recent study with the EPPA model (Gurgel et al., 2007) tests the sensitivity of biomass production estimates with respect to different land supply representations. An explicit representation of land conversion costs slows the initial penetration of bioenergy but increases the amount of biofuels production by 2100 in the range of 220–270 EJ/year in the reference scenario, with a strong growth in biofuels production starting in 2040.

Box 3.1. Defining atmospheric stabilization

The multigas suite of substances with different radiative potency and different lifetimes in the atmosphere presents a challenge to defining what is meant by atmospheric "stabilization". Specification in terms of quantities of the gases themselves is problematic because there is no simple way to add them in their natural units such as tons or parts per million by volume. One alternative would be to define stabilization in terms of an ultimate climate measure, such as the change in global average temperature. Unfortunately, a measure of actual climate change would necessarily introduce uncertainties into the analysis given that the climate system response to added GHGs is uncertain. Complex and uncertain interactions and feedbacks include increasing levels of water vapour, changes in reflective Arctic ice, cloud effects of aerosols and changes in ocean circulation that determine the ocean's uptake of CO_2 and heat. Given these problems, scientists have instead used an intermediate, less uncertain measure of climate effect: the direct heat trapping (or light reflecting, in the case of cooling aerosols) impact of a change in the concentration of such substances. It is constructed to represent the change in the net energy balance of the Earth and the sun ("energy in" versus "energy out") where the units are watts per square meter of the Earth's shell (W/m^2). A positive value means a warming influence and is referred to as radiative "forcing".

Specifically, these radiative forcing levels were chosen so that the associated CO_2 concentrations (measured in ppvm – parts per million by volume) would be roughly 450 ppmv (level 1), 550 ppmv (level 2), 650 ppmv (level 3) and 750 ppmv (level 4). Obviously, the CO_2-equivalent (CO_2-e) concentration considering radiative forcing from other greenhouse gases is higher than the CO_2 concentration itself.[37]

The four stabilization scenarios were developed so that the increased radiative forcing from greenhouse gases was constrained to no more than 3.4 W/m^2 for level 1, 4.7 W/m^2 for level 2, 5.8 W/m^2 for level 3 and 6.7 W/m^2 for level 4 (see box 3.1 for the definition of this measure). These levels are defined as increases above the pre-industrial level, i.e., they include the 2.2 W/m^2 increase that has already occurred as of the year 2000.

To meet these radiating forcing levels, an idealized worldwide cap and trade system is set to begin in 2015. The price path of the emissions constraint over the whole period (2015–2100) is implemented to rise at a 4 per cent rate to simulate cost-effective allocation of abatement over time. Thus, banking and borrowing of allowances over time is allowed.

The numbers for biomass represent only the production of biomass energy from the advanced technologies represented in the EPPA model and do not include, for example, the own-use of wood wastes for energy in the forest products industry. Those are implicit in the underlying data to the extent that the forest industry uses its own waste for energy (thus it purchases less commercial energy). Similarly, to the extent that traditional biomass energy is a substantial source of energy in developing countries, it implies less purchase of commercial energy.[38]

Figure 3.2 presents global "advanced" biomass production across the four stabilization scenarios and in the reference one. Tighter emissions constraints (represented by level 1) lead to an earlier increase in bioenergy production. Global biomass production reaches nearly 250 EJ/year in the climate policies scenarios, against 180 EJ/year in the reference scenario (in the year 2100).

The maximum potential of bioenergy is not very different in the stabilization scenarios by 2100 due to limited land availability. The types of land are not modelled explicitly in the version

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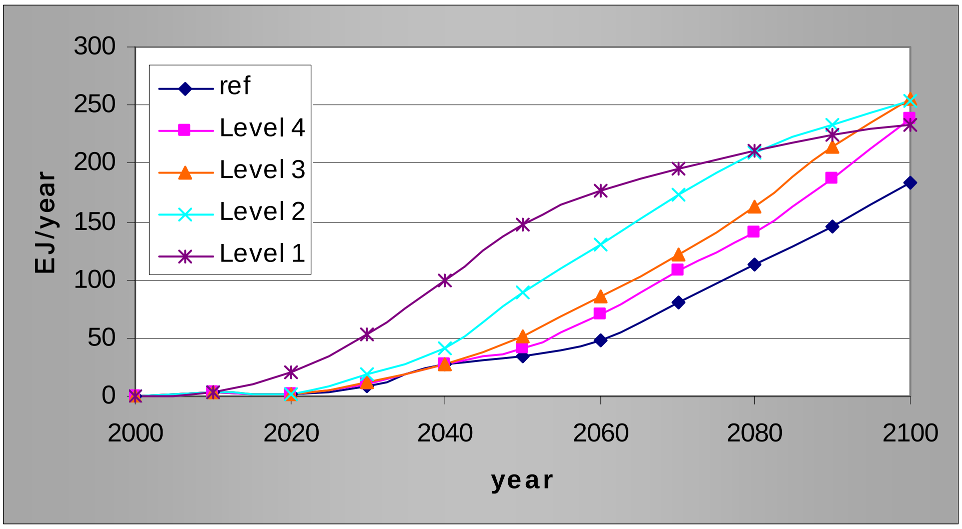
[37] A correspondence between CO_2 and CO_2-equivalent targets for these scenarios is provided in Paltsev et al. (2007).

[38] Developing countries are likely to transition away from this non-commercial biomass use as they become richer and this is likely one reason why we do not observe the rates of energy intensity of GDP improvements in developing countries that we observe in developed countries. EPPA accommodates this transition by including lower rates of Autonomous Energy Efficiency Improvement in poorer countries, thus capturing the tendency this would have to increase commercial fuel use without explicitly accounting for non-traditional biomass use.

of the EPPA model used for the CCSP exercise, but, as discussed before, it is possible to estimate the amount of physical land that would be required. Estimates for the world are provided in table 3.4 and in table 3.5 for the United States: the land area requirement is substantial even with the assumed significant improvement in land productivity. Globally, land area required for bioenergy production in 2100 is over 700 Mha (million hectares) in the reference case, and approximately 1,000 Mha in the stabilization scenarios.

Figure 3.2. Global biomass production across CCSP scenarios



Source: Reilly and Paltsev (2007).

For the United States, estimated land use for bioenergy reaches about 150 to 190 Mha in 2100, across all scenarios. This level of land use is close to the 177 Mha of current cropland (from table 3.5). Similarly, at the global level, the requirement of 1,000 Mha is close to the total current cultivated land reported by IPCC (2001) at 897 Mha.[39] Improved land productivity leads to reduction in land required for biofuels after 2050.

Table 3.4. Global land area (Mha) required for biomass production in CCSP scenarios

	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Ref	46	27	88	261	281	346	496	601	672	728
Level 4	46	27	115	267	341	501	663	752	857	942
Level 3	46	29	134	271	422	619	753	868	987	1011
Level 2	46	30	209	391	739	933	1070	1117	1071	1002
Level 1	46	268	589	958	1229	1264	1208	1122	1032	921

Table 3.5. United States land area (Mha) required for biomass production in CCSP scenarios

	2010	2020	2030	2040	2050	2060	2070	2080	2090	2100
Ref	11	5	16	48	50	61	91	114	131	147
Level 4	11	5	21	49	63	96	132	155	175	158
Level 3	11	5	25	51	82	128	166	191	179	170
Level 2	11	6	41	79	175	238	237	200	198	187
Level 1	11	56	144	253	272	261	251	226	202	174

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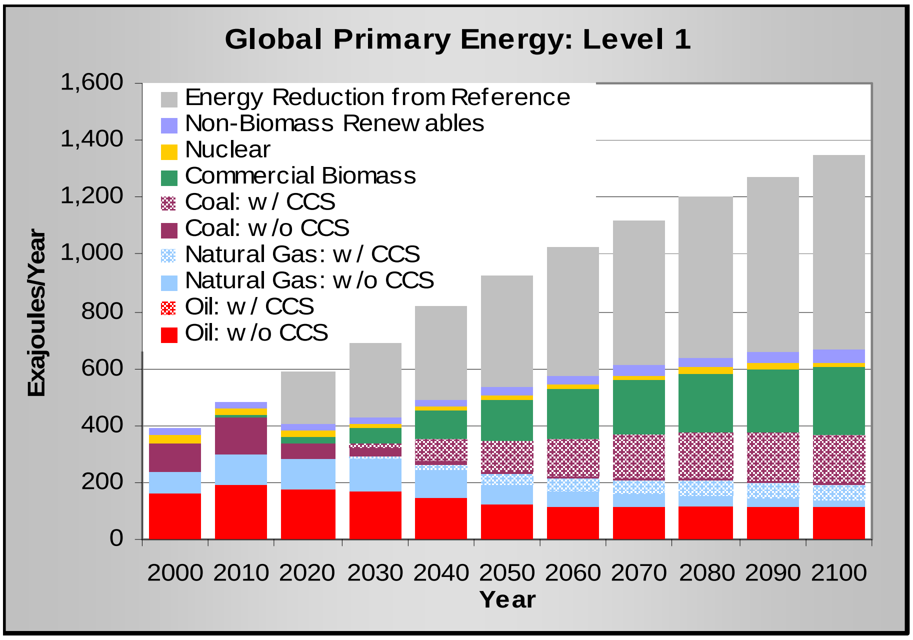
[39] IPCC (2001) reports 0.897 Gha for global cultivated land in 1990 and 2.495 Gha for total land with crop production potential.

Figures 3.3 and 3.4 show the composition of global primary energy for the level 1 and level 3 scenarios, respectively.[40] Across the stabilization scenarios, the energy system relies more heavily on non-fossil energy sources and biomass energy plays a major role. Total energy consumption, while still higher than current levels, is lower in the stabilization scenarios than in the reference scenarios.

In the stabilization scenarios, there is a variety of low-carbon and carbon-free generation technologies that outperform bioelectricity.[41] An important reason for this is that the demand for liquid biofuels from biomass (which we loosely refer to as bio-oil) is high since there are no other good low-carbon substitutes for petroleum products used in the transportation sector. As a result, this demand drives up the land price and raises the cost of bioelectricity. We expect increasing utilization of carbon capture and storage technologies (CCS) associated with natural gas and coal, especially after 2040.[42]

Figure 3.3. Global primary energy in the level 1 scenario (with and without carbon capture and storage technologies, or CCS)



Source: CCSP (2007).

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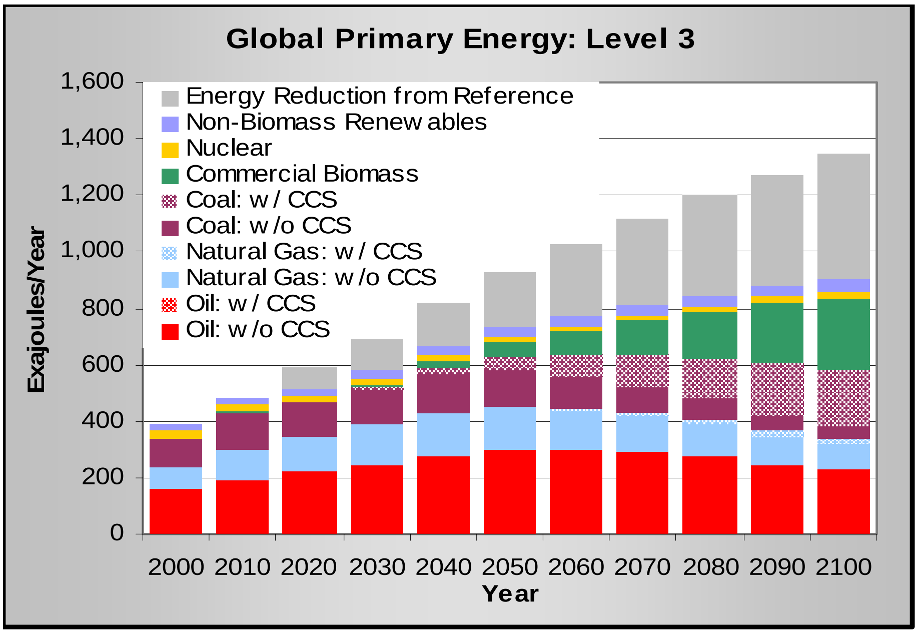
[40] The level 1 scenario is the 450 ppmv scenario, which is often used in climate policy discussions. The level 3 scenario is provided for a comparison here. See CCSP (2007) for the corresponding numbers for the other scenarios.

[41] Bioelectricity is bagasse and biomass used in co-firing in coal electric plants. Coal continues to be an inexpensive source of energy for power generation in the reference case and therefore bioelectricity is not a competitive source of energy.

[42] CCS is used mostly for electricity. Oil is not widely used in electricity production, so researchers mostly envision CCS on coal (as coal is cheap) and gas. Biofuels with CCS is another possibility, but so far there are no reliable estimates on this technology. We have not considered biomass with CCS in the current analysis.

Figure 3.4. Global primary energy in the level 3 scenario (with and without CCS technologies)



Source: CCSP (2007).

We now turn to the role of bioenergy under mitigation scenarios in the United States. We refer to Congressional GHG scenarios based on the level of GHG emissions allowed in the atmosphere between 2012 and 2050 and the implications of a restricted or unrestricted trade framework.

D. Bioenergy under a GHG mitigation scenario in the United States, with and without trade restrictions

Interest in GHG mitigation legislation in the United States Congress has grown substantially and by the end of 2007 there were several proposals to establish a nationwide cap and trade system.[43] Some of the proposed bills envision emissions reductions of 80 per cent below the 1990 level by 2050. Such a steep reduction would entail significant cuts of CO_2 emissions from transportation, which currently account for 33 per cent of American CO_2 emissions related to fossil fuel combustion (Energy Information Administration (EIA), 2006).

The initial allowance level is set to the estimated GHG emissions in the United States in 2008. We distinguish three scenarios for the path followed by annual allowance allocations until 2050:

(a) 2008 emissions levels;

(b) 50 per cent below 1990; and

(c) 80 per cent below 1990.

Over the 2012–2050 period, the cumulative allowance allocations under these three scenarios are 287, 203 and 167 billion metric tons (bmt), or gigatons, of carbon dioxide equivalent (CO_2-e) emissions. The GHG scenarios are designated with the shorthand labels 287

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[43] A more complete discussion and analysis of current Congressional proposals is provided in Paltsev et al. (2007).

bmt, 203 bmt and 167 bmt. The last is thus the most stringent scenario for the United States' climate policy.

The banking of GHG allowances (for use in later periods) in the United States is allowed by meeting the target with a CO_2-e price path that rises at a rate of interest assumed to be 4 per cent.[44] Other developed countries are assumed to pursue a policy whereby their emissions also fall to 50 per cent below 1990 levels by 2050. Moreover, all other regions are assumed to return to the projected 2015 level of emissions in 2025, holding at that level until 2035, when the emissions cap drops to the year 2000 level of GHG emissions.

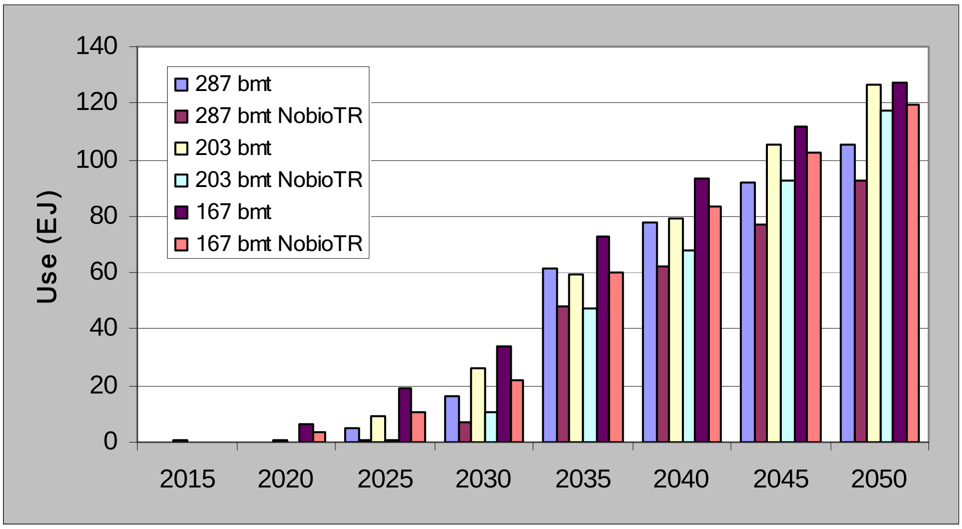
The economywide trading among greenhouse gases at their Global Warming Potential (GWP)[45] value is simulated. All prices are thus CO_2-e. The carbon dioxide prices required to meet these policy targets in the initial projection year (2015) are $18/t, $41/t and $53/t CO_2-e for the 287, 203 and 167 bmt cases, respectively.

These three scenarios are evaluated under two different assumptions: with and without restrictions in biofuels trade. Under free trade, significant amounts of biofuel are used in the United States and nearly all of it is imported. Under trade restriction (denoted here by the extension NobioTR), all biofuels used in the United States (and in other regions of the world) must be produced domestically. Figure 3.5 presents an estimate of global liquid biofuels use in the three scenarios and including the two sets of trade scenarios.

Biofuels use in the United States is substantial in the 203 bmt and 167 bmt cases, rising to 30–35 EJ in 2050 (figure 3.5, panel b). The 287 bmt case results in limited biofuels consumption (less than 1 EJ/year). Global liquid biofuels use is substantial in all three cases, reaching 100–120 EJ in 2050, since the rest of the world is pursuing aggressive GHG policies.

Figure 3.5. Liquid biofuels use, with and without international trade in biofuels

a. World total



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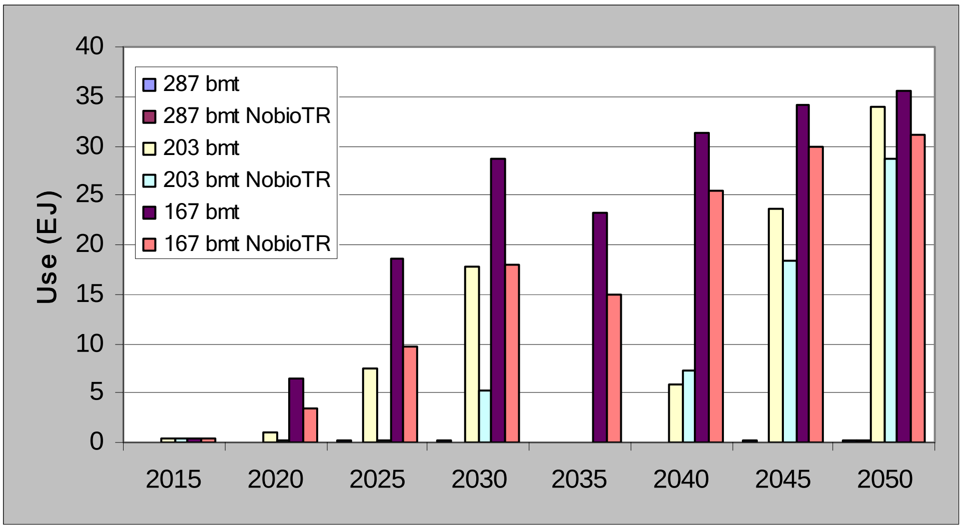
[44] This refers to banking and borrowing of emission allowances over time. For example, an entity can buy an allowance and use it only after 10 years.

[45] The Global Warming Potential (GWP) of a greenhouse gas is a measure of the contribution of a particular gas to global warming over a specific time interval (relative to carbon dioxide). Commonly, a time interval of 100 years is used.

b. United States



Source: The EPPA model (Paltsev et al., 2007).

When biofuels trade is restricted, we project lower biofuels use in the United States and in the total for the world (figure 3.5, panels a and b). However, biofuels use and hence production in the United States remain substantial, falling in the 25–30 EJ range rather than 30–35 EJ by 2050. Biofuels would substantially displace petroleum products, accounting for nearly 55 per cent of all liquid fuels in the United States.

When biofuels trade is restricted, we project lower biofuels use in the United States and in the total for the world.

As discussed above, the amount of land required for biofuels production in these scenarios can be calculated. Estimates for the United States are reported in table 3.6. In the policy scenarios the land required in 2050 approaches or exceeds that in the CCSP scenarios in 2100. The reason is that these policy scenarios for the United States require a much more rapid reduction in greenhouse gas emissions, particularly in developed countries with large transportation fuel demand. Thus, the demand for carbon-free fuel rises faster. The slower growth in the CCSP scenarios after 2050 takes advantage of further land productivity improvements.

Table 3.6. United States land area (Mha) required for biomass production considering Congressional analysis scenarios

	2015	*2020*	*2025*	*2030*	*2035*	*2040*	*2045*	*2050*
287 bmt	0	0	0	0	0	0	0	0
287 bmt NobioTR	0	0	0	0	0	0	0	1
203 bmt	0	0	0	0	0	0	0	4
203 bmt NobioTR	5	3	2	60	1	71	165	239
167 bmt	0	0	0	0	0	0	0	6
167 bmt NobioTR	5	44	116	202	155	246	268	260

1. Implications for the agricultural sector in the United States

Figure 3.6 illustrates an important implication of biofuels production for the broader agricultural sector, focusing on the 167 bmt case (the strictest one in terms of allowed CO_2 emissions). The United States is currently a substantial net agricultural exporter, and under the EPPA reference scenario (without GHG policy) this is projected to continue. In the 167 bmt case, American net agricultural exports are projected to double in comparison with the reference case.

As other regions expand ethanol production, they import more agricultural goods and thus the United States' net exports grow.[46]

However, in the 167 bmt Nobio TR case (i.e., with trade restrictions on biofuels) the implications for net biofuels flows are quite different. Forcing biofuels to be produced domestically under a stringent climate policy translates into a significant reduction in American agricultural production. Instead of being a net exporter of agricultural commodities, the United States becomes a large net importer. Whereas net exports today are in the order of $20 billion, by 2050 in the 167 bmt NobioTR case, the United States becomes a net importer of nearly $80 billion in agricultural commodities.

It is worth mentioning that the agricultural sector in the EPPA model is highly aggregated. As a result, the absolute value of net exports in the reference scenario is just a rough estimate; it could be higher or lower depending on how agricultural productivity advances in the United States relative to other regions of the world.

Therefore, if approximately 25 EJ of ethanol must be produced in the United States (requiring around 500 million acres, or 200 Mha, of land), it is almost inevitable that this would transform the United States into a substantial agricultural importer.

Figure 3.6. Net agricultural exports in the 167 bmt case, with and without biofuels trading

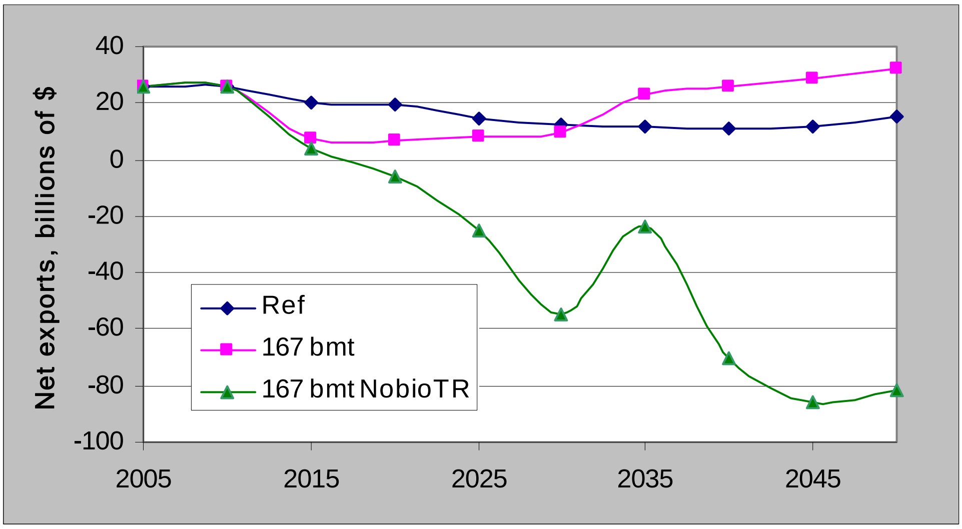


Figure 3.7 shows an index of the land and agricultural commodity prices and agricultural production in the United States in the 167 bmt NobioTR case, relative to the reference scenario. Agricultural land prices fall in 2015 relative to the reference case, while agricultural product prices rise. This reflects greenhouse gas mitigation costs in agriculture that slightly depress land prices and agricultural production while leading to overall higher production costs and agricultural prices.

Agriculture uses a significant amount of energy that emits CO_2, and is also a significant source of N2O and CH_4. The CO_2-e price in 2015 in the 167 bmt NobioTR case is $67, and this added cost is reflected in a combination of lower land prices and higher commodity prices determined by underlying demand and supply elasticities.[47]

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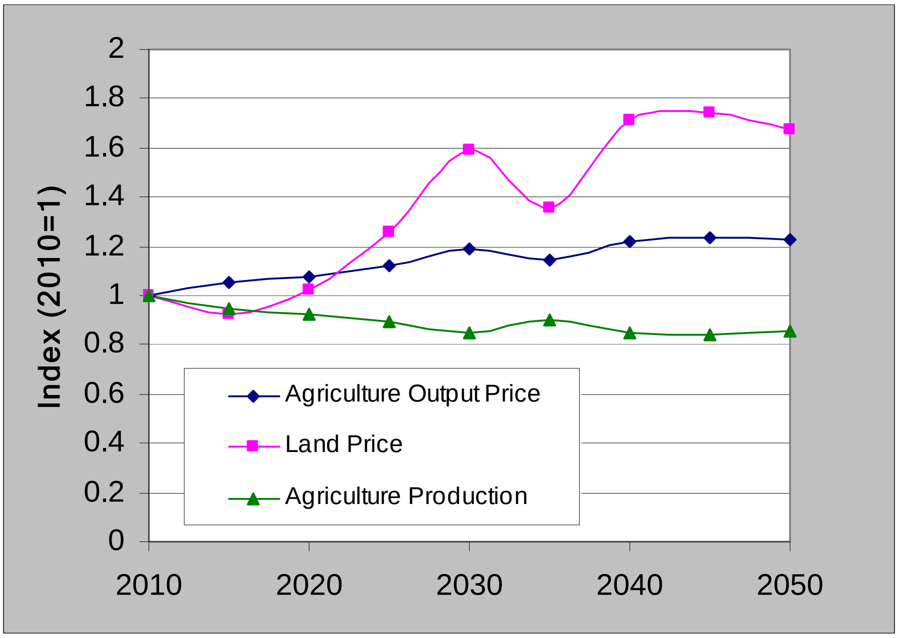
[46] As a result from the model, tropical countries would specialize in biofuels production and import agricultural goods from other countries, including the United States.

[47] The values for elasticities are provided in Reilly and Paltsev (2007).

Once biofuels production increases, land prices recover relative to the reference case, agricultural commodity prices rise further and agricultural production falls. The large shock in 2035 reflects the significant tightening of the carbon constraint in developing countries in that year. The United States reduces biofuels production and imports petroleum. As a result, land prices decrease temporarily but remain above the reference.

Figure 3.7. Indexes of agriculture output price, land price and agriculture production in the United States in the no biofuels trading (167 bmtnb) scenario relative to the reference (2010=1.00)



E. Where will biomass production occur?

In order to estimate regional biofuels production and how biofuels policies and the trade regime affect world production, we make some changes to the above assumptions. First, to consider similar reductions in developed countries, we focus on the 203 bmt scenario discussed above.[48] Second, the scenario is extended to 2100 in order to limit global cumulative GHG emissions to 1,490 billion metric tons (bmt) from 2012 to 2050 and 2,834 bmt from 2012 to 2100.

These numbers are equivalent to 60 per cent of the emissions in the reference scenario (no climate policy) in the 2012–2050 period, and 40 per cent over the full period. The cumulative level of GHG emissions is consistent with the 550 ppmv CO_2 stabilization goal discussed before (level 2). The policy is implemented as a cap and trade system in each region. This system limits the amount of fossil fuels that can be used and thus provides an economic incentive for biofuels production and other low-carbon energy sources.

Table 3.7 presents the bioenergy production in selected world regions, with other regions aggregated.[49] Africa and Latin America are the two most important producing regions. In both regions land availability is crucial to achieving high production levels. The greater land productivity in biomass crops allows Latin America to supply between 45 per cent and 60 per cent of world production for most of the model horizon. Africa would supply about 30 per cent.

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[48] For a global analysis we focus on the 203 bmt scenario as it corresponds to a 50 per cent reduction relative to 1990, which is similar to the latest Group of Eight (G8) proposal of a 50 per cent reduction by 2050.

[49] These results are from the EPPA model with observed land supply response. For more information about modelling land transformation, see Gurgel et al. (2007).

The United States is the third largest world producer, supplying between 33 and 36 EJ (10 per cent of total production) of biomass in 2100 in the policy case. Australia, Mexico and New Zealand are also able to produce large amounts of biomass. The contribution to biomass production from others is very small (approximately 1 per cent of world production). This reflects the presence of large areas of natural forest and pasture in those countries and regions and the fact that biomass is more productive in tropical areas. China and India are exceptions to this pattern. Growth of food demand and modelling of trade in biofuels and agricultural goods are key aspects of the model that drive this result. Both China and India have increasing demand for food and relatively lower biomass land productivity than other regions and therefore priority is given to land use for agricultural production.

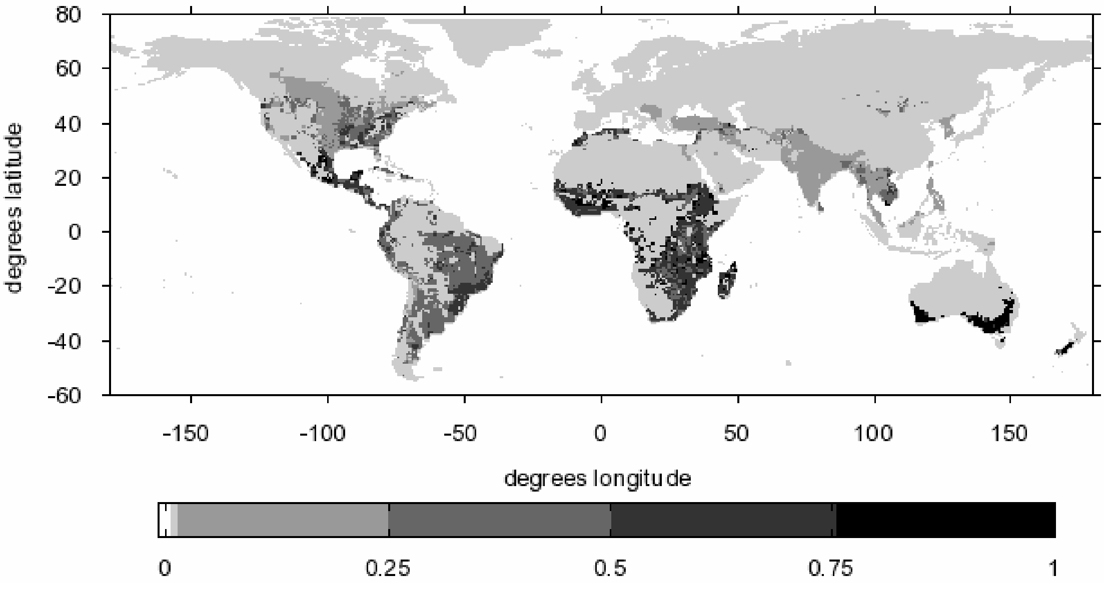
Table 3.7. Regional second generation biomass production in the policy case (EJ/year)

	USA	*Mexico*	*Australia and New Zealand*	*Latin America*	*Africa*	*Other regions*	*Global*
2010	0	0	0	0	0	0	0
2020	0	0	0	0	2	0	2
2030	1	0	1	4	19	0	25
2040	4	2	2	26	30	5	69
2050	13	4	4	54	41	6	122
2060	17	4	6	71	48	6	152
2070	20	5	8	87	58	7	185
2080	24	6	11	107	71	10	229
2090	28	7	13	127	85	13	273
2100	33	8	16	147	98	18	320

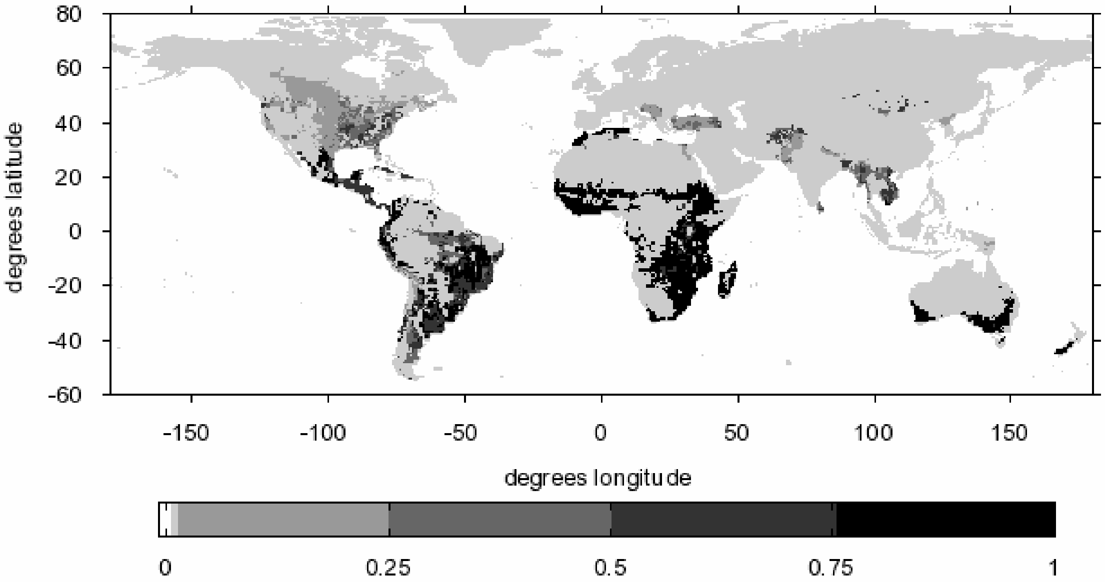
Figure 3.8 presents the share of land devoted to biomass production in a policy scenario in 2050 and 2100 (assuming that second generation biomass is not yet economic in 2010). The red colour represents regions with 80–100 per cent shares (Africa, Australia, Latin America, New Zealand and the United States).

Figure 3.8. Share of land devoted to biomass production in a policy case – OLSR model

Panel a. 2050



Panel b. 2100



An important factor driving these results is the assumption of unrestricted trade in biofuels. Free trade leads to the specialization of production in Africa and Latin America, where land is cheaper. This low cost results from a combination of low land prices and high biomass productivity per hectare. This implies that regional production of biofuels is insensitive to the location of demand: global demand is supplied by those regions with the lowest cost of production. Only an increase in land prices (caused by a rise in biofuels production) in a low-cost region could lead to increased biofuels production elsewhere. The amount of bioenergy exports would be about 80 EJ/year by 2050 and 200 EJ/year by 2100.

However, if trade barriers are in place, the geographical location of production will change. Almost all regions of the world would produce bioenergy, with the main producers being Africa, Europe, Latin America and the United States. The level of global bioenergy production would be lower: 30–40 EJ/year in 2050 and 70–110 EJ/year in 2100.

Thus, we project that energy from biomass will be an important component of world energy consumption. Nevertheless, even in the policy case with unrestricted trade, biofuels would account for around 30 per cent of global energy consumption. The larger share of biomass in the policy case is due to the replacement of oil production, since biofuels are a low-carbon alternative in the transportation sector.

Now we turn to the following question: how would increased biofuels production affect global land cover and food and land prices?

F. Land-use implications

As discussed in chapter II, biofuels production has significant impact on global land use. Figure 3.9 illustrates the competition among land uses, using different approaches for land conversion modelling.

Gurgel et al. (2007) discuss two possibilities for land supply representation in the EPPA model: one approach allows unrestricted conversion of natural forest and grasslands (as long as conversion costs are covered by returns), which is labelled as the Pure Conversion Cost Response (PCCR) model.

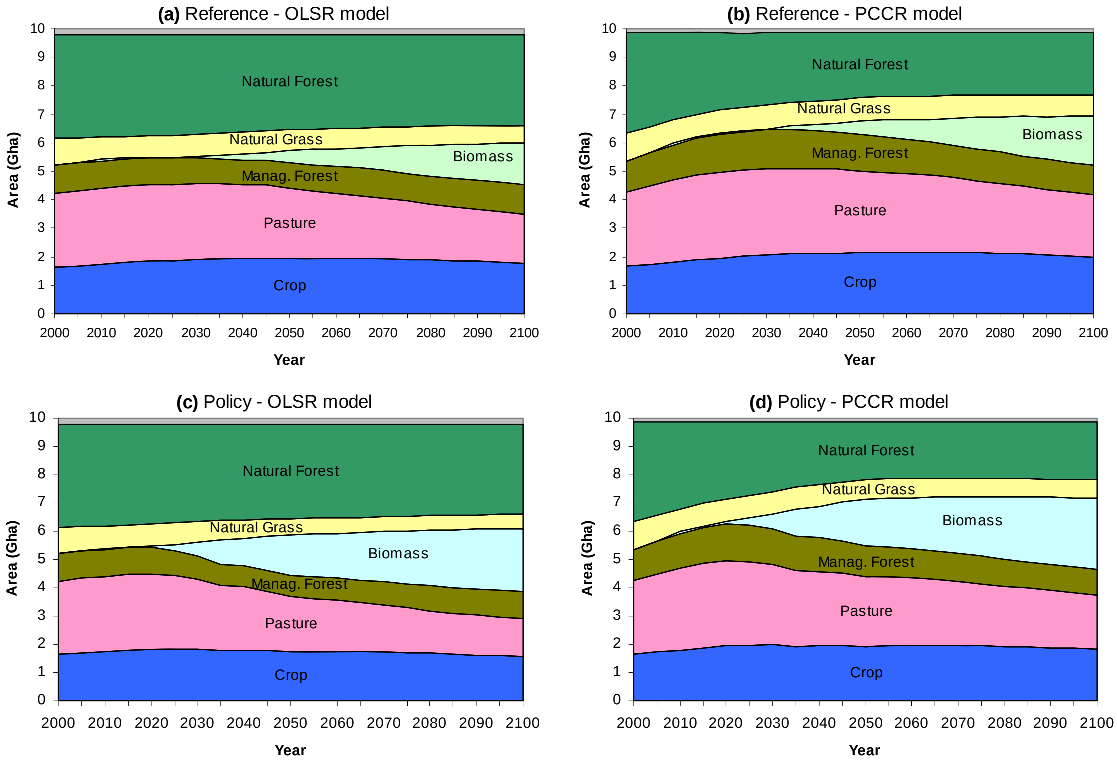
Another approach is to parameterize the model to represent land conversion that occurred in recent years. This version of the EPPA model is labelled as the Observed Land Supply Response (OLSR) model. Land conversion in the latter model is less common than in the PCCR model.

These versions capture two extremes: the OLSR version assumes that the response we have witnessed in recent years in land conversion is representative of the long-term response. The PCCR version assumes that conversion will proceed unhindered as long as the value of converting land is greater than the cost.

> *If trade barriers are in place, the geographical location of production will change. Almost all regions of the world would produce bioenergy, with the main producers being Africa, Europe, Latin America and the United States.*

The two approaches for land conversion are applied both to the reference and policy case described before.

Figure 3.9. Global land use: (a) reference case – OLSR model, (b) reference case – PCCR model, (c) policy case – OLSR model, (d) policy case – PCCR model



Total land area is 9.8 Gha, but the use of this land changes considerably from 2000 to 2100.[50] The area covered by biomass in 2050 ranges from 0.42 to 0.47 Gha in the reference scenario, and from 1.46 Gha to 1.67 Gha under the policy case. In 2100 biomass production covers between 1.44 and 1.74 Gha in the reference case, and from 2.24 to 2.52 Gha in the policy case. Currently, cropland occupies 1.6 Gha.

Natural forests are affected in all scenarios and under both model assumptions, but, as expected, much more conversion occurs under the PCCR model. In this case, natural forests are reduced from the original 3.7 Gha to 2.2 Gha in the reference scenario, and to only 2.0 Gha in the policy case (a 40 per cent reduction in natural forest area).

In contrast, the OLSR model shows less reduction in natural forest area, with a substantial reduction in pasture land. This version of the model makes room for biofuels production by

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[50] Figure 3.9 does not include the 3.2 Gha of land not available to agriculture, which by assumption remains unchanged.

greatly intensifying production on existing agricultural land, especially pasture land. In both models natural forest and pasture land are the main land types converted to biofuels production; land dedicated to crops, managed forest and natural grassland show little net changes.

Indeed, crop areas present low sensitivity to the biomass expansion. The original 1.6 Gha covered by crops increase to 1.8 Gha at the end of the century in the reference scenario under the OLSR model, and to almost 2 Gha under PCCR model. In the policy scenario the area covered by crops is reduced slightly to 1.57 Gha under the OLSR model, but still increases to 1.8 Gha under PCCR model assumptions.

This result indicates that crop production and crop area are not greatly affected by biomass expansion, stemming from the relatively inelastic demand for food.

G. Long-term effects on agricultural prices and land rents

The impact of biofuels production on global agricultural and industrialized food prices is shown in figure 3.10. To show the average effect on world prices we compute global price indices using the Walsh index as described by the IMF (2004). The simulated price levels reflect the combination of increasing demand for food, fibre and forestry products as gross domestic product (GDP) and population grow, given our assumption of increasing land productivity.

In the reference scenario we observe price increases in forestry and livestock products, while crop prices remain stable through the century. Forestry and livestock price increases reflect the competition for land from biofuels and higher demand growth for these products than for crops. In the climate policy scenario we see an increase in crops, food and livestock prices of around 5 per cent, which is likely attributable to biofuels' competition for land. The OLSR version of the model shows price increases of 2 to 3 percentage points more than the PCCR model, as a consequence of the lower flexibility in terms of land conversion (from natural areas to agricultural use).

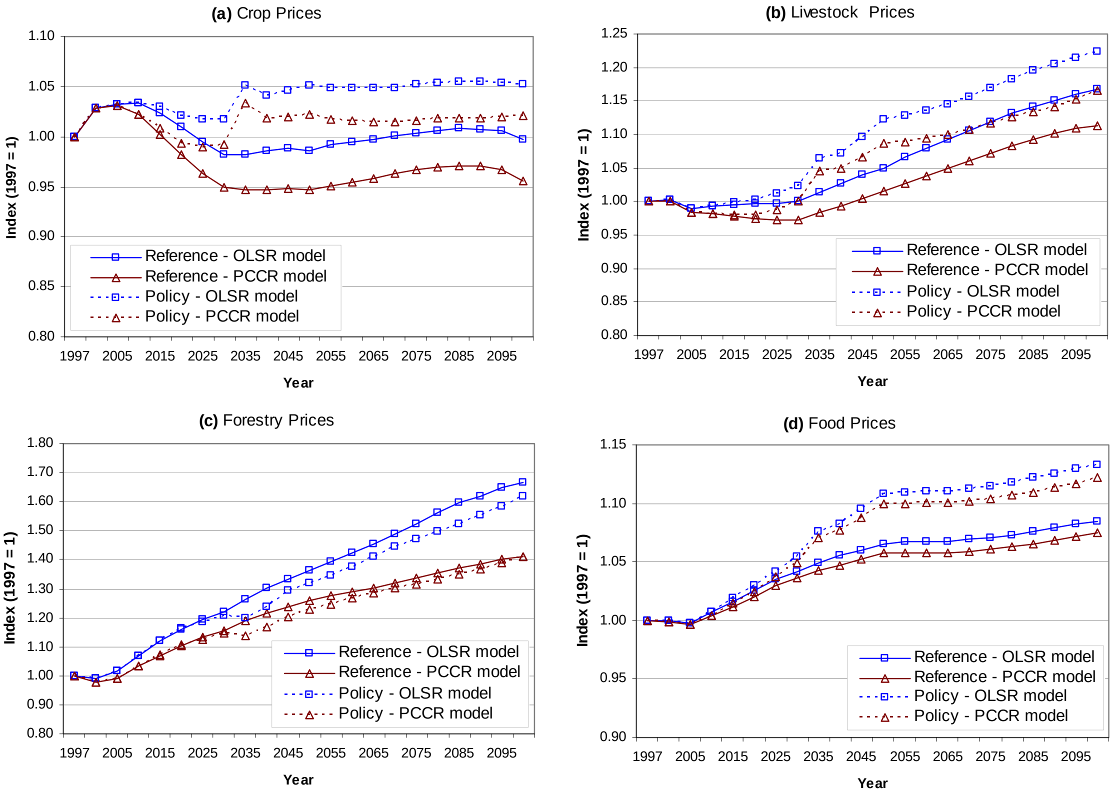
The impact of the biofuels industry on food and commodity prices is projected to be relatively small compared to recent price increases of maize.

The relative changes in prices of crops, livestock and forestry reflect the share of land in the production of each group. They also reflect the fact that livestock production is affected both by the increase in the pasture land rent and the increase in crop prices.

The impact of the biofuels industry on food and commodity prices is projected to be relatively small compared to recent price increases of corn (corn prices rose by nearly 70 per cent from September 2005 to September 2007).

One aspect that should be considered is that the EPPA model projection involves all crops, thus the average price increase does not reflect prices for only one crop. The modelling also reflects long-run elasticities that give time for the sector to adjust, and over the longer term agriculture has proved to very responsive to increasing demand. In fact, the current run-up in corn prices has led to a rapid response by farmers, who have been planting more corn, and with more supply the price may retreat. We also expect less direct effects on crop prices because corn-based ethanol directly affects the corn market whereas cellulosic crops would only indirectly affect crops though the land rent effect.

Figure 3.10. World agricultural and food price indexes



In this regard, the EPPA model simulations suggest that it is possible to integrate a relatively large ethanol industry into the agricultural system over time without causing dramatic effects on food and crop prices.

H. Concluding remarks

Second generation biofuels are expected to have great potential in terms of energy output per unit of land area and cost of production. Technology is expected to be of “cellulosic” or “lignocellulosic” conversion due to the great availability of cellulosic resources. Nevertheless, second generation technology is not yet competitive: most studies report that the current cost is 2.1 times higher than the cost of gasoline production (IEA, 2006; IMF, 2007; Reilly and Paltsev, 2007). Expectations about future costs vary: the IEA estimates that the cost will be similar to ethanol from sugar cane by 2030 while other researchers are not so optimistic. Expectations about energy output per unit of land also vary, with most optimistic estimates being twice as high as current figures of around 30 oven-dry ton/hectares for sugar cane.

Competition for land (which would lead to an increase in agriculture, land and food prices) would still exist, but it is expected to have less impact on prices than the current “first generation” technology. This would be so especially if there is time for the agriculture system to adjust to increased demand. While climate policy can spur bioenergy production, rising oil prices could be enough to bring along second generation technology even if production costs do not fall. For example, Reilly and Paltsev (2007) and Gurgel et al., (2007), using versions of the MIT Emissions Prediction and Policy Analysis (EPPA), project that second generation biomass may produce around 30–40 EJ/year by 2050 and around 180–260 EJ/year by 2100. As a comparison, in 2005 global bioenergy production was less than 1 EJ.

The EPPA projections suggest that, under an unrestricted trade scenario, the largest producers would be Africa, Latin America and the United States, where there is a relative abundance of land with significant biomass productivity per hectare. As a general rule, availability of land, land prices, improvements in agricultural management, seed quality and use of better soils are needed for a country to become a large feedstock producer. Therefore, due to relatively low land prices, African countries seem better placed than Asian countries to become large feedstock producers, given conditions of political stability and improvements in agricultural management and seed quality. The amount of bioenergy trade among EPPA regions reaches about 18 EJ/year in 2050 and around 125 EJ/year in 2100.

Under a restricted trade scenario, Africa, Latin America and the United States would still be the largest producers, but other regions and countries, namely Europe, India and China would play a major role. The level of global bioenergy production would be lower by 3–6 EJ/year in 2050 and by 70–110 EJ/year in 2100 in comparison to the unrestricted trade scenario. Thus, trade restrictions limit biofuels' potential.

The existence of a CO_2 policy, such as a cap and trade system, would result in an increase in fossil fuel prices and in the demand for carbon-free fuels. Therefore, bioenergy would become competitive earlier, if compared to a scenario without a climate policy in place (the exact year depending on the relative price of fossil fuels and biofuels). A climate policy targeting 550 ppmv stabilization of CO_2 concentrations could lead to bioenergy production of 90–130 EJ/year by 2050 and 250–370 EJ/year by 2100 according to studies by Paltsev et al. (2007) and Gurgel et al. (2007). This amounts to approximately 30 per cent of global energy use derived from bioenergy.

If climate policies are in place and trade is unrestricted, trade in bioenergy among EPPA regions reaches 80 EJ/year by 2050 and around 200 EJ/year by 2100. Restricting trade in bioenergy in the presence of climate policy leads to production in almost all regions of the world with the main producers being Africa, Europe, Latin America and the United States. The level of global bioenergy production is lower by 30–40 EJ/year in 2050 and again by 70–110 EJ/year in 2100 in comparison to unrestricted trade.

Regarding the projected results for the United States, we found that the country would be an importer of biofuels under two conditions, namely the existence of a stringent domestic mitigation policy and of unrestricted trade. Rather than for energy feedstock production, American farmland would be used to produce food for export, while regions abroad would devote more of their agricultural land to feedstock production and import food products from the United States. If the United States' biofuels use is restricted to domestically produced feedstock (i.e., under a situation of restricted trade), about 500 million acres (200 Mha) of American land would be required for production. This is more than the total current cropland in the United States. In this case, the country would become a large importer of food, fibre and forest products, rather than the net exporter of these products that it is now.

The global area required to grow biomass crops by the end of the century in the reference scenario is about 1.5 to 1.7 Gha, similar to the amount of land area used for crops today. Under the policy scenario, the land required for biomass production reaches 2.2 to 2.5 Gha in 2100. Global prices for food, agriculture and forestry products increase relative to the reference case as a result of a more rapid expansion of biofuels when there is a strong climate policy. That said, these price increases are relatively modest. Thus, it appears to be possible to introduce a large cellulosic biofuels industry without dramatically upsetting agricultural markets if there is time for the agricultural sector to respond to this increased demand. However, the expansion of the industry could result in substantial deforestation and the unintended release of carbon emissions.

Since trade regimes play a key role in determining which countries and regions are likely to become leading biofuel producers and exporters, the next chapter analyses trade opportunities for developing countries.

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