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Potential Land Use Implications of a Global Biofuels Industry

Angelo Gurgel* John M. Reilly† Sergey Paltsev‡

*Massachusetts Institute of Technology, gurgel@mit.edu
†Massachusetts Institute of Technology, jreilly@mit.edu
‡Massachusetts Institute of Technology, paltsev@mit.edu

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Angelo Gurgel, John M. Reilly, and Sergey Paltsev

Abstract

In this paper we investigate the potential production and implications of a global biofuels industry. We develop alternative approaches to consistently introduce land as an economic factor input and in physical terms into a computable general equilibrium framework. The approach allows us to parameterize biomass production consistent with agro-engineering information on yields and a "second generation" cellulosic biomass conversion technology. We explicitly model land conversion from natural areas to agricultural use in two different ways: in one approach we introduced a land supply elasticity based on observed land supply responses and in the other approach we considered only the direct cost of conversion. We estimate biofuels production at the end of the century could reach 221 to 267 EJ in a reference scenario and 319 to 368 EJ under a global effort to mitigate greenhouse gas emissions. The version with the land supply elasticity allowed much less conversion of land from natural areas, forcing intensification of production, especially on pasture and grazing land, whereas the pure conversion cost model led to significant deforestation. These different approaches emphasize the importance of somehow reflecting the non-market value of land more fully in the conversion decision. The observed land conversion response we estimate may be a short turn response that does not fully reflect the effect of long run pressure to convert land if rent differentials are sustained over 100 years.

KEYWORDS: biofuels, land use change, computable general equilibrium modeling, climate change

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1. Introduction

Bioenergy has a mixed record. On one hand it is often seen as a renewable source of clean energy, a substitute for fossil fuels people fear are growing scarcer, offering energy security for countries without other domestic resources, and a source of income for farmers. On the other hand, current production methods often involve the use of fossil fuels so that the CO_2 benefits are minimal, rely on crops such as maize, rapeseed, or oil palms where the potential to supply significant energy is limited, and through competition for these crops and for land significantly affect food prices and create additional pressure for deforestation. The US and Europe have proposed major initiatives to expand biofuel use in the past couple of years. But even before these programs were fully realized, expansion of the industry has revealed what analysts have long understood—there would be food price and environmental consequences even for an industry that is supplying no more than a few percent of, for example, US gasoline use. The US industry has been seen as responsible for recent rises in world maize prices, with consequences for poorer consumers worldwide. European blending requirements and the demand for biodiesel, in particular, have been linked to expanding oil palm plantations and deforestation in Indonesia. The promise of improving farm income has been realized as commodity prices have risen sharply but that success also spells the limits of the technology in terms of providing a substantial domestic supply of energy.

Advocates for the development of cellulosic conversion methods believe such a second generation technology avoids many of these consequences. It is able to use crops such as switchgrass or waste such as corn stover so the technology does not directly compete for food. Perennial grasses would have less environmental impacts than row crop agriculture, and per hectare energy yield could be on the order of 5 times that of maize because the entire plant can be converted to fuel. Does the cellulosic technology offer a biofuels option that avoids some of the negative consequences we have seen with current technologies? What is the potential size of a cellulosic biofuels industry? What are the limitations in terms of land availability and the impacts on natural environments? If this technology matures, where and when will biomass production occur? How would development affect land cover, food and land prices and energy markets? Would greenhouse gas mitigation policies create greater demand for biofuels?

We apply a Computable General Equilibrium (CGE) model with significant detail on the energy sector and on land use to address such questions. The model is an extension of the MIT Emissions Prediction and Policy Analysis (EPPA) model (Paltsev *et al*., 2005) that has been widely applied to address energy, agriculture, and climate change policy. A previous application of the model to the biofuels question is reported in Reilly and Paltsev (2007). We have augmented that version of the model in several ways to address the questions we raise here. In particular we have included multiple agricultural sectors and land types. We include natural areas explicitly and allow for future conversion to agricultural land when economic conditions favor it. Multiple land types have been used in CGE models before, but we adopt a different approach to model land transformation among land use categories that better captures the long-run capability to transform land. We apply the model to estimate biomass production in the 21st century considering two alternative scenarios, with and without a policy to mitigate greenhouse gas emissions. We focus on the cellulosic conversion technology, as it is clear from previous work that the likely contribution of conventional technology is limited in terms of global energy needs.

2. Relationship to Existing Literature

There have been a number of attempts to assess the implications of worldwide bioenergy production in recent years. Reilly and Paltsev (2007) have estimated the energy production potential from the development of cellulosic biomass technologies in a CGE model. Their approach, however, did not account explicitly for competition among different land uses, and followed a standard approach for accounting of inputs in a CGE framework where the quantity of land service available annually is represented by the total rental value of land. The approach followed economic convention of aggregating land of different productivities based on rental value and data on annual returns to land. While a start, the approach does not provide a direct connection to physical quantity of land use in hectares, or the capability to make use of agro-engineering data on regional production potential. In particular, Reilly and Paltsev (2007) assumed the same land productivity in biomass production across all regions in terms of land input in rental value units. Msangi et al. (2007) explored scenarios of biomass expansion using the IFPRI Impact model. Although all the details in the representation of demand and supply of different agriculture products are included, their Impact model is a partial equilibrium approach that does not represent other energy markets.

Moving from a single land input to multiple land classes requires a modeling approach to represent the ability to shift land from one use to another. Several studies have represented competition among different use categories. These include Adams *et al*. (1996), Darwin (1995), Ianchovichina *et al*. (2001), Ahammad and Mi (2005) and Golub *et al*. (2006). These studies have used a Constant Elasticity of Transformation (CET) function to represent the allocation of land among different uses. A land supply elasticity of each type is implied by the elasticity of substitution and implicitly reflects some underlying variation in suitability of each land type for different uses and the cost to or willingness of owners to switch land to another use.

The CET approach can be useful for short term analysis where there are data on the apparent elasticity of substitution. However, a well-known property of CET and closely related Constant Elasticity of Substitution (CES) functions is that they are share preserving. This feature assures that radical changes in land use does not occur, making short term projections more "realistic." However, for longer term analysis where demand for some uses could expand substantially the CET approach may unrealistically limits land use change. Our interest is major changes of land use—from natural forest or grassland cover to, for example, cropland and for this purpose an alternative to the CET approach is to explicitly include a cost to transform land from one type to another. The CET approach also does not explicitly account for conversion costs, nor does it address the value of the stock of timber on virgin forest land that substitutes for forest harvest on managed forest land.

We therefore explicitly address the cost of conversion and timber stocks. The advantages include the ability to track land area consistently in a general equilibrium framework and explicitly represent conversion costs and to account for the harvest of timber on virgin forest land. Our method implies that intensively managed land (i.e. cropland) can be "produced" from less intensively or unmanaged land, with the specific approach and data sources discussed in detail in section 3 of the paper. In Section 4 we present the results from the model for two alternative scenarios, with and without climate change policy and two formulations of the economics of land conversion. Section 5 presents some conclusions.

3. The Model

3.1. The EPPA model

Our point of departure is the MIT Emissions Prediction and Policy Analysis (EPPA) model described in Paltsev *et al*. (2005). EPPA is a recursive-dynamic multi-regional computable general equilibrium (CGE) model of the world economy. The GTAP data set provides the base information on Social Accounting Matrices and the input-output structure for regional economies, including bilateral trade flows, and a representation of energy markets in physical units as shown in Table 1 (Hertel, 1997; Dimaranan and McDougall, 2002). We aggregate the data into 16 regions and 21 sectors.

Other important data sources in EPPA are data on greenhouse gas (CO_2, CH_4, N_2O, HFCs, PFCs, and SF_6) and air pollutant emissions (SO_2, NO_x, black

Table 1. Regions and Sectors in the EPPA4 Model

Country/Region	Sectors
Annex B	***Non-Energy***
United States (USA)	Crops (CROP)
Canada (CAN)	Livestock (LIVE)
Japan (JPN)	Forestry (FORS)
European Union+ (EUR)	Food (FOOD)
Australia/New Zealand (ANZ)	Services (SERV)
Former Soviet Union (FSU)	Energy Intensive Products (EINT)
Eastern Europe (EET)	Other Industries Products (OTHR)
Non-Annex B	Industrial Transportation (TRAN)
India (IND)	Household Transportation (HTRN)
China (CHN)	***Energy***
Indonesia (IDZ)	Coal (COAL)
Higher Income East Asia (ASI)	Crude Oil (OIL)
Mexico (MEX)	Refined Oil (ROIL)
Central and South America (LAM)	Natural Gas (GAS)
Middle East (MES)	Electric: Fossil (ELEC)
Africa (AFR)	Electric: Hydro (HYDR)
Rest of World (ROW)	Electric: Nuclear (NUCL)
	Advanced Energy Technologies
	Electric: Biomass (BELE)
	Electric: Natural Gas Combined Cycle (NGCC)
	Electric: NGCC with CO_2 Capture and Storage (NGCAP)
	Electric: Integrated Coal Gasification with CO_2 Capture and Storage (IGCAP)
	Electric: Solar and Wind (SOLW)
	Liquid fuel from biomass (BOIL)
	Oil from Shale (SYNO)
	Synthetic Gas from Coal (SYNG)

Note: Detail on the regional composition is provided in Paltsev *et al.* (2005). CROP, LIVE, FORS, FOOD, SERV, EINT, OTHR, COAL, OIL, ROIL, GAS sectors are aggregated from the GTAP data (Dimaranan and McDougall, 2002), TRAN and HTRN sectors are disaggregated as documented in Paltsev et al. (2004), HYDR and NUCL are disaggregated from electricity sector (ELY) of the GTAP dataset based on EIA data (2006b), BELE, NGCC, NGCAP, IGCAP, SOLW, BOIL, SYNO, SYNG sectors are advanced technology sectors that do not exist explicitly in the GTAP dataset

carbon, organic carbon, NH_3, CO, VOC), which are based on United States EPA inventory data and projections, and advanced energy technology sectors which have been developed using engineering cost estimates and data on conversion efficiencies as discussed further below.

The base year of the model is 1997. EPPA simulates the economy recursively at 5-year intervals from 2000 to 2100. Economic development in 2000 and 2005 is calibrated to the actual GDP growth data. Production and consumption sectors in EPPA are represented by nested Constant Elasticity of Substitution (CES) functions, which include the Cobb-Douglas and Leontief special cases. The model is written in the GAMS software system and solved using the MPSGE modeling language (Rutherford, 1995). The model was developed to examine climate and energy policy applications such as those in Reilly *et al*. (1999), Paltsev *et al*. (2003), Babiker, Reilly and Metcalf (2003), Reilly and Paltsev (2007), Paltsev *et al*., 2007, and CCSP (2007).

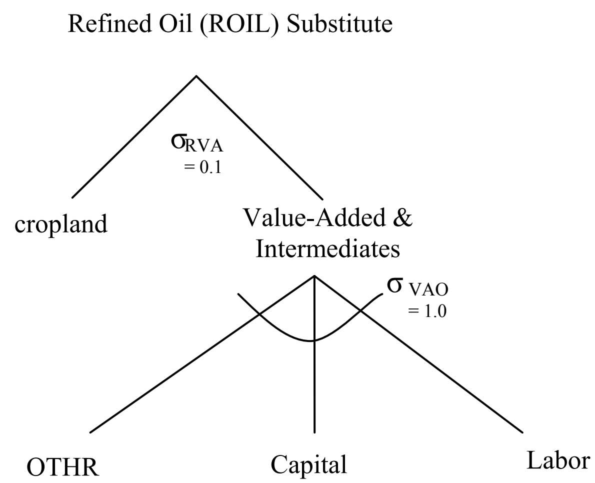
Given the focus on energy and climate change policy, the EPPA model uses additional exogenous data to disaggregate the GTAP data for transportation to include household transport (i.e. personal automobile), the electricity sector to represent existing supply technologies (e.g. hydro, nuclear, fossil), and includes several alternative energy supply technologies (e.g. shale oil, wind/solar, biomass) not extensively used or available in 1997 but that could potentially be demanded at larger scale in the future depending on energy prices and/or climate policy conditions. To represent such technologies, the model takes into account detailed bottom-up engineering parameters. The parameterization of these sectors is described in detail in Paltsev *et al*. (2005).

Future scenarios are driven by economic growth that results from savings and investments and exogenously specified productivity improvement in labor, energy, and land. Growth in demand for goods produced from each sector including food and fuels occurs as GDP and income grow. Stocks of depletable resources fall as they are used, driving production to higher cost grades. Sectors that use renewable resources such as land compete for the available flow of services from them, generating rents. These together with policies, such as constraints on the amount of greenhouse gases, change the relative economics of different technologies over time and across scenarios. The timing of entry of advanced technologies, such as cellulosic bio-oil, is endogenous when they become cost competitive with existing technologies.

3.2. Biomass technologies in EPPA

Bioenergy in EPPA is represented through two technologies whose production structure is shown in Figure 1: a liquid fuel production (Panel A) referred to with the shorthand “bio-oil”and electricity production (Panel B) referred to as “bio-electric”. Land is a renewable resource with five land types: crop land, pasture land, harvested forest land, natural grass land, and natural forest land. The crops sector and the two biomass sectors (liquids and electric) compete for cropland. Pasture land is used exclusively in the livestock sector, and harvested forest land is used exclusively in the forest sector. Natural grass land and natural forest land

Panel a. Bio-oil



Panel b. Bio-electric

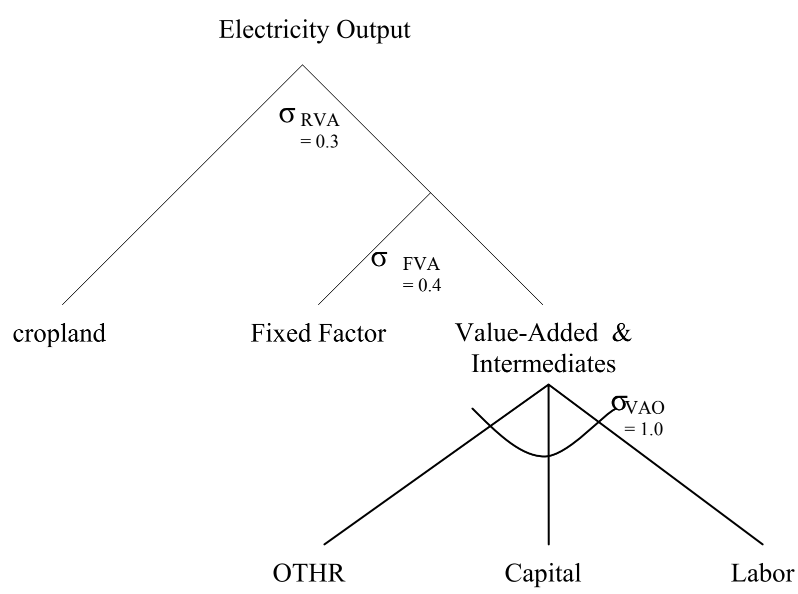


Figure 1. Structure of Biotechnology Production Functions for (a) Bio-Oil and (b) Bio-Electric

enters the utility of the representative agent, for which it has "non-use" value. Transformation among these types is detailed in Section 3.3. Other land types—tundra, wetlands, deserts, and built-up areas—are not explicitly represented in the economic model. In the economic data land in built up areas is part of the capital stock and returns are not distinguished from returns to capital. The structure of these sectors is unchanged from that described in detail in Reilly and Paltsev (2007).

This structure collapses the crop production and biofuel transformation into a single sector, accounting for input use at all stages in a single production function.[1] Also as pointed out earlier, the intent here is to model a "second generation" cellulosic production process. In considering input requirements, the crop "implicit" in the parameterization is a high biomass producing crop such as switch grass, rather than a grain, sugar, or oil seed crop that is more expensive, produces a lower energy yield per unit of land, and uses more fertilizer and other inputs. On the other hand, the input costs also reflect the higher cost of conversion than for conventional ethanol production. As Reilly and Paltev (2007) have pointed out, current corn and soybean based biofuel liquid production potential is relatively limited and usually can release nearly as much CO_2 as is offset when the ethanol is used to replace gasoline. Potential production from these sources is too limited to ever play a role much beyond that of producing enough ethanol to serve as an oxygenating additive to gasoline. The most critical parameters in the production function formulation are the land input share, how process energy requirements are treated, and the overall cost mark-up relative to the existing technology; i.e. either gasoline or electricity. These are discussed below.

Also note that to the extent that ethanol production exists in the base year input-output tables, it is reflected in the inter-industry demands implicitly. In simulations of the model, this demand grows as the gasoline use grows so there continues to be a conventional ethanol industry that makes use of traditional crops. But this exists only implicitly in the existing I-O structure. To explicitly track this industry would require disaggregation of the make and use tables for these crops and for the existing industry that produces ethanol. Our approach is focused on the long-term, second generation technology and, for simplicity, leaves the conventional ethanol production implicit.

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[1] The firm structure of the actual economy—whether individual stages of production are done by separate firms or the entire process is vertically integrated—does not affect outcomes in a standard neoclassical representation of the economy. For our purposes, we have no particular reason to model a separate production function for the raw biomass and for the conversion process. This could be done as a separate sector, or as separate production nests within a single sector. In dealing with advanced technologies that are not fully described, there is limited information on which to establish the values for many different parameters and so elaborating the structure in great detail can suggest false precision.

The parameters used to specify the biomass technologies are presented at Table 2. Here the detail on land types has allowed us to improve the representation in Reilly and Paltsev (2007). We assume the basic production and conversion technology is the same across regions but the land share varies regionally. The land value share required for bioenergy is determined on the basis of the value of crop land per unit area and the physical productivity of the land in terms of biomass productivity measured in oven-dry-tons (odt) which is then directly convertible to gigajoules (GJ) of energy. In this way we are able to parameterize the CGE model in a way that is consistent with supplementary physical land data in GTAP (Lee *et al*., 2005) and energy use tables, assuring that the implied efficiency of production and conversion of biomass and fuels is consistent with agro-engineering data. The USA is taken as the reference region. The main significance of this is that the input shares, including land, add up to 1 in the USA. When input shares add to 1 the technology is competitive with the reference technology (i.e. gasoline) in the model base year of 1997. However, we then apply a mark-up, a factor by which input requirements are multiplied, in order to represent how the cost differs from the reference technology in 1997 following a convention adopted for the addition of other new technologies in the EPPA model (see Paltsev, et al., 2005).

Table 2. Parameters used for Biomass Technologies

		Input Shares			
Supply Technology	Mark-up Factor	Capital	Labor	OTHR	Fixed Factor
Bio-oil	2.5	0.39	0.09	0.12	--
Bio-electric	1.4	0.33	0.1	0.13	0.04

Land Input Shares in Both Technologies (Regionally Specific)

USA	CAN	MEX	JPN	ANZ	EUR	EET	FSU
0.4	0.3	0.8	0.9	0.3	0.6	0.3	0.3
ASI	CHN	IND	IDZ	AFR	MES	LAM	ROW
0.65	0.3	0.3	0.7	0.12	0.9	0.16	0.45

The mark-ups of 2.5 for bio-oil and 1.4 for bi-electric are applied to all factors, and are based on cost estimates in Hamelinck *et al*. (2005). For the USA this implies that the cellulosic conversion technology is 2.5 times more expensive than gasoline in 1997. Gasoline sold for about $1.25 per gallon in 1997 according to the Energy Information Administration (in 1997 $) implying cellulosic conversion costs of about $3.12/gasoline-gallon-equivalent[2] for land prices in

[2] The comparison here is in terms of the equivalent energy content of gasoline (116,090 BTUs/gallon). Ethanol has 76,000 BTUs per gallon, and to be competitive as a fuel, the per gallon price of ethanol must be 76,000/116,900~2/3 that of gasoline. Much of the market for ethanol in the US in the past few years was driven by its use as an oxygenating additive to

1997. Inflation from 1997 to 2006 was about 22% according to the Economic Report of the President (CEA, 2007), and so in today's prices the breakeven price would have be about $3.81/gallon. The real price of farmland, again according to the Economic Report of the President (CEA, 2007), rose 78 percent between 1997 and 2005, thus adding another $0.31 (increasing the land cost from $0.40 to $0.71) and effectively the break even cost is on the order of $4.00. Thus, even with the high petroleum and gasoline prices, the technology, if it were fully demonstrated would not, according to this parameterization be competitive today.

Because land prices and productivity vary regionally, the factor shares do not add up to one in non-USA regions which implies that the cellulosic biomass technology is more or less competitive in other regions owing to difference in land cost and productivity. Regions with relatively higher prices for cropland, such as Japan, have larger value shares for land in the production function. On the other hand, land costs are relatively low in LAM and AFR reflecting some combination of low land rents and/or high biomass productivity.

For land rent data we make use of Lee *et al*., 2005 which was developed for the purpose of providing a correspondence between physical quantity of land and its rental value in the economic data in the GTAP dataset. For data on biomass productivity we begin with the IPCC (1996, 2001) and Moreira (2004) that report maximum biomass productivity under current conditions of between 10 and 15 odt/ha/year with the possibility of reaching 30 odt/ha/year by the end of the century. The region with highest energy potential of land-based biomass in those studies is the Central and South America (LAM) EPPA region. We thus assume that the current potential of the LAM region is 15 odt/ha/year and a rate of productivity increase that raises this to 30 odt by 2100. Region-specific productivities in odt of biomass per hectare (ha) are based on estimates from Chou *et al*. (1977), Edmonds and Reilly (1985), and the more recent work of Bot *et al*. (2000) taking account of growing season limits either because of cold temperatures or lack of rainfall. The potential of other regions expressed as a fraction of LAM are: IDZ: 0.9; ASI: 0.61; IND: 0.8; USA, MEX, EUR, EET, CHN and ROW: 0.5 to 0.6; ANZ, FSU, MES and AFR: 0.3 to 0.4; CAN: 0.2. These fractions reflect climatological differences among the regions.

Our interest in biofuels as a renewable fuel option leads us to make an assumption that all energy required in the biofuels production process comes from biomass. This is enforced by assuming 40% conversion efficiency from biomass to a liquid energy product. For example, LAM is able to produce biomass at 15 odt/ha/year with a heating value of 20 GJ/odt. This corresponds to

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gasoline, rather than as energy value, and for that use the market price is driven by supply and demand factors in the additive market and is not related to the energy content of gasoline or the gasoline price. If ethanol is to expand beyond the additive market, the price must compete with gasoline on energy content as it does in Brazil where ethanol is a larger share of the fuel supply.

300 GJ/ha/year, what can be transformed to 120 GJ/ha/year of liquid (or electricity) energy product. Reported results for physical biofuel is the energy content of the final liquid (or electricity). Internal supply of energy for conversion of ethanol actually reflects the practice for current ethanol production in Brazil where the bagasse provides an energy source for distilling ethanol produced from sugar cane.

3.3. Modeling land use conversion in EPPA

The main version of the EPPA model has just one aggregate agriculture sector, which uses a single land category as a factor specific input. To address biomass potential and limitations, we have developed a version of the model where the agriculture sector is further disaggregated into three different sub-sectors: crops, livestock and forestry. Land is then divided among the 5 types discussed in the previous section.

Each land type is a renewable resource whose quantities can be altered through conversion to another type or abandonment to a non-use category. Land is also subject to exogenous productivity improvement set at 1% per year for each land type, reflecting assessment of potential productivity improvements (Reilly and Fuglie, 1998) that show historical crop yields to grow by 1% to 3% per year. Regarding land use transformation, land area of one type can be expanded by conversion of land of another type. For example, roads and access to natural forestry area can be developed and the land harvested and then replanted as managed forest land, or cleared for pasture or cropland. The opposite direction can also be observed, i.e., cropland can be abandoned to re-grow secondary forests or reorganized as managed pasture or managed forest land.

Integrating land use conversion into the CGE framework has two key requirements: (1) that we retain consistency between the physical land accounting and the economic accounting in the general equilibrium setting, and (2) that we develop the data in a manner that is consistent with observation as recorded in the CGE data base for the base year. Failure on the first account would mean that we could not consistently ensure that the physical accounts “add up.” Simulated economic land use in value terms in the CGE model would imply that either more land than existed in a region was being used or that some of it was not accounted for at all. Failure on the second account would mean that the base year data would not be in equilibrium and so the model would immediately jump from the base year to the equilibrium state consistent with parameterization of land rents and conversion costs.

The first of these conditions is achieved by assuming that 1 hectare of land of one type is converted to 1 hectare of another type, and through conversion it takes on the productivity level of the average for that type for that region. It is in that sense that cropland, pastureland, and managed forest land are "produced." The second of these conditions is achieved by observing that in equilibrium the marginal conversion cost of land from one type to another should be equal to the difference in value of the types. We require that conversion uses real inputs through a land transformation function as in Figure 2. The dashed line at the top indicates a fixed coefficient multi-product production function that produces, in addition to accessible cleared land, a forestry product (i.e. timber and other forestry products) that is a perfect substitute for output of the forestry sector.

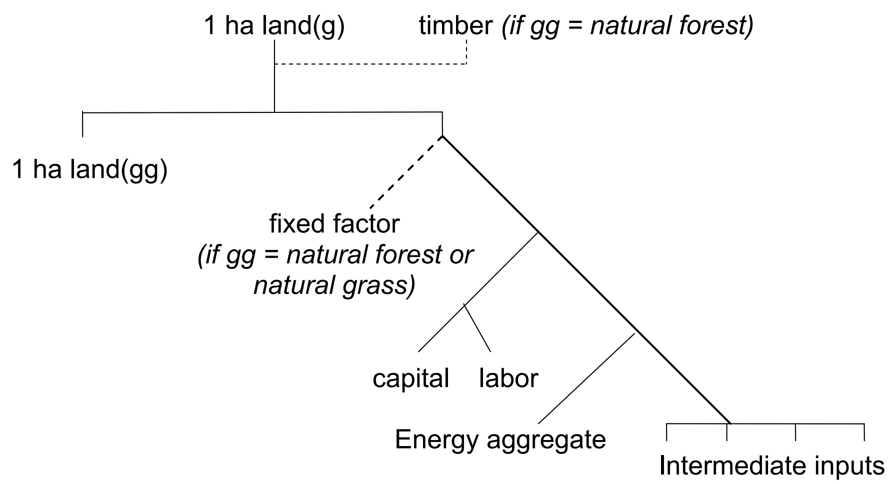

Figure 2. Structure of Land Transformation Functions

We also implement two versions of the model illustrated with the lower dashed fixed factor input: One version, without the fixed factor, allows unrestricted conversion of natural forest and grass land (as long as conversion costs are covered by returns) which we label as the Pure Conversion Cost Response (PCCR) model. The second version, with the fixed factor, allows us to parameterize the elasticity of substitution between it and other inputs to represent observed land supply response. We label this version the Observed Land Supply Response (OLSR) model. These two versions capture what might be considered extremes. The OLSR version assumes the response we see in land conversion in recent years is representative of the long-term response. The PCCR version assumes there is no such elasticity, and that conversion will proceed unhindered as long as the value of converting land is greater than the cost. We suspect that the truth lies in between, and explore consequences of each, allowing the reader to judge which approach is a better representation.

Abandonment of land with return to natural conditions is also possible. Should that happen we assume it occurs costless, and that any investment in conversion is fully depreciated—if at some distant date in the future there was reason to convert it back the cost of conversion would be borne again.

As noted earlier, Lee *et al*. (2005) provide the data on land rents. These are aggregate rental values for all land of each type. These must be considered “use” values as they come from national economic statistical agencies that represent actual monetary transactions or in the case of land an inferred payment that must be consistent with data on revenue, input costs and returns to other factors. Thus, it is inappropriate to attribute these rental values to lands that are not in current use such as unmanaged forest and grassland. To get per hectare rents the aggregate rental data needs to be divided by the physical quantity of land, but to be comparable to observed rents the physical quantity can include only that land that is used on some regular basis. To separate out unmanaged land that is not producing any current income flow we use the data base of Hurtt *et al*. (2006), which is an elaboration of the underlying physical data used in Lee *et al*. (2005). From this data set we get the areas of natural grassland, natural forest and other land (tundra, built up land, wetlands, and desert). These broad classes of land are also sometime referred to as “land cover”. Table 3 presents the land cover data for each EPPA region, measured in Mha.

While conversion costs from managed forest to cropland and pasture, or from pasture to cropland, is by our equilibrium assumption, equal to the difference in value of these types, we have no information on the “value” of land not currently in use, or the cost of conversion. A particular issue for unmanaged forests is that these by definition include a large stock of standing timber that is potentially very valuable. In contrast, land in the managed forestry sector will be at various stages of a rotation—assuming for simplicity that an optimal rotation is 30 years then only on the order of one-thirtieth of the area is harvested in any one year.

To get estimates of the land conversion/access costs and the potential value of the land we use data from Sohngen *et al.* (in press), and available from Sohngen’s website (Sohngen, 2007). Following assumptions similar to ours, he deduces conversion costs from equilibrium conditions. In particular, he assumes that at the margin the cost of access to remote timber lands must equal the value of the standing timber stock plus that of future harvests as the forest regrows. He then calculates the net present value using his optimal timber harvest model for each region of the world and for different timber types. Setting the access costs to this value establishes the equilibrium condition that observed current income flow (i.e rent and returns) from currently unaccessed land is zero because the timber there now and in the future can only be obtained by bearing costs to access it equal to its discounted present value.

Table 3. Land Cover by EPPA Regions (Mha)

	Pasture	Cropland	Managed Forest	Natural Grass	Natural Forest	Other Land	TOTAL
USA	119.2	186.6	119.4	98.4	263.8	174.3	962
CAN	12.1	52.8	34.6	11.1	333.3	574.9	1019
MEX	59.6	21.9	45.6	15.8	52.2	8.6	204
JPN	0.6	4.6	10.3	0.0	25.7	0.5	42
ANZ	301.2	22.5	38.6	52.3	190.8	22.1	628
EUR	43.2	87.5	67.7	21.8	96.1	88.9	405
EET	10.9	49.5	20.0	2.4	4.5	3.6	91
FSU	294.4	272.9	90.8	68.0	756.0	536.2	2018
ASI	0.1	46.5	6.1	6.6	74.4	4.2	138
CHN	184.8	199.5	53.3	60.3	185.3	256.3	939
IND	6.2	177.0	31.1	12.7	77.0	17.4	321
IDZ	4.9	25.6	7.3	0.4	142.8	26.5	208
AFR	744.4	160.8	290.2	296.7	497.4	1031.4	3021
MES	183.2	13.7	14.5	96.1	68.0	147.9	523
LAM	377.9	158.3	202.9	149.9	749.0	236.0	1874
ROW	149.7	119.3	31.3	99.6	191.9	272.5	864
TOTAL	2493	1599	1064	992	3708	3401	13257

Source: Underlying data based on Hurtt *et al.* (2006), here summarized by EPPA region

We make use of his data and some simplifying assumptions to calculate an average standing stock of timber for each of our regions and the value of the land. In particular, we observe that:

$$NPVofVirginForest = X_0 + \sum_{t=1}^{\infty} \frac{X_t}{(1+r)^t} \qquad (1)$$

where X_0 is the value of the standing timber stock on the virgin forest, X_t is the value of future harvests and r is the interest rate. The value of future harvests we take to be the value of land once the timber stock is gone: i.e. the value of the land rests in its ability to produce future harvests. We assume that future harvests are some fraction, θ, of X_0.[3] Sohngen (2007) also provides the optimal rotation length for these lands.

Assuming optimal rotation once the virgin forest is harvested means that X_t=0 in every year except when there is a harvest. Recognizing this fact allows us to rewrite equation (1) where we define the time period to be of length equal to the optimal rotation, and then make the value of *r* consistent with that time period length. For example, for an optimal rotation of 30 years, t=1 will occur when 30 years have passed, and t=2 when 60 years have passed, etc. Assuming an

[3] As a first approximation we assume θ=1.

interest rate of 5% per annum means that r= 1.05^{30}-1= 3.32. This allows us to rewrite equation 1 as:

$$NPVofVirginForest = X_0 + \sum_{t'=1}^{\infty} \frac{\theta X_0}{(1+r)^{t'}} \qquad (2)$$

where t' is the time index where a period is of length equal to the optimal rotation for the forest which varies by region. With future harvests kept constant (independent of t) and recognizing that infinite discount factor is just 1/r, equation 2 can be solved for X_0:

$$\frac{NPVofVirginForest}{1 + \theta / r} = X_0 \qquad (3)$$

This allows us to deduce from the Sohngen (2007) data the value of stock of timber in virgin forests, and for CGE purposes the quantity, in value terms, of timber when it is harvested. The residual value is then the value of future timber harvests—i.e. the value of the land. Sohngen (2007) provides the areas in each type of forest, the NPV, and optimal rotation. Since we have only one "unmanaged" forest land type, we calculate a weighted average among different types for each of our regions. We do not have similar data for natural grassland, which obviously does not have a timber stock on it. We assume that natural grassland rent relative to pasture is the same as rent of natural forest relative to managed forest. The resulting regional land rents by land class are shown in Table 4.

To calibrate the land conversion function of natural forests to harvested forests in the base year we need to split the forestry output and their land requirements in two: the value of production from managed forest land and the value of production from clearing natural forests. Sohngen (2007) provides information on total hectares occupied by forestry plantations, the annual forest area harvested and changes in the area of forests (plantation and natural) by region. The output share from natural forest areas can be quite large even though the land amount in any one year is small relative to the managed forest area because the stock of timber on natural forest land is large: by definition all of it is being harvested that year whereas much of the managed forest land is in some stage of regrowth and not yet harvestable. We use these shares to re-benchmark the output of the forestry sector and its land requirements and also to assign the value of timber production from the conversion of virgin forest.

Table 4. Land Rents per hectare at Regional Level (1997 US$/ha)

	Pasture	Cropland	Managed Forest	Natural Grass	Natural Forest
USA	42.8	193.2	2.5	6.8	0.4
CAN	36.4	52.3	19.5	0.0	1.0
MEX	13.2	358.7	6.6	0.8	0.4
JPN	1140.1	1705.1	29.2	0.0	10.5
ANZ	4.1	102.3	7.8	0.7	1.4
EUR	131.8	405.5	9.3	63.3	4.5
EET	91.9	115.8	15.0	44.1	7.2
FSU	4.6	30.0	3.3	1.0	0.7
ASI	88.5	494.6	49.7	0.0	17.4
CHN	13.9	221.7	12.7	0.8	0.8
IND	447.1	212.3	15.9	0.0	1.6
IDZ	122.1	547.8	55.4	18.3	8.3
AFR	2.1	45.7	2.0	0.1	0.1
MES	4.3	251.0	20.7	2.1	10.4
LAM	14.3	142.1	1.5	1.3	0.1
ROW	18.7	193.5	21.9	2.1	2.4

The above data completely parameterizes the PCCR model version. The OLSR version requires an elasticity of substitution between the fixed factor and other inputs represented in Figure 2. We parameterize it to represent observed land supply response in the 1990s to present. Underlying this response may be increasing costs associated with specialized inputs, timing issues in terms of creating access to ever more remote areas, and possible resistance to conversion for environmental and conservation reasons that may be reflected in institutional requirements and permitting before conversion.

We calculate the own-price land supply elasticity for each region in the following manner. We observe the average annual percentage land price increase from 1990 through 2005 and the average annual natural forest area converted to managed land as a percentage of managed land over the same period which allows calculation of the elasticity of supply (ε_S) using the definition:

$$\varepsilon_S = \frac{\%\Delta Q}{\%\Delta P} \tag{4}$$

where Q and P are land quantity and price, respectively. We follow Hyman *et al.* (2002) to determine the relationship between the elasticity of substitution (σ) and the elasticity of supply:

$$\sigma = \frac{\varepsilon_S}{1-\alpha} \tag{5}$$

where α is the cost share of the fixed factor.

For the land price changes we consider data from 1990 to 2000 for the US from the Economic Report of the President (CEA, 2007). Land price data are not easily available in much of the world but because of global commodity trade we expect similar price movements of land globally. Beyond this theoretical argument, evidence that land prices move in parallel internationally are provided by Sutton and Web (1988). Based on this assumption, we use the US percentage price change for all regions. Average annual conversion rates of land over the 1990s are derived from the land cover database of Hurtt *et al.* (2006).

Table 5 presents the parameters associated with the natural forest land parameterization including the share of forest product from managed and natural forests, the share of land converted, our calculated elasticity of supply of land based on equation 4, and the elasticity of substitution from equation 5.

Table 5. Parameters to Model Natural Land Use Transformation Functions

	Share of forestry output from cleared natural forest	Share of natural forest land being cleared out of total land used to produce forestry output	Elasticity of land supply	Elasticity of substitution among fixed factor and other inputs
USA	0.10	0.004	0.12	0.120
CAN	0.05	0.001	0.12	0.120
MEX	0.20	0.031	0.60	0.609
JPN	0.05	0.008	0.12	0.121
ANZ	0.09	0.014	0.12	0.122
EUR	0.05	0.002	0.12	0.120
EET	0.14	0.007	0.12	0.120
FSU	0.05	0.001	0.12	0.120
ASI	0.80	0.214	0.38	0.382
CHN	0.05	0.003	0.15	0.150
IND	0.10	0.011	0.31	0.312
IDZ	0.68	0.231	0.60	0.613
AFR	0.48	0.235	0.60	0.617
MES	0.05	0.017	0.32	0.326
LAM	0.20	0.027	0.60	0.603
ROW	0.36	0.151	0.42	0.430

While the land supply elasticity is estimated very simply, we note that Sohngen and Mendelsohn (2007) use a land supply elasticity of 0.25 in their forest modeling study, conducting sensitivity analysis for elasticities of 0.13 to 0.38 arguing that these are representative of the range in the literature. The average global response we would get from our regionally varying elasticities is well within this range. Our approach based on observed conversion rates has the advantage of giving us variation in regional response consistent with recent data, and the general observation of a greater willingness to convert land in tropical developing countries than in developed regions.[4]

4. Results

4.1 Scenarios

We use the alternative OLCR and PCCR land conversion formulations of the extended version of the EPPA model to implement two alternative future scenarios in order to investigate the potential, limitations and impacts of large scale "second generation" biomass technologies. The first scenario is the reference or business-as-usual (BAU), where there is no attempt to control greenhouse gases emissions. In this scenario biomass production enters because dwindling supplies of high grade crude oil drive up the oil price to make cellulosic ethanol competitive. The second scenario simulates a global effort to control greenhouse gas emissions that starts with the Kyoto Protocol, and intensifies emissions reductions in succeeding years. The GHG policy scenario follows Paltsev *et al*. (2007) and reflects a path whereby developed countries would gradually phase in a 50% reduction in emissions by 2050, like that suggested in recent G8 meetings and consistent with proposed goals in Europe and in pending Bills before the US Congress. Developing countries delay their mitigation action until 2025, and intensify reductions in 2035.[5] The result is to limit global cumulative GHG emissions to about 1,490 billion metric tons (bmt) from 2012 to 2050 and 2,834 bmt from 2012 to 2100. Those numbers are equivalent to 60% of the emissions in the BAU scenario in the period from 2012 to 2050, and 40% over the full period. The cumulative level of GHG emissions is approximately consistent with a frequently discussed 550 ppm CO_2 stabilization goal. The policy is implemented as a cap and trade policy in each region, which limits the amount of fossil fuel that can be used, and thus provides economic incentive for biofuel and other low carbon energy sources.

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[4] Some regions had virtually no conversion in the historical data. For these regions we assigned an elasticity of 0.12.

[5] See Paltsev *et al*. (2007), p. 49, Table 12. The scenario constructs a linear time-path that reduces greenhouse gases from present levels to 50% below 1990 levels by 2050 in US, Europe, Japan, Canada, Australia and New Zealand (the 203 bmt path in Paltsev *et al.* (2007) paper). The other regions in the model begin mitigation policies in 2025, reducing emissions to their 2015 levels through 2034, and then reducing them to 2000 emissions levels in 2035 to 2050. There is no international trade in allowances. Paltsev et al. (2007) provide other results such as CO_2 and energy price effects.

4.2 Global and regional biofuel production

The global production of advanced biofuels in both scenarios, in terms of energy, is presented in Figure 3. The bioenergy production in the reference case is below 16 Exajoules (EJ) per year until 2040, after which it grows rapidly reaching 221 EJ by the end of the century for the observed land supply response (OLSR) model and 267 EJ in the pure conversion cost response (PCCR) model. The driving factor for biofuels penetration in the BAU is the world oil price which rises by a factor of four from the base year level of around $25/barrel. Under the CO_2 policy cases, the expansion of biomass energy starts much sooner, around 2025, and reaches 320 EJ in 2100 in the OLSR model and 368 EJ in the PCCR model. Virtually all of the bioenergy is liquid fuel. Bioelectricity represents much less than 1% of total energy from biomass. The reason is that, at least as represented in the EPPA model, there are other low carbon options for electricity generation (e.g. fossil fuel power generation with carbon capture and storage) but no other low carbon alternatives in transportation. Demand for biofuels in transportation then makes biomass too expensive to compete in electric generation.

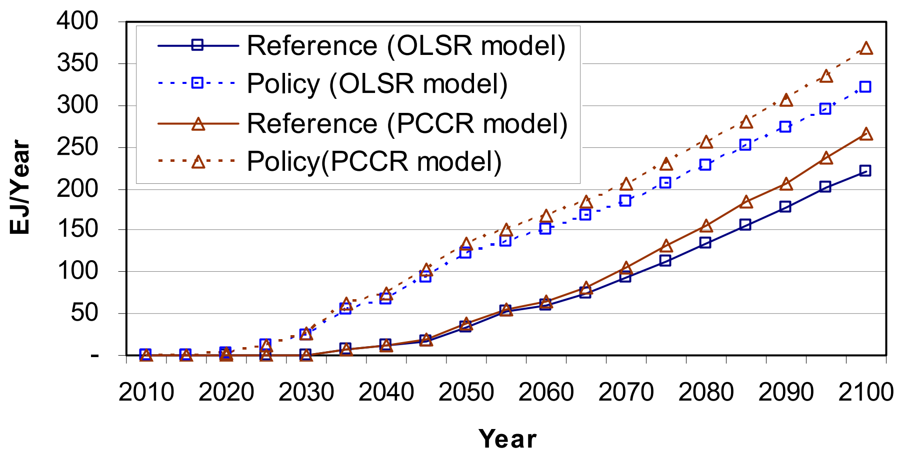

Figure 3. Global Biomass Production

Comparing the results under alternative modeling assumptions, bioenergy production is 10% to 20% greater with the PCCR model assumptions owing to the greater flexibility in conversion of natural lands. While limiting conversion has some effect on the biofuels production levels it does not put as strong a damper on production as we expected. Reasons for this are explored below.

Table 6 presents the biomass production in selected regions in EPPA, with other regions aggregated. Central and South America (LAM) together with Africa

(AFR) are the two most important regions supplying biomass. In both regions land availability is crucial to achieving these production levels. The greater land productivity in biomass crops allows LAM to supply between 45% and 60% of world production for most of the model horizon. The US is the third largest world producer, supplying between 33 and 36 EJ of biomass in 2100 in the policy case. Mexico (MEX), Oceania (ANZ), and the aggregate of rest of the world (ROW), which includes several countries in tropical areas of South Asia, are also able to produce large amounts of biomass in the policy scenario. The contribution to biomass production from others is very small (~1% of world production) in the reference case. In the policy case the contribution of other regions reaches as much 4% of the world production with the PCCR model assumptions. An important factor driving the regional results is that we allow unrestricted trade of biofuels, a homogeneous good, which tends to lead to specialization of production in LAM and AFR where the land input is least costly. This low cost results from a combination of low land prices and high biomass productivity per hectare. An implication of this is that regional production of biofuels is mostly insensitive to where the demand for them develops. The global demand will be supplied by those regions with the lowest cost of production. Only when biofuels production in a low cost region causes land prices in the region to rise enough so that the cost of biofuels rises and makes other regions competitive will we see production expand in other regions. Reilly and Paltsev (2007) and Paltsev, et. al (2007) consider a wider range of climate policy scenarios, and scenarios that restrict trade in biofuels such that domestic use must be produced domestically. Clearly, policies that block or distort trade will change where biomass is produced, and as shown by Reilly and Paltsev (2007) such policies can then have implications for trade in other agricultural products.

The regional implications of the OLSR and PCCR model versions are driven by multiple forces. The OLSR version would, in a closed economy, mean less conversion than with the PCCR version and we generally see that result, but for individual regions such as MEX and ANZ there is actually more biofuel production in the OLSR model version. The relatively high land supply elasticity likely contributes to this response in MEX, while in ANZ the relatively open markets in agricultural trade allow greater flexibility to produce fuel and reduce

Table 6. Regional Biomass Production, EJ/year, Selected Regions.

Reference Scenario														
	USA		MEX		ANZ		LAM		AFR		ROW		Others	
	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR
2010	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2030	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2040	0	0	0	0	0	0	1	1	11	11	0	0	0	0
2050	0	0	0	0	0	0	17	19	18	20	0	0	0	0
2060	0	0	0	0	0	0	32	34	28	30	0	0	0	0
2070	0	0	1	0	0	0	53	63	38	42	0	0	0	1
2080	4	6	3	1	0	0	77	93	51	55	0	0	0	1
2090	10	11	4	2	0	0	99	120	64	70	0	2	0	1
2100	16	17	5	2	0	0	121	155	79	87	0	3	1	2

Policy Scenario														
	USA		MEX		ANZ		LAM		AFR		ROW		Others	
	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR
2010	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2020	0	0	0	0	0	0	0	0	2	2	0	0	0	0
2030	1	0	0	0	1	1	4	3	19	19	0	2	0	2
2040	4	4	2	2	2	2	26	22	30	30	3	6	2	9
2050	13	16	4	4	4	3	54	53	41	39	5	9	1	10
2060	17	21	4	4	6	2	71	73	48	46	5	9	1	11
2070	20	25	5	5	8	4	87	96	58	58	6	10	1	10
2080	24	28	6	6	11	5	107	124	71	72	8	11	2	10
2090	28	32	7	7	13	7	127	153	85	86	10	13	3	9
2100	33	36	8	7	16	8	147	186	98	101	12	15	6	14

exports of food.[6] LAM represents the expected result that biomass production is larger in the PCCR version. This region has the largest stock of natural forest available and the highest productivity in biomass production. If natural land can be easily converted to agriculture in this region, it will be able to answer to the demand by imposing strong pressure to convert natural forests. However, if the costs of deforestation are high enough and these are reflected in economic, environmental and institutional barriers captured in the land supply elasticity then capacity to supply biofuels decreases somewhat.

4.3. The biofuel contribution to global energy supply

The energy from biomass is an important component of world energy consumption as shown in Figure 4. In the OLSR model biofuels account for

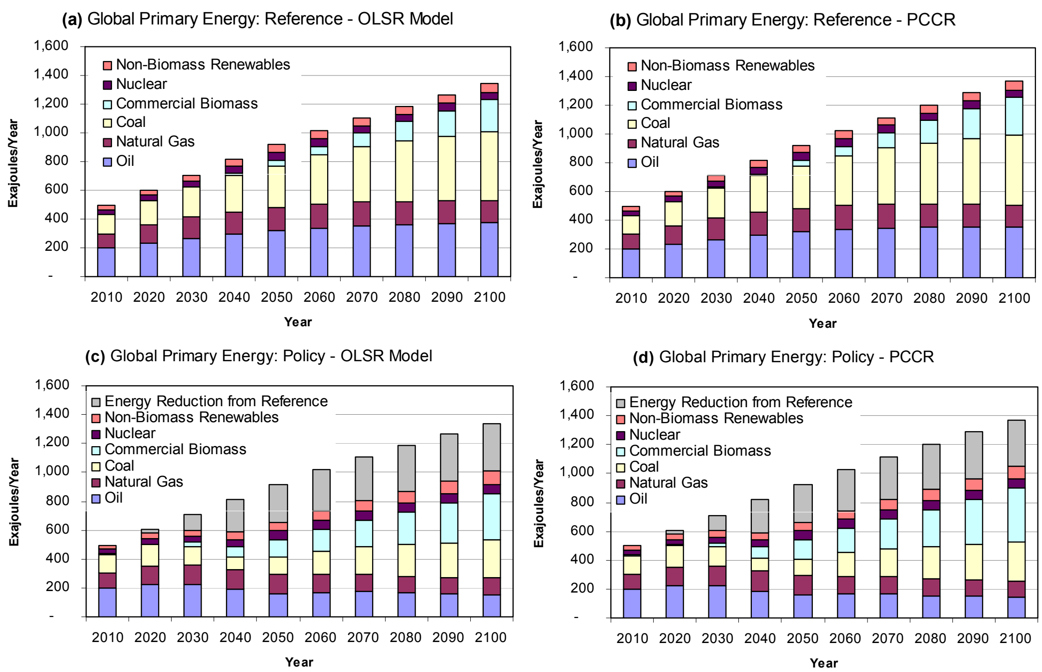

Figure 4. Global Energy Demand: (a) reference case – OLSR model, (b) reference case – PCCR model, (c) policy case – OLSR model, (d) policy case – PCCR model.

[6] International trade is represented with the Armington trade assumptions in EPPA using CES functions, except for crude oil and liquids from biomass, which are homogenous products. Armington elasticities are assumed identical across regions but the share preserving nature of the CES functions means that regions that have little trade in the base year do not expand or contract agricultural trade very much, whereas a change in the trade share of 10 or 15% in a region where trade is 20 or 30% of production in the base year will have much bigger absolute effect.

almost 17% of primary energy demand in the reference case in 2100, and 32% in the policy case. With the PCCR version 20% of the primary energy is supplied by biomass in the reference at the end of the model horizon, and 35% in the policy case. The larger share of biomass in the policy case is due to the replacement of the oil production, since bio-fuels are the only low carbon alternative in transportation in the model. However, even with biomass production energy prices rise, reducing global energy demand in the policy case from the BAU by about 28% (260 EJ) in 2050 and 24% (325 EJ) in 2100 under both the OLSR and PCCR model versions.

4.4. Land use implications

The large amount of biomass energy has significant implications for global land use as shown in Figure 5, and this is where we see greater differences in the OLSR and PCCR model versions. In total, the land area in our 5 land types is 9.8

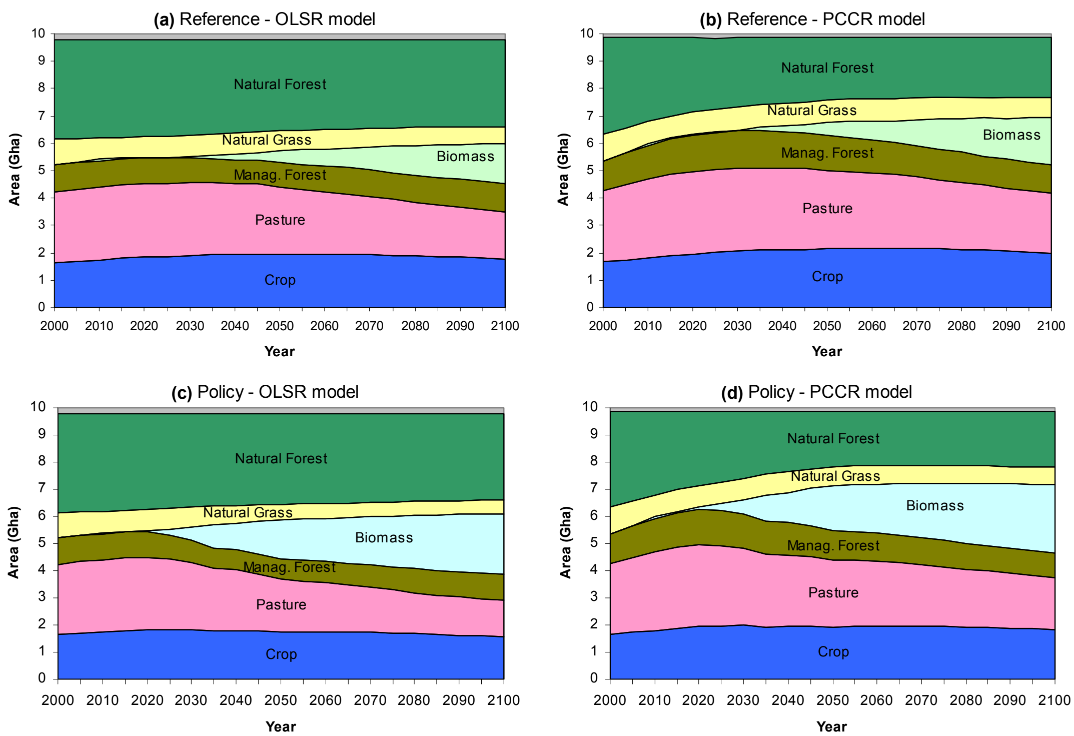

Figure 5. Global Land Use: (a) reference case – OLSR model, (b) reference case – PCCR model, (c) policy case – OLSR model, (d) policy case – PCCR model.

Gha, but the use of this land changes considerably from 2000 to 2100[7]. 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 BAU, and from 2.24 to 2.52 Gha in the policy case. This compares with 1.6 Gha currently in cropland. Biofuels production at this level thus has major consequences for land use on a global scale.

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 its original 3.7 Gha to 2.2 Gha in the reference scenario, and to only 2.0 Gha in the policy case, a 40% reduction in natural forest area. In contrast, the OLSR model shows much less reduction in natural forest area with a big reduction in pasture land. Thus, this version of the model makes room for biofuels production by greatly intensifying production on existing agricultural land, especially pasture land.

In both model versions natural forest and pasture land are the land types most reduced to make room for biofuels, with land in crops, managed forest, and natural grassland showing little net change. We note that the model formulation allows us only to project the amounts in each type in each region. We do not explicitly track whether, for example, specific parcels of land that were pasture land became cropland while other cropland was converted to biomass production. If equal amounts of land were converted to cropland and from cropland the net change would be zero and that is all we see in our model projection.

Another aspect of the land cover transformation projected in Figure 5 is the low sensitivity of crop areas to 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, from 1997 to 2100. It reveals that the crop production and crop area is less affected by the biomass expansion, stemming from the relatively price inelastic demand for food.

Table 7 presents regional land requirements for biomass production. Large areas in Africa and Central and South America are devoted to biomass, reflecting the regional biofuel production levels in Table 6. Large areas with biomass crops are also observed in the US, Mexico, Rest of the World and Australia and New Zealand, especially in the policy case. This reflects the fact that 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, not surprisingly,

[7] We do not represent in Figure 5 the 3.2 Gha referred to in Table 3 as Other Land (land not available to agriculture), which by assumption remains unchanged.

exceptions to this overall pattern. Key aspects of the model that drive this result are growth of food demand and modeling of trade in biofuels and agricultural goods. Both India and China have increasing demand for food and relatively lower biomass land productivity than other regions. With regard to trade, we simulate trade of bio-oil as a Hecksher-Ohlin good while food and agricultural commodities are assumed to be Armington goods. The combination of strong growth of domestic food demand with these trade assumptions favors dedication of land to agricultural production to supply domestic food needs, and if necessary the importation of biofuels to meet a carbon dioxide reduction target.

Table 7. Global Land Area (Mha) Required for Biomass Production of 10% Compared with the BAU Scenario from About 2030/35 Forward.

Reference

	USA		MEX		ANZ		LAM		AFR		ROW		Others		TOTAL	
	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR
2010	34	37	0	0	1	1	1	1	1	1	1	1	15	22	53	63
2020	0	0	0	0	1	1	1	2	1	2	2	2	14	15	20	21
2030	0	0	0	0	1	1	1	31	1	0	3	3	8	14	13	19
2040	0	0	0	0	2	2	9	200	11	207	0	4	8	8	222	232
2050	0	0	0	0	2	2	117	377	135	325	0	3	8	11	419	476
2060	0	0	0	0	2	2	205	443	216	450	0	0	6	14	629	682
2070	5	5	10	0	2	2	303	493	360	558	0	0	5	23	830	948
2080	40	59	28	10	2	2	394	542	478	661	0	0	9	32	1078	1242
2090	87	96	37	15	1	1	457	578	560	760	0	24	13	35	1280	1491
2100	127	140	42	22	5	1	504	604	652	851	0	30	18	44	1454	1740

Policy

	USA		MEX		ANZ		LAM		AFR		ROW		Others		TOTAL	
	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR	OLSR	PCCR
2010	34	37	0	0	1	1	1	1	1	1	1	1	15	22	53	63
2020	0	0	0	0	1	1	2	2	35	40	2	2	14	15	54	60
2030	12	0	0	0	24	24	31	29	386	383	3	33	10	35	466	504
2040	57	64	28	27	44	44	200	173	546	544	48	101	26	133	949	1086
2050	175	216	54	52	78	56	377	372	666	641	72	139	39	192	1461	1668
2060	201	250	59	58	104	43	443	459	694	671	62	124	29	186	1592	1791
2070	215	267	61	60	124	58	493	550	764	774	73	117	30	168	1760	1994
2080	232	275	63	67	152	77	542	641	851	870	83	120	39	172	1962	2222
2090	246	281	68	66	172	86	578	714	907	935	97	133	56	150	2124	2365
2100	258	287	70	64	185	91	604	785	943	997	105	133	75	165	2240	2522

4.5 Effects on agricultural prices and land rents

The impacts on global agricultural and industrialized food prices are shown on Figure 6. Because agricultural goods are Armington goods, each region has its own Armington price series. To simplify the presentation and to show the average effect on world prices we compute global price indices using the Walsh index[8] as described in IMF (2004). Note that we do not see directly the impact of biofuels on prices because we do not have a scenario without biofuels, however,

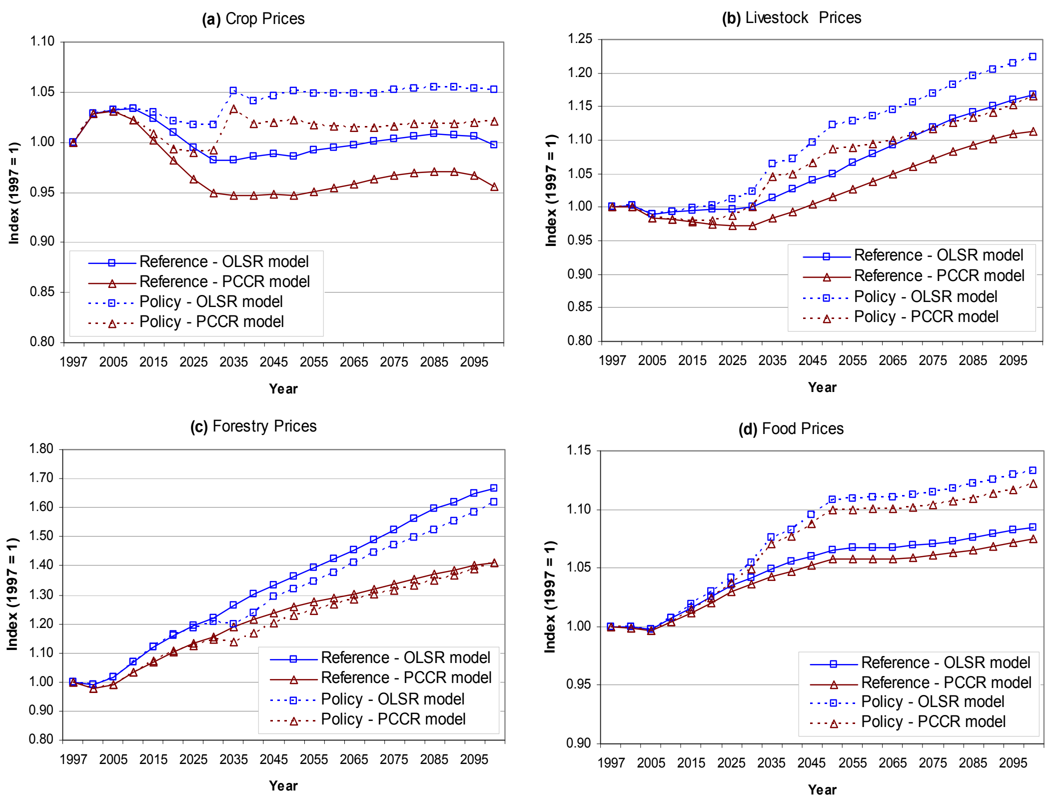

Figure 6. World Agricultural and Food Price Indexes.

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[8] The Walsh price index can be calculated from the formula:

$$P_W^t(p^0, p^t, q^0, q^t) \equiv \sum_{i=1}^{n} p_i^t \sqrt{q_i^0 q_i^t} \bigg/ \sum_{j=1}^{n} p_j^0 \sqrt{q_j^0 q_j^t}$$

where P_W is the Walsh price index as a function of prices p and quantities q at time 0 and time t. n represents the goods and services in the economy. In our case, we apply the index to each agriculture product and take n as the regions in EPPA. Other price indices (Laspeyres, Paasche, Fisher and Marshall-Edgeworth) give very similar results.

we can infer the impact of biofuels by comparing prices in the climate policy scenario and the BAU especially in the 2020 to 2050 period where the BAU has little biofuels and the climate policy scenario has a large biofuel production. Differences in commodity prices between these scenarios are thus mainly due to the biofuels industry that competes for available land.

The simulated price levels reflect the combination of increasing demand for food, fiber, and forestry products as GDP and population grow with our assumption of the increasing productivity of land. In the BAU we observe price increases in forestry and livestock products, while crop prices are little changed through the century. Forestry and livestock price increases likely reflect the competition for this land from biofuels that develop over the century and more rapid growth in demand for these products than for crops. With the climate scenario we see an increase in crops, livestock and food prices of about 5%. This corresponds to the time when biofuels production expands in the climate policy scenario, and thus is likely attributable to the biofuels competition for land. The OLSR model shows price increases of 2 to 3 percentage points more than the PCCR model, as a consequence of lower flexibility in the land transformation from natural areas to agricultural use.

The relative changes in prices of crops, livestock, and forestry reflect the share of land in the production of each and the fact that livestock are affected both by the increase in the pasture land rent and by the increase in crop prices. Also note that these are price indices, rather than absolute price levels. In a CGE framework prices are equal to the marginal cost of production by definition. Since total arable land is fixed, its rental value changes among scenarios more than other inputs. As shown in Figures 7 and 8 land prices move in parallel which is an equilibrium condition we expect given the conversion structure. Note also that the parallel movement means that the percentage increase in cropland is much less than the percentage increase in pasture and forestland. The crop price thus reflects the smaller percentage increase in cropland rent and the land rent share in crop production. The pasture land rent increase in percentage terms is much larger than the cropland increase, and this is reflected as a higher percentage increase in livestock prices. Similarly, the percentage land rent increase and the land share is much larger in forest products, translating into a much larger percentage price increase in forest products.

In many respects the impact of the biofuels industry on our simulated food and commodity prices is relatively small compared to recent price increases in corn that have at least been casually attributed to expansion of ethanol production in the US. For example, corn prices have risen by nearly 70% from September 2005 to September 2007. There are several important aspects of this comparison. One is that our simulation is for all crops and the potential impact on single crop can be greater. Our modeling also reflects longer run elasticities that give time for the sector to adjust, and over the longer term agriculture has proved very responsive to increasing demand and so our parameterization appears to capture that aspect of the sector. In fact, the current run-up in corn prices has led to a rapid response by farmers in planting more corn, and with more supply the price may retreat. We also expect less direct effect 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. In this regard, our simulations suggest that it is possible to integrate a substantial ethanol industry into the agricultural system over time without having dramatic effects on food and crop prices. And, it is even possible to do it without converting large amounts of natural forest if resistance to conversion is reflected in a land supply response as modeled in our OLSR model.

We present the impacts on land rents for the US in Figures 7 and for LAM in Figure 8, selecting these regions as representative of the land rent patterns we observe in the simulations. Here we see a substantial difference between the OLSR and PCCR models. In the PCCR model, rents to natural forest land rise substantially and this is the mechanism that eventually prevents even further deforestation. These are "non-market" or "non-use" rents because as the model is formulated the land has value to the representative consumer, entering the utility function directly. The increasing scarcity leads to increased value in the utility function. In the OLSR model the natural forest land value does not rise but the unwillingness to convert may in part reflect a societal value on preserving it. To the extent this unwillingness to convert the land actually is due to desire for preservation it would probably be more consistent to reflect that in a higher rental value of this land rather than only implicitly capturing this value through the land supply elasticity. As would be expected the PCCR model shows nearly parallel movements in prices for each type of land, with the possibility of conversion and abandonment assuring this result. If there is a tendency for the rent of one type of land to rise faster because of demand for that type of product more of that land type is "produced" from other land types, raising the rents of these land types and lowering the one that was originally in shorter supply. In the OLSR version of the model, the inability to freely convert from natural forest prevents this equilibration of rents for natural forest land. While the OLSR version is based on observed land supply response, the growing divergence in the value of natural forest land and other types is indicative of the strong pressure there would be to convert this land, and one might ask whether that pressure would be resisted if it persisted over the course of a century.

The change in rents in the two regions shows broadly similar results. In fact, the land price trends should be tied because of international trade. Modeling of biofuels as a Heckscher-Ohlin good should tie these very closely because trade in biofuels will tend to lead to factor price equalization (controlling for differences in land quality as reflected in biomass productivity). Land prices start out much lower in LAM, rise faster, and eventually catch up to rents in the US, reflecting the tendency toward factor price equalization.

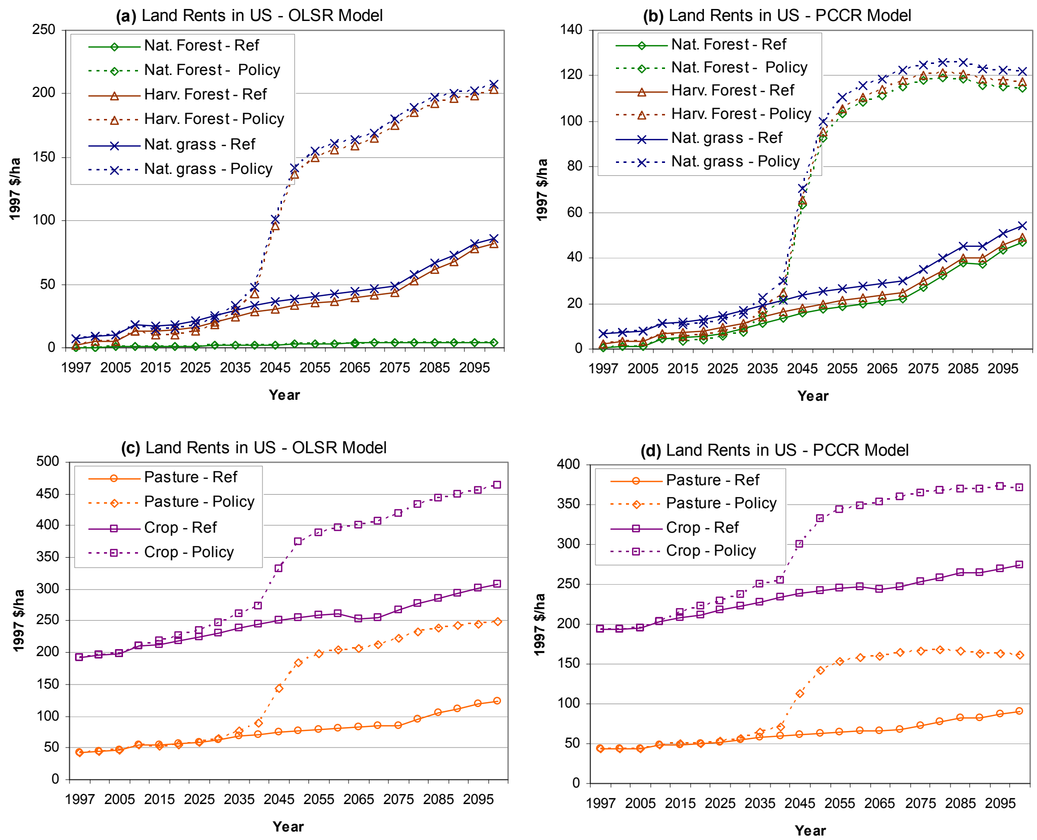

Figure 7. Land Rents in US: (a) natural areas and harvested forest - OLSR model, (b) natural areas and harvested forest - PCCR, (c) pasture and crop land - OLSR model, (d) pasture and crop land - PCCR.

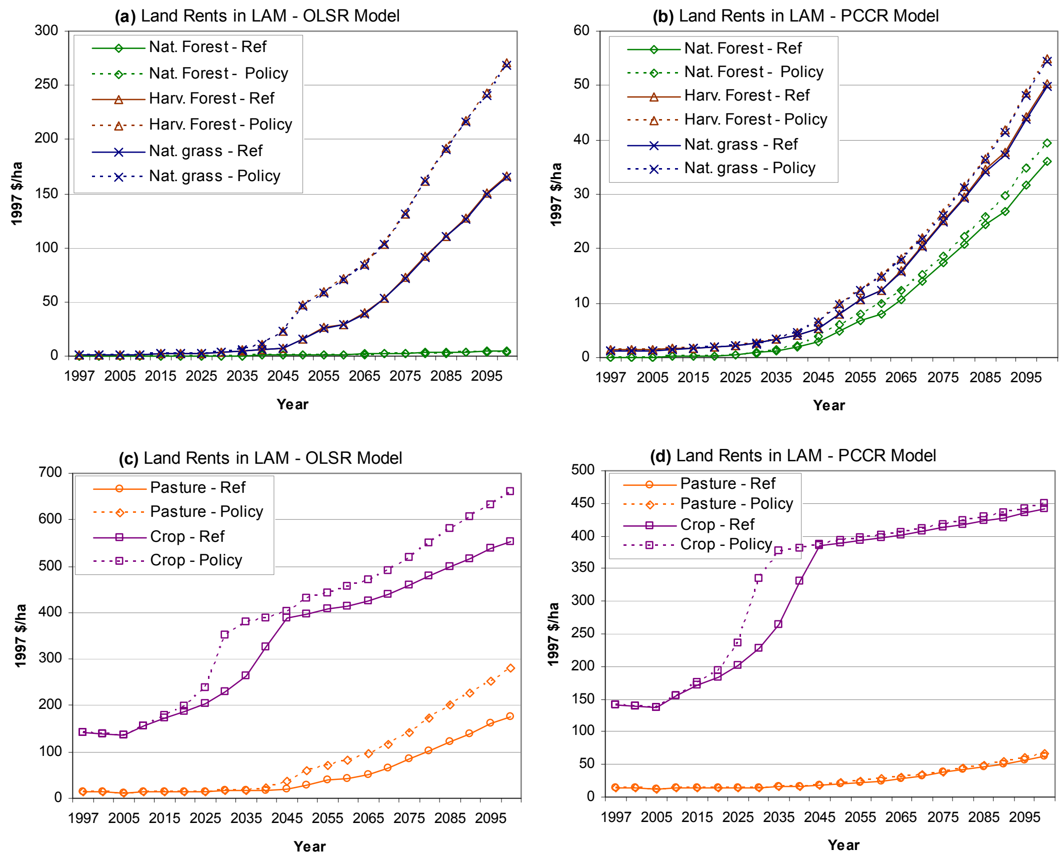

Figure 8. Land Rents in LAM: (a) natural areas and harvested forest - OLSR model, (b) natural areas and harvested forest - PCCR, (c) pasture and crop land - OLSR model, (d) pasture and crop land - PCCR.

5. Conclusions

The paper provides some novel approaches for introducing land into a computable general equilibrium framework in a way that allows us to consistently treat land as an economic factor input and in physical terms. The approach allows us to parameterize biomass production to be consistent with agronomic information on yields, and to see better the potential physical consequences in terms of land area needed for a large biofuels industry. We model a "second generation" cellulosic biomass conversion technology and biomass used in electricity generation. The liquid fuels technology turns out to dominate the electricity generation technology in both a BAU and a climate policy scenario. Our modeling approach treats five land types: crops, pasture, managed forest, natural forest and natural grass, and allows conversion (or abandonment) from one type to another.

We considered two alternative formulations of land conversion from natural areas to agricultural use. One approach introduced a land supply elasticity based on observed land supply responses that were estimated to vary regionally. The other approach only considered the direct cost of conversion. As it turned out the different approaches did not substantially change the amount of biofuels produced but it did change which land type is used for biomass production. The version with the land supply elasticity allowed much less conversion of land from natural areas, forcing intensification of production, especially on pasture and grazing land, whereas the pure conversion cost model led to significant deforestation. Thus, these approaches have very different consequences for the environment. While the observed conversion response may reflect an unwillingness to convert land, and therefore bodes well for conservation of forests, the significant pressure for conversion as reflected in diverging land rents may prove to overwhelm this resistance unless specific protection measures are enforced. The observed land conversion response we estimate may be a short run response that does not fully reflect the effect of long run pressure to convert land if rent differentials are sustained over 100 years. These different approaches emphasize the importance of somehow reflecting the non-market value of land more fully in the conversion decision.

With regard to the global biomass industry, we estimate production of between 35 and 39 EJ in 2050 under a reference or business as usual scenario, which increases to 221 to 267 EJ in 2100. Under a global effort to mitigate greenhouse gas emissions, biomass production in 2050 reached levels between122 and 135 EJ in 2050 and 319 to 368 EJ in 2100. Tropical areas in Central and South America and Africa become the biggest biomass suppliers, although other regions, such as the US, Mexico and Australia and New Zealand are also able to produce bioenergy on a large scale. 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 areas used for crops today. Under the policy scenario, the land required for biomass production reaches 2.2 to 2.5 Gha in 2100. The 2.5 Gha means an amount greater than any other land cover category in that year, including the area covered by natural forests.

Global prices for agriculture and forestry products increase relative to the reference case as a result of more rapid expansion of biofuels when there is a strong climate policy. Somewhat surprisingly these price increases are relatively modest—5 to 10%. Thus, it appears to be possible to introduce a large cellulosic biofuels industry without dramatically upsetting agricultural markets. This result is quite different than what we have seen in recent years with the expansion of corn-based ethanol in the US. However, the very large increases in the price of corn in the US may reflect a short-run phenomenon that with time would fall back somewhat. We would expect, however, that the cellulosic technology we model to have less direct effects on commodity prices.

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