The Contribution of Biomass to Emissions Mitigation under a Global Climate Policy

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Niven Winchester*,† and John M. Reilly*

Abstract

What will large-scale global bioenergy production look like? We investigate this question by developing a detailed representation of bioenergy in a global economy-wide model. We develop a scenario with a global carbon dioxide price, applied to all anthropogenic emissions except those from land-use change, that rises from $15 per metric ton in 2015 to $59 in 2050. This creates market conditions favorable to biomass energy, resulting in global non-traditional bioenergy production of ~150 exajoules (EJ) in 2050. By comparison, in 2010 global energy production was primarily from coal (139 EJ), oil (175 EJ) and gas (108 EJ). With this policy, 2050 emissions are 16% less in our Base Policy case than our Reference case, although extending the scope of the carbon price to include emissions from land-use change would reduce 2050 emissions by 57% relative to the same baseline. Our results from various policy scenarios show that lignocellulosic (LC) ethanol may become the major form of bioenergy, if its production costs fall by amounts predicted in a recent survey and ethanol blending constraints disappear by 2030; however, if its costs remain higher than expected or the ethanol blend wall continues to bind, bioelectricity and bioheat may prevail. Higher LC ethanol costs may also result in expanded production of first-generation biofuels (ethanol from sugarcane and corn) so that they remain in the fuel mix through 2050. Deforestation occurs if emissions from land-use change are not priced, although the availability of biomass residues and improvements in crop yields and conversion efficiencies mitigate pressure on land markets. As regions are linked via international agricultural markets, irrespective of the location of bioenergy production, natural forest decreases are largest in regions with the lowest political constraints to deforestation. The combination of carbon price and bioenergy production increases food prices by 2.6%–4.7%, with bioenergy accounting for 1.3%–2.6%.

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1. INTRODUCTION

Policies in Europe and in the United States have created an expanding market for biofuels, on top of the successful sugar-based biofuels development in Brazil. These biofuels mandates are part of a suite of current or proposed policies to address energy security, climate change and sustainability issues. Greenhouse gas (GHG) emissions abatement through biomass energy production raises a number of questions, such as:

- Given the multiple pathways with which biomass can be used to produce energy, what bioenergy technologies will prevail?
- What are the GHG implications of expanding bioenergy when accounting for the potential need to expand cropland or apply nitrogen fertilizer?
- Where will bioenergy feedstocks be grown?
- How will large-scale bioenergy production affect food prices?
- Will land-use limitation policy, intended to protect forested land with large carbon stocks, also limit bioenergy expansion by increasing land prices?

Although a large body of literature on bioenergy has emerged, most studies consider forced targets with specific and limited fuel conversion pathways, rather than considering the optimal use of biomass feedstocks and conversion technologies in abating emissions while accounting for economic and physical constraints. For example, Rahdar *et al.* (2014) examined competition for biomass between bioelectricity and biofuels in the US under a renewable electricity standard and renewable fuel mandates. Wise *et al.* (2014) evaluated the impact of existing, moderate and high (up to 25% of transportation fuel) global biofuel mandates using the Global Change Assessment Model. Melillo *et al.* (2009) and Reilly *et al.* (2012) considered large-scale biofuel development with a simplified second-generation biofuel production technology; however, this provided no insight into the potential competition among first- and second-generation biofuel pathways or uses of biomass for fuels, power generation, and industrial heat.

We contribute to the existing literature by evaluating the role of bioenergy under a global carbon price, where the level and composition of bioenergy production is determined on an economic basis, and identifying numerous crops and pathways through which biomass could supply global energy needs. Our analysis employs a global model of economic activity and energy production that is augmented to represent bioenergy in detail. Bioenergy technologies represented include (1) seven first-generation biofuel crops and conversion technologies; (2) an energy grass and a woody crop; (3) agricultural and forestry residues; (4) two lignocellulosic biofuel conversion technologies, which can operate with and without carbon capture and storage (CCS); (5) an ethanol-to-diesel upgrading process; (6) electricity from biomass, with and without CCS; and (7) heat from biomass for use in industrial sectors. The model also includes explicit representation of bioenergy co-products (e.g. distillers' dry grains and surplus electricity), international trade in biofuels and pelletized woody feedstocks, land-use change with explicit representation of conversion costs and political constraints, limits on the blending of ethanol with

gasoline, endogenous changes in land and other production costs, and price-induced changes in energy efficiency and alternative vehicle technologies. Compared to previous investigations, our approach has far more detail on the conversion pathways and potential role of biomass energy.

This paper has five further sections. Section 2 outlines the core economy-wide model used for our analysis. Section 3 sets out the representation of bioenergy in the model. The scenarios implemented are outlined in Section 4. Section 5 presents and discusses results. Section 6 concludes.

2. THE EPPA MODEL

Our analysis builds on version 5 of the Economic Projection and Policy Analysis (EPPA) model, a recursive-dynamic, multi-region computable general equilibrium global model of economic activity, energy production and GHG emissions (Paltsev *et al.*, 2005), as augmented to consider land use change (Gurgel *et al.*, 2007, 2011). We further extend the model to include a detailed representation of bioenergy production and use. Version 5 of the EPPA model is solved through time in five-year increments and is calibrated using economic data from Version 7 of the Global Trade Analysis Project (GTAP) database (Narayanan & Walmsley, 2008), population forecasts from the United Nations Population Division (UN, 2011), and energy data from the International Energy Agency (IEA, 2004). Regional economic growth through 2015 is calibrated to International Monetary Fund (IMF) data (IMF, 2013). The model is coded using the General Algebraic Modeling System (GAMS) and the Mathematical Programming System for General Equilibrium analysis (MPSGE) modeling language (Rutherford, 1995).

Regions and sectors represented in the model are outlined in **Table 1**. For each of the 16 countries or regions in the model, 14 broad production sectors are defined: five energy sectors (coal, crude oil, refined oil, gas and electricity), three agricultural sectors (crops, livestock and forestry), and six other non-energy sectors (energy-intensive industry, commercial transportation, private transportation, food products, services and other industries). Several commodities in the model can be produced using different technologies and/or resources, including 'advanced technologies'. For example, refined oil can be produced both from crude oil and biofuels. Due to their higher costs, advanced technologies typically do not operate in the base year (2004) but may become cost competitive due to changes in relative prices caused by policies or resource depletion. For example, in the base year electricity is produced by traditional coal, gas, nuclear and hydro generation, but in future years it may also be produced from advanced technologies such as biomass with carbon capture and storage.

Production sectors are represented by nested constant elasticity of substitution (CES) production functions. Inputs for each sector include primary factors (labor, capital, land, and energy resources) and intermediate inputs. For energy and climate policy analysis, important substitution possibilities include the ability for producers to substitute among primary energy commodities, and between aggregate energy and other inputs. Goods are traded internationally and differentiated by region of origin following the Armington assumption (Armington, 1969), except for crude oil and biofuels, which are considered to be homogenous goods.

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Factors of production include capital, labor, six land types, and resources specific to energy extraction and production. There is a single representative utility-maximizing agent in each region that derives income from factor payments and allocates expenditure across goods and investment. A government sector collects revenue from taxes and (if applicable) emissions permits, and purchases goods and services. Government deficits and surpluses are passed to consumers as lump-sum transfers. Final demand separately identifies household transportation and other commodities purchased by households. Household transportation is comprised of private transportation (purchases of vehicles and associated goods and services) and purchases of commercial transportation (e.g., transport by buses, taxis and airplanes). The model projects emissions of GHGs (carbon dioxide (CO_2), methane, nitrous oxide, perfluorocarbons, hydrofluorocarbons and sulfur hexafluoride) and urban gases that also impact climate (sulfur dioxide, carbon monoxide, nitrogen oxide, non-methane volatile organic compounds, ammonia, black carbon and organic carbon).

Table 1. Aggregation in the EPPA model extended to represent bioenergy in detail.

	Sectors	
Energy	COAL	Coal
	CRU	Crude oil *Conventional crude oil; oil from shale, sand*
	ROIL	Refined oil *From crude oil, first and second generation biofuels*
	GAS	Gas *Conventional gas; gas from shale, sandstone, coal*
	ELEC	Electricity *Coal, gas, refined oil, hydro, nuclear, wind, solar, biomass with and without CCS, natural gas combined cycle, integrated gasification combined cycle, advanced coal and gas with & without CCS*
Agriculture	CROP	Crops *Food crops; biofuel crops (corn, wheat, energy beet, soybean, rapeseed, sugarcane, oil palms, represent. energy grass, represent. woody crop)*
	LIVE	Livestock
	FORS	Forestry
Non-Energy	FOOD	Food products
	EINT	Energy-intensive industry
	OTHR	Other industry
	TRAN	Commercial Transportation
	HTRAN	Household transportation *Conventional, hybrid and plug-in electric vehicles*

Countries or Regions	
USA	United States
CAN	Canada
MEX	Mexico
JPN	Japan
ANZ	Australia-New Zealand
EUR	European Union
ROE	Rest of Europe and Central Asia
RUS	Russia
CHN	China
IND	India
ASI	Dynamic Asia
REA	Rest of East Asia
BRA	Brazil
LAM	Other Latin America
AFR	Africa
MES	Middle East

Factors

Capital
Labor
Land
   Crop, managed forest, natural forest, managed grassland, natural grassland, other
Resources
   For coal; crude oil; gas; shale oil; shale gas; hydro, nuclear, wind and solar electricity

3. BIOENERGY IN THE EPPA MODEL

For this study, as noted in Section 2, the EPPA model is augmented to include a detailed representation of bioenergy production and related technologies. **Figure 1** provides an overview of bioenergy feedstocks, technologies and uses included in the model, which are described in detail below.
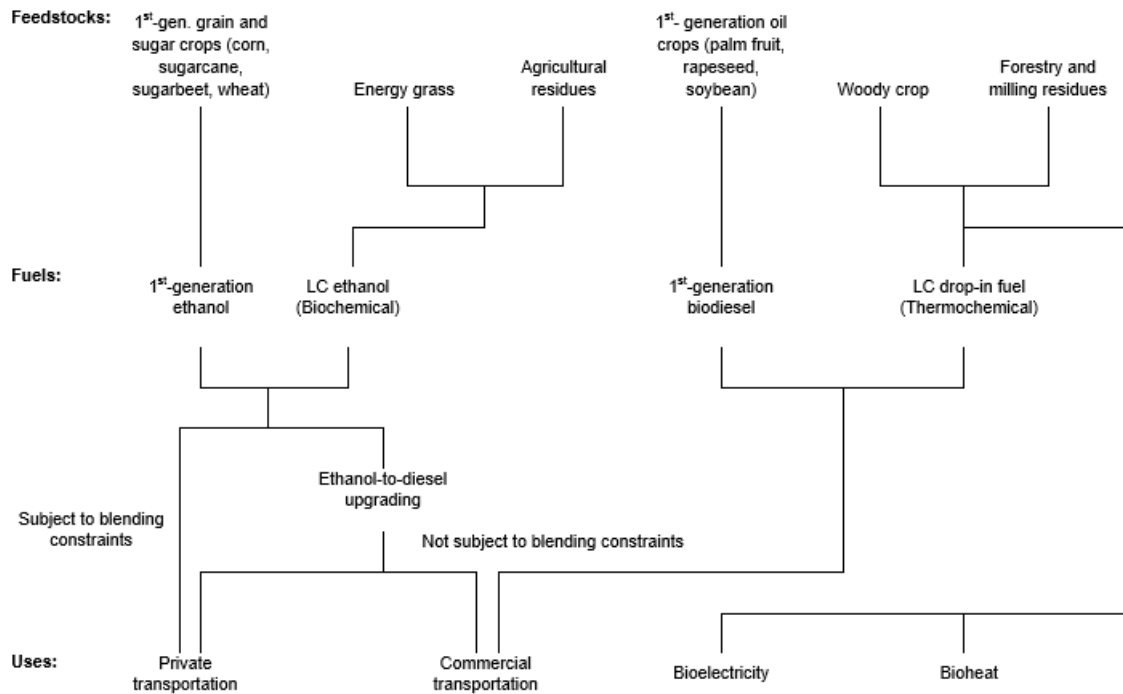

Figure 1. Bioenergy feedstocks, fuels and uses in the extended EPPA model.

3.1 Biofuels

The EPPA model's crop sector is an aggregate of all food crops, which is used as an input into food, livestock and other sectors. Crops grown for biofuel production are represented separately. First-generation biofuels include ethanol from corn, sugarcane, sugar beet and wheat; and diesel from palm fruit, soybean and rapeseed/canola. For each first-generation pathway, separate production functions are included for crop production and conversion of the feedstock to liquid fuel. As these crops are grown in the base year for food and other uses, their production for non-biofuel uses continues to be captured within the aggregate crops sectors, and the separate production function for each crop represents the quantity of the crop grown solely for biofuel production.

Two lignocellulosic (LC) biofuel conversion technologies are included: a biochemical process that produces ethanol (LC ethanol), and a thermochemical process that produces drop-in fuels (LC drop-in fuel). Feedstocks for LC pathways include a representative energy grass, a representative woody crop, and agricultural, forestry and milling residues. The energy grass and agricultural residues can be used for LC ethanol; and the woody crop and forestry and milling residues can be used for LC drop-in fuel, bioelectricity and bioheat.

As represented in **Figure 2**, production of each biofuel crop is represented by a series of nested CES functions. For sugarcane, energy grass and woody crops, soil carbon credits are produced as a co-product with biofuel feedstocks. The nesting structure facilitates endogenous yield responses to changes in land prices by allowing substitution between land and the energy-materials composite (e.g., fertilizer) and between the resource-intensive bundle and the capital-labor aggregate. The model also includes exogenous yield improvements of 1% per year for all crops (including food crops). Benchmark yields for each first generation biofuel crop in each region are calculated as production-weighted averages of observed yields by country from FAOSTAT (2013) and are reported in **Table 2.** As FAOSTAT provides yields for palm oil fruit, palm oil per hectare will depend on extraction rates. Guided by statistics from the Malaysian Palm Oil Board (see http://bepi.mpob.gov.my/), we specify a yield of four metric tons of palm oil per hectare for Dynamic Asia (ASI). We calculate yields for other regions based on their palm fruit oil yields relative to Dynamic Asia.[1]
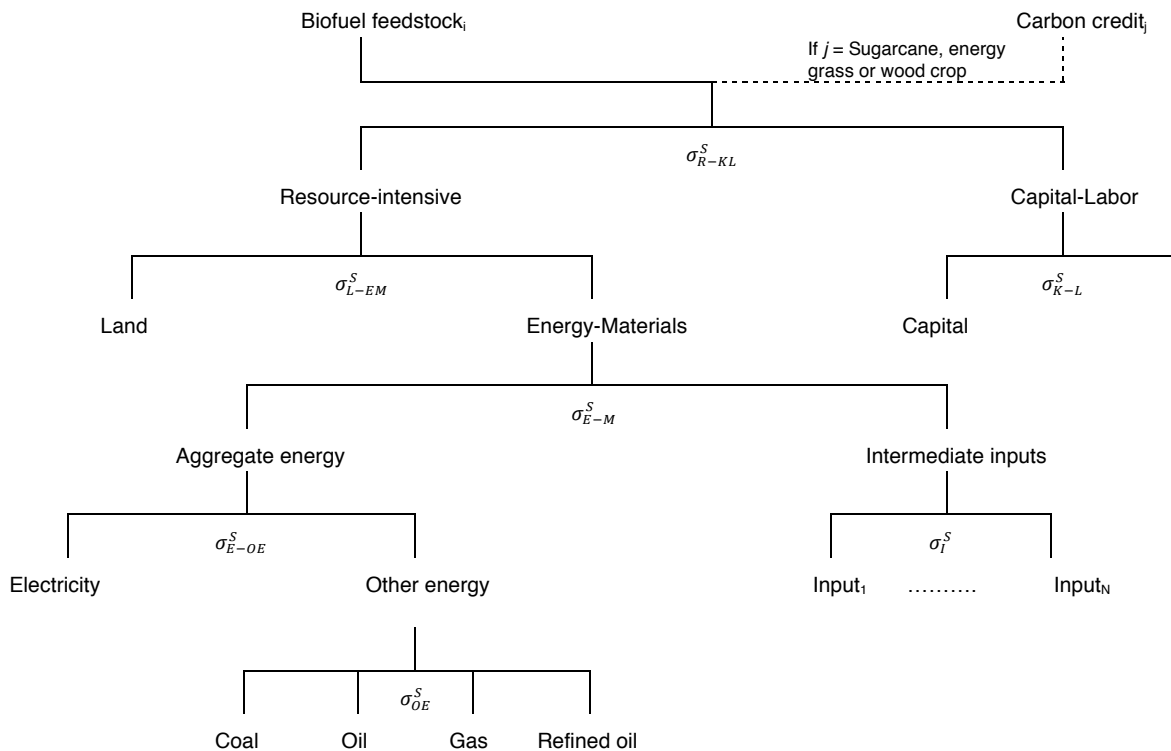
Figure 2. Bioenergy crop production (j = corn, sugarcane, sugar beet, wheat, palm fruit, rapeseed, soybean, energy grass, woody crop).

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[1] Although almost all crops are produced in all regions, production of some crops is limited in some regions. For example, the European Union (EUR) has relatively high yields for sugarcane, but produces only a small amount. Based on production data from FAOSTAT (2013), we represent these constraints by excluding or limiting production of sugarcane in the EU and the US, and all first-generation bioenergy crops in the Middle East.

Table 2. Bioenergy crop yields, wet metric tons per hectare per year (unless stated otherwise).

	USA	CAN	MEX	BRA	LAM	EUR	RUS	ROE	CHN	IND	JPN	ASI	REA	ANZ	MES	AFR
Corn	9.5	8.5	3.2	3.8	5.9	5.0	2.9	4.8	5.2	2.3	2.6	3.4	3.6	6.2	7.0	1.7
Rapeseed	1.4	1.5	1.3	1.3	2.2	2.5	1.2	1.3	1.9	1.1	1.2	1.2	0.9	1.0	2.1	1.2
Soybean	2.8	2.3	1.4	2.8	2.9	1.4	0.9	1.4	1.5	1.2	1.6	1.4	1.4	2.4	2.4	1.0
Sugar beet	63.2	55.2	0.0	0.0	76.6	47.0	29.2	35.1	41.3	0.0	64.5	0.0	41.7	0.0	36.8	51.3
Sugarcane	78.0	-	75.4	77.6	78.9	80.3	-	-	71.2	69.0	67.9	68.7	53.5	83.3	86.9	59.0
Wheat	2.7	2.3	5.1	2.2	2.9	3.4	2.1	2.3	4.6	2.7	4.3	3.5	2.5	1.1	2.5	2.0
Palm fruit	-	-	12.3	10.6	18.1	-	-	-	13.9	-	-	19.0	-	-	-	3.8
Energy grass*	16.8	12.7	14.0	42.5	42.5	14.7	11.3	14.8	9.4	8.8	14.8	41.5	13.2	16.0	6.8	15.5
Woody crop*	12.3	8.2	13.4	21.1	21.1	12.3	8.2	12.3	9.4	8.5	9.2	15.9	10.5	15.9	4.9	14.6

* Oven dry metric tons per year.

Source: Yields for all crops except energy grasses and woody crops are sourced from FAOSTAT (2013). Yields for energy grasses and woody crops in the US are based on a literature survey. Yields for these crops in other regions are calculated by applying yield adjust factors to US yields calculated using the TEM for the energy grass and Brown (2000) for the woody crop.

For the energy grass, we assign yields in the US and multiply by adjustment factors from the Terrestrial Ecosystem Model (TEM, see http://ecosystems.mbl.edu/tem/) to estimate yields for other regions. Using a process-level agroecosystem model, Thomson *et al.* (2009) estimate that on all continental US cropland, switchgrass—an important energy crop—yields an average of 5.6 oven dry tons (ODT) per ha. Schmer *et al.* (2008) observed switchgrass yields of 5.2–11.1 ODT/ha in field trials on marginal cropland in the mid-continental US, and McLaughlin and Kszos (2005) observed yields from 18 field sites in 13 states ranging from 9.9–23.0 ODT/ha, with an average of 13.4 ODT/ha (Heaton *et al.*, 2008). For Miscanthus, another important potential energy crop, Lewandowski *et al.* (2000) report results from field trials on unirrigated land in Southern Europe of 10–25 t/ha. Heaton *et al.* (2008) compared Miscanthus and switchgrass in side-by-side field trials in Illinois and observed average yields of 30 t/ha for Miscanthus and 10t/ha for switchgrass. Based on this literature, we assign a US yield of 16.8 ODT/ha for the representative energy grass. To calculate energy grass yields for other regions, we multiply the US yield by net primary productivity for C3-C4 grasslands estimated by the TEM in each region divided by that in the US. Energy grass yields for Brazil and Other Latin America (listed in Table 2) are higher than yields typically estimated for energy grasses in the US, but are consistent with the findings of Morais *et al.* (2009), in which yields for elephant grass (*Pennisetum purpureum Schum.*) were observed at 45–67 ODT/ha in trials at the Embrapa Agrobiologia field station in Brazil. For the woody crop, we assign a yield of 12.3 ODT/ha in the US and calculate yield adjustment parameters for other regions based on forestry yields reported in Brown (2000, Tables 6 and 7).

Calibration of production activities for biofuel feedstocks requires assigning cost shares per gasoline-equivalent gallon (GEG) for each pathway. We calculate land costs per GEG by combining the crop yields in Table 2 with estimates of feedstock requirements per GEG of fuel and land rents. Feedstock requirements are based on a literature survey and are displayed in **Table 3.** Land rental costs per hectare are calculated using data on total land rents from the

GTAP database and land-use estimates from the TEM. Costs for other crop production inputs are sourced from the GTAP database for first-generation crops, and from Duffy (2008) for energy grasses. For corn, rapeseed, soybean and wheat, we also track residues that can be sustainably removed and used as feedstock for LC ethanol. Residues are produced in fixed proportion to the output of each crop, and are calculated by applying residue ratios, retention shares and energy contents from Gregg and Smith (2010).

For soil carbon accumulation, we assume that sugarcane, energy grass and woody crop accumulate, respectively, 3.7, 1.8 and 3.3 metric tons of CO_2 per hectare (ha) per year. These numbers are based on estimates by Cerri *et al.* (2011) for sugarcane, Anderson-Teixeira *et al.* (2009) for energy grass, and the Forest and Agricultural Sector Optimization Model with GHGs (FASOM-GHG) for woody crops.

Table 3. Bioenergy conversion requirements and co-products.

Technology	Energy conversion requirement	Co-product(s)
Corn ethanol	31.0 lb per GEG	9.5 lb of DDGS per GEG
Sugarcane ethanol	190.7 lb per GEG	Electricity
Sugarbeet ethanol	125.0 lb per GEG	-
Wheat ethanol	33.2 lb per GEG	9.9 lb of DDGS per GEG
Palm oil diesel	42.4 lb per GEG	-
Rapeseed diesel	17.9 lb per GEG	9.7 lb of meal per GEG
Soybean diesel	36.4 lb per GEG	28.8 lb of meal per GEG
LC ethanol	40% energy conversion efficiency	Electricity
LC drop-in fuel	35% energy conversion efficiency	Electricity
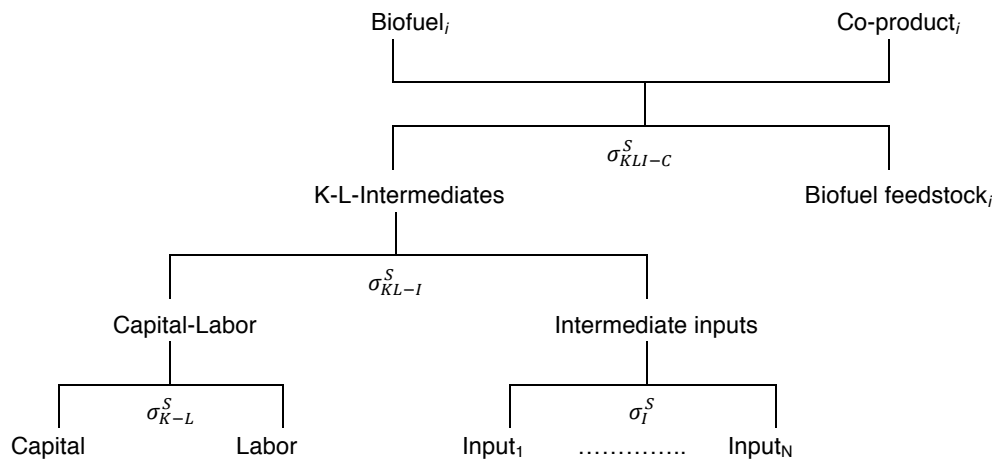
Figure 3. Biofuel production (*i* = corn ethanol, sugarcane ethanol, sugar beet ethanol, wheat ethanol, palm oil diesel, rapeseed diesel, soybean diesel, LC ethanol, LC drop-in fuel).

Shown in **Figure 3**, production functions for each biofuel combine inputs of pathway-specific feedstocks and other inputs, including capital, labor and intermediate inputs. For first-generation biofuels, we set the elasticity of substitution between the biofuel feedstock and other inputs (σ_{KLI-C}^{S}) equal to zero, so a fixed quantity of feedstock is needed per GEG of fuel. For second-generation

pathways, we assign a positive value for σ^S_{KLI-C}, allowing producers to respond to relative prices by extracting more energy per ton of feedstock at an increasing marginal cost.

Some processes also produce other co-products in addition to biofuel. Output from these sectors is modeled using a joint production function, where fuel and co-products are produced in fixed proportions. Co-products represented include distiller's dried grains with solubles (DDGS) for corn and wheat ethanol, electricity for sugarcane ethanol, LC ethanol and LC drop-in fuel, and meal for soybean and rapeseed diesel. Non-electricity biofuel co-products substitute for output from the crops sector, and electricity co-products substitute for output from the electricity sector. Co-products produced per GEG for each fuel are described in Table 3.

To calibrate cost functions for first-generation biofuel production, we aggregate to EPPA sectors input cost data sourced from Tiffany and Edman (2003), Shapouri and Gallagher (2003), IEA (2004), Haas *et al.* (2005), USDA (2006), Cardno ENTRIX (2010) and IRENA (2013). Cost estimates for our LC ethanol pathway out to 2015 are based on a production cost survey by Bloomberg New Energy Finance (2013). Due to the lead time between technology availability and plant operations, cost estimates in this survey are lagged by two years. LC ethanol costs fall by 81% between 2010 and 2015 due to assumed decreases in enzyme costs and learning effects. From 2015 to 2030, reflecting the scope for development of new technologies, we assume that LC ethanol costs fall an additional 2.5% per year.
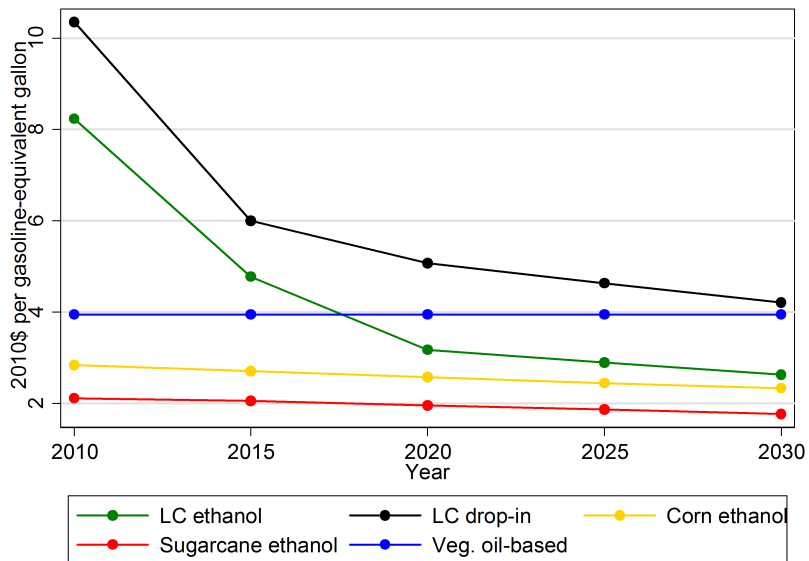
Figure 4. Benchmark biofuel costs in the US (for corn and LC ethanol and vegetable oil-based fuels) and Brazil (for sugarcane ethanol), 2010$ per gasoline-equivalent gallon.

In **Figure 4**, we display years 2010–2030 refinery gate costs per GEG for selected biofuels at benchmark input prices and labor productivity. All biofuel costs are US-based except sugarcane ethanol, which is based in Brazil. Due to the mature nature of first-generation biofuel technologies, there are small or no changes in costs for these technologies over time. After 2030, benchmark costs are constant for all biofuels, but these fuels benefit from exogenous economy-wide labor productivity and yield improvements. As the model is solved through time,

production costs are calculated endogenously based on changes in input prices, including changes in land rents and energy prices. We assume that conversion technologies are the same in all regions but that feedstock costs vary regionally according to differences in yields and land rents. Consequently, differences in land costs per GEG of fuel ultimately drive differences in biofuel production costs across regions.

As the uptake of ethanol will be limited by constraints on blending ethanol with gasoline and on ethanol use in some transportation modes (see Section 3.3), we also include an ethanol-to-diesel technology. Guided by Harvey and Meylemans (2014) and Staples *et al.* (2014), we assume that the cost of upgrading ethanol to diesel is $0.8 per gallon of diesel ($0.704 per GEG of diesel) and the energetic conversion efficiency when converting ethanol to diesel is 95%. This technology is able to upgrade both LC and first-generation ethanol.

3.2 Agriculture and Forestry Residues

In addition to dedicated bioenergy crops (and residues from these crops), we include residues from other agricultural, forestry and milling activities that could be harvested without a detrimental effect on erosion or soil nutrients. Gregg and Smith (2010) produced estimates of residues[2] that can be sustainably harvested for seven crop categories (e.g., stalks, stover and chaff), forestry (tree tops, branches and slash) and milling (sawdust, scraps, pulping liquors) in 2005. We aggregate the crop categories to a single group and include crop residues as a joint output with crops for food and feed in our aggregate crops sector. Likewise, forestry and milling residues are included as joint outputs with, respectively, conventional forestry products and other industry output (which includes wood processing). We set the energy content of residues in 2004 equal to the estimates from Gregg and Smith (2010) and for subsequent years assume that, for each sector, residues are produced in fixed proportion to output. **Figure 5** displays the maximum amount of energy available from residues by type and region in 2004. The contribution of residues to final energy depends on the feedstock pathway and the energy efficiency associated with each use. Energy embodied in residues is largest in China, Dynamic Asia (driven by residues in Indonesia and Malaysia), the EU, Africa, and the US. Crop residues are the largest source of residues in all regions except Russia.

Residue collection and transportation costs are explicitly included in the production of collected biomass, as outlined in **Figure 6**. We specify rising collection costs per unit of collected biomass by including 'collection resources' as a joint output with residue production and requiring inputs of these resources to produce collected biomass. In the top level of the production nest, collection inputs and uncollected biomass are combined in a Leontief nest to maintain a one-to-one

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[2] Gregg and Smith (2010) report residue estimates for selected regions. We thank the authors for kindly providing country-level estimates underpinning their calculations, which we aggregated to the 16 regions represented in the EPPA model.

relationship between the energy content of uncollected and collected residues. Collection inputs are an aggregate of capital, labor, transportation and collection resources, which are produced in fixed proportion to uncollected residues. Specifically, δ_R ($0 < \delta_R < 1$) collection resources are produced for each unit of residues and δ_C collection resources are required per unit of collected biomass. If $\delta_R < \delta_C$, the proportion of residues that can be collected at the base cost is determined by δ_R/δ_C, and additional residues can only be collected at a higher cost. The shape of the 'supply curve' for collected residues is driven by the elasticity of substitution between collection resources and other inputs (σ_{RC}). Guided by residue supply curves estimated by Gallagher *et al.* (2003) and USDA (2011), we set σ_{RC} equal to 0.9, $\delta_C = 1$ and $\delta_R = 0.1$.
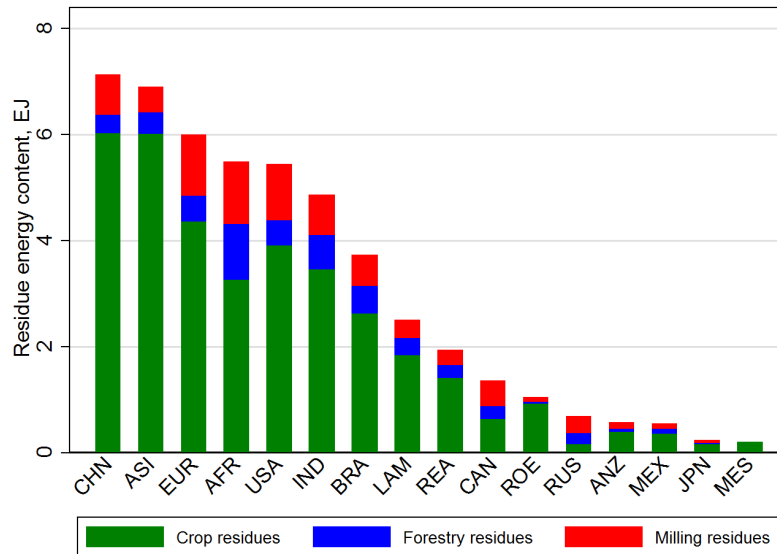
Figure 5. Residue biomass potential by type and region in 2004 (EJ). *Source:* Authors' aggregation of estimates from Gregg and Smith (2010).
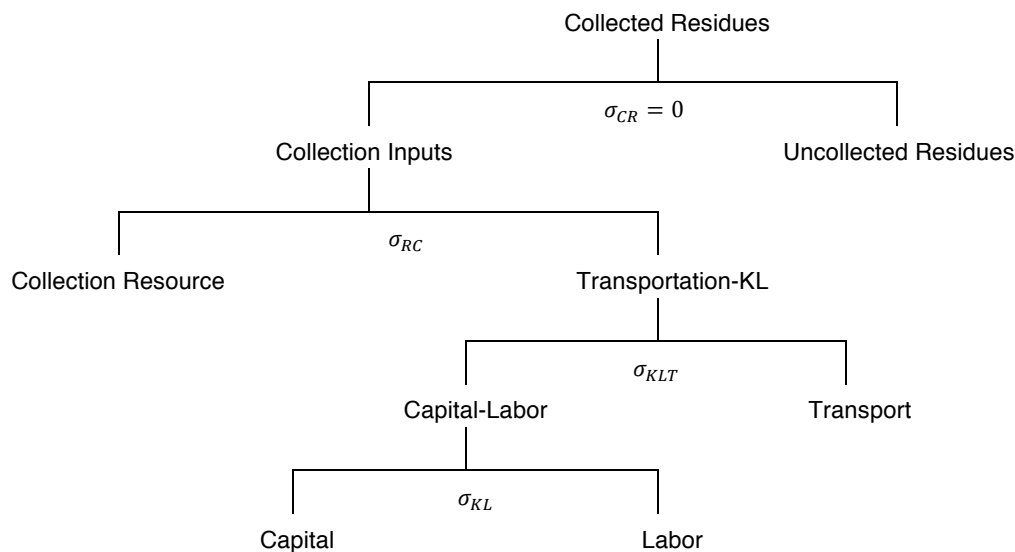
Figure 6. Production of collected biomass residues.

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3.3 Changes in Land Use

As demand for different types of land will change through time due to policies and changes in relative prices, we allow conversion from one land type to another. Land-use change is determined on an economic basis, subject to conversion costs and—for conversion of natural to managed land—non-economic constraints calibrated using observed relationships between land supplies and relative rents. Our representation of land-use change builds on that employed by Gurgel *et al.* (2007) and Melillo *et al.* (2009) and is depicted in **Figure 7**. The approach explicitly represents conversion costs by requiring inputs of capital, labor and intermediate inputs in the transformation process, and consistency in land accounting is maintained by combining land and other inputs in a Leontief nest (i.e., one ha of land type *x* is required to produce one ha of land type *y*). If land is being converted from natural forests, in addition to one ha of another land type, there is a one-time output of timber.

Conversion of natural forestland or natural grassland to a managed land type includes an elasticity of substitution between a fixed factor and other inputs (σ_{FF}^{S}), which allows us to represent historical relationships between changes in land use and land rents. As noted by Gurgel *et al.* (2007), "underlying this response may be increasing costs associated with specializing 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 conservation." Historical natural land supply responses are summarized using the supply elasticities calculated by Gurgel *et al.* (2007). These supply elasticities are then imposed in the model by assigning values for σ_{FF}^{S} following the calibration routine outlined by Rutherford (2002). The model includes above and below ground emissions from land-use change using carbon coefficient estimates from the TEM.
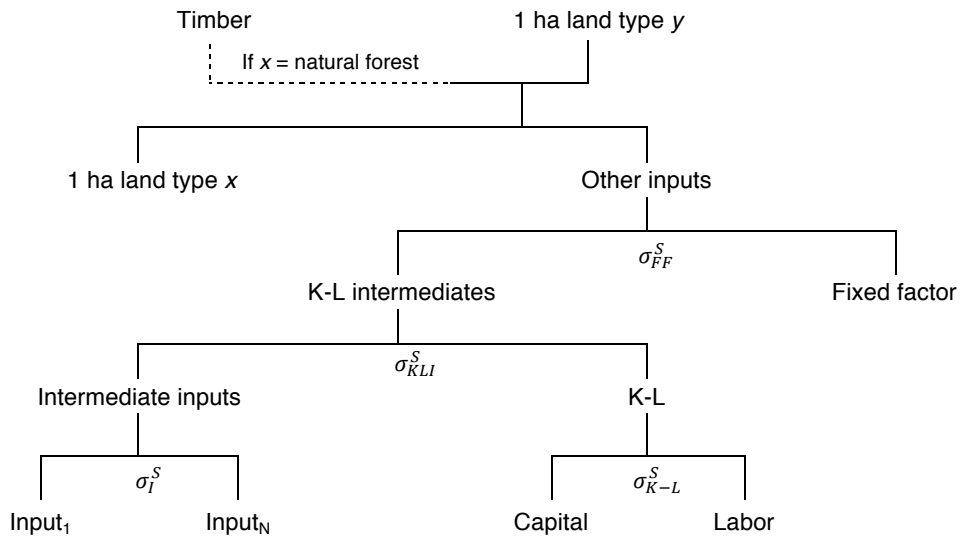
Figure 7. Land conversion in the EPPA model.

3.4 Other Bioenergy Features

Our analysis also augments several other features of the EPPA model in order to facilitate a detailed representation of bioenergy. First, several existing policies promoting biofuel were added to the model for inclusion in the study. These additions include renewable fuel standards in the EU and the US and estimates of how these policies may evolve in the future. To capture the EU policy, we impose minimum shares of renewable fuel in the transport sector of 5.75% in 2010, 10% in 2020 and 13.5% in 2030 and beyond. Additionally, to reflect a 2012 proposal by the European Commission, we constrain fuel produced using food crops to a maximum of 50% of the EU mandates from 2015 onwards. For the US, for 2010, 2015 and 2020, we impose the minimum volumetric targets for biomass-based diesel, cellulosic biofuels, undifferentiated advanced biofuel and total renewable fuel outlined in the Energy Independence and Security Act of 2007. As targets are not specified beyond 2022, we convert the volumetric targets in 2022 to proportions of total transportation fuel and impose these targets into the future. In the model, the constraints are imposed using a permit system, as depicted in **Figure 8**. One permit is issued for each GEG of renewable fuel produced, and retailers of both conventional fuel and renewable fuel are required to surrender α (set exogenously; $0 < \alpha < 1$) permits for each GEG of fuel sold. Under such a system, α determines the share of renewable fuel in total fuel consumption. This procedure can be used to target volumetric biofuel mandates by solving the model iteratively for alternative values of α. For the US, we include a separate permit system for each fuel type mandated.

Figure 8. Production and blending of renewable fuel permits into **(a)** Conventional fuel and **(b)** Biofuels.

Second, the consumption of ethanol in each time period and region may be limited by the ability of the prevailing infrastructure and vehicle fleet to absorb this fuel, commonly known as the 'blend wall'. We consider two blend wall cases applied to aggregate fuel purchases, which are illustrated in **Figure 9**. In our core scenario, we assume a 'base' blend wall case. In Brazil, we set an upper limit for ethanol in blended gasoline of 60% in 2015 (based on predicted sales and current stocks of flexible-fuel vehicles and vehicles able to accept blended fuel containing up to 25% ethanol). This upper limit is relaxed over time to reflect greater penetration of flex-fuel vehicles and the availability of molecules that can be blended to higher levels in gasoline (e.g., butanol and drop-in gasoline), so by 2035 there is no blend wall constraint. For other regions, we assume slower progress towards the use of 15% and 20% fuel blends between 2010 and 2025, but greater acceptance of ethanol and/or development of molecules that can be blended to higher

levels after 2025. As an alternative, we also construct a 'low' blend wall scenario. In this specification, the upper limits for ethanol use in private transportation are lower, which is consistent with slower progress towards higher ethanol blends and/or a failure to commercialize drop-in fuels. We model the blend wall constraint using a permit system similar to that outlined in Figure 8. Specifically, each GEG of ethanol requires an ethanol permit, and λ permits are 'produced' for each GEG of fuel used in private transportation, where λ is equal to the maximum proportion (in GEGs) of ethanol permitted in fuel used for private transportation.
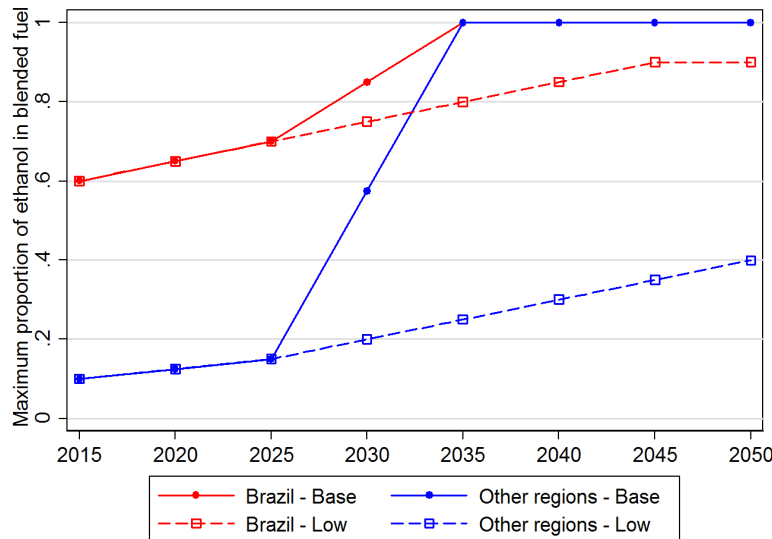
Figure 9. Maximum proportion of ethanol in gasoline-ethanol fuel blends by volume.

Third, the substitution of ethanol for conventional refined oil products will also be influenced by the use of fuels with carbon chains in the kerosene and diesel range in commercial transportation, and the use of diesel vehicles for private transportation. We impose the first constraint in the model by assuming that ethanol cannot be used in commercial transportation. As diesel is only a small proportion of fuel consumed for private transportation in most regions, we only consider diesel used in private transportation in the EU region. Based on estimates from the European Automobile Manufacturers Association (EAMA, 2013), we assume that diesel accounts for 36% of refined oil energy used in the EU for private transportation until 2015. After 2015, to reflect possible responses of new vehicle purchases to changes in relative fuel prices, we assume that the proportion of diesel in household refined oil energy use falls by 2.4 percentage points per year, reaching zero by 2030. In the EU, ethanol can only be blended with non-diesel private transportation fuel, up to the blend wall limits noted previously.

4. SCENARIOS

We simulate a reference scenario to be used as a benchmark for five additional scenarios that implement a global climate policy under alternative modeling assumptions (summarized in **Table 4**). The *Reference* scenario simulates assumptions about economic, population and productivity growth, as well as renewable fuel mandates in the EU and the US; however, it does not include the EU Emissions Trading Scheme.

Table 4. Scenarios considered.

Scenario	Description
Reference	'Business as usual' assumptions about economic, population and productivity growth and renewable fuel mandates extending current policies in the EU and the US.
Base Policy	Global carbon price on all GHG emissions except those from land-use change beginning in 2015 and rising by 4% per year. The 2015 carbon price is chosen to induce 150 EJ of primary bioenergy by 2050.
Low Ethanol Blending	Global carbon price simulated in the base policy case with tighter ethanol blending constraints.
Expensive LC Ethanol	Global carbon price simulated in the base policy scenario with 50% more expensive LC ethanol costs relative to the Base policy case.
Low Crop Yield	Global carbon price simulated in the base policy with exogenous crop yield improvements of 0.75% per year (compared to 1% per year in the base case).
Land Carbon	Global carbon price simulated in the base policy scenario extended to emissions from land use and land-use change.

As we wish to let different bioenergy and other low-GHG options compete on a level playing field under GHG constraints, we simulate a global cap-and-trade policy rather than forcing the use of renewables through policy mandates (although existing renewable standards and an estimation of how they may evolve are captured in the *Reference* scenario). Our policy shock imposes a cap on cumulative global emissions between 2015 and 2050 and allows banking of emissions permits. Under such a policy, optimal banking will result in the carbon price increasing, each year, by the rate investors use to discount future costs. Therefore, the carbon price path is determined by the 2015 carbon price and the assumed discount rate, which—following Paltsev *et al.* (2009)—we set to 4%. As noted previously, our goal is to simulate a large use of biomass energy by 2050, where 'large' is defined as approximately 150 EJ of primary biomass. We iteratively searched for an initial carbon price that generated the target level of biomass, and found that a price of $15 (in 2010 dollars) per ton of CO_2 (tCO_2) in 2015, rising at 4% per year, generated approximately the right level. Each price path we considered generated a period-by-period price, which we set by simulating a cap-and-trade system with an endogenous emissions cap. The global allocation of emissions permits imposes equal proportional reductions in emissions in all regions, but permits are tradable across regions and sectors. Revenue from emissions permits is returned to governments in a lump-sum fashion.

In the *Base Policy* scenario, this carbon price is applied to all GHG emissions from economic activity except land-use change. The same carbon price is imposed in the four other scenarios, which also include alternative modeling assumptions. In the *Low Ethanol Blending* scenario, we impose the low maximum ethanol blending volumes reported in Figure 9. In the *Low Crop Yield* scenario, the exogenous increase in crop yields, for both bioenergy and food crops, is assumed to be 0.75% per year (compared to 1% per year in the base case). In the *Expensive LC Ethanol* scenario, we impose less optimistic assumptions about the development of this technology over time and assume that, at constant input prices, costs are 50% higher than in *Base Policy*. In the *Land Carbon* scenario, the *Base Policy* carbon price is extended to emissions from land-use change (including soil carbon accumulation).

As modeling assumptions in some policy scenarios differ from those in the *Reference* scenario, we implement separate reference scenarios for the *Low Ethanol Blending*, *Low Crop Yield* and *Expensive LC Ethanol* policy cases. These reference scenarios differ from the core *Reference* scenario in that we have included the alternative assumption examined in each policy case (e.g., the reference scenario for the *Low Crop Yield* scenario imposes the same business-as-usual assumptions and RFS policies as in the core *Reference* case, plus the crop yield assumptions in the *Low Crop Yield* case). Results for these additional reference scenarios are not reported, but are used to calculate relative changes in the relevant policy scenarios. For each policy scenario, we also simulate the carbon price when bioenergy technologies are unavailable. Results for these simulations are also not reported, but we compare differences between results to quantify the independent impacts of using biomass to produce energy.

5. RESULTS

Results for all scenarios are presented in **Table 5** and Figures 10–17. Results reported include CO_2 equivalent (CO_2e) emissions; changes in food prices and use; global primary energy, electricity and transportation fuel production; bioenergy production by region, type and feedstock; and land-use change. As noted in Section 4, the carbon price, which is included in all scenarios except the *Reference* case, is determined in a pre-simulation exercise and is (in 2010 dollars) $15/tCO_2$ in 2015, rising to $59.2/tCO_2$ in 2050. All scenarios maintain the same CO_2 price path and so, while the initial target level of biomass energy was 150 EJ by 2050, the level of bioenergy varies across scenarios. In addition to stimulating additional biomass energy, the CO_2 price also affects energy supply, energy demand, and the broader economy.

Table 5. Summary of global results in 2050.

	Reference	Base policy	Low ethanol blending	Expensive LC ethanol	Low crop yield	Land carbon
Welfare change (%)*	-	-2.5	-1.9	-1.9	-2.3	-3.1
CO_2e emissions (MMt)	87,868	74,140	77,474	80,316	78,160	37,381
Primary bioenergy (EJ)	49.5	152.4	96.9	82.0	140.8	152.5
Final bioenergy (EJ)	25.8	76.6	52.9	46.0	69.7	77.0
Bioenergy land (Mha)	64	229	138	135	213	266
Natural Forest land (Mha)	3,780	3,584	3,551	3,545	3,506	5,043
Food crop land (Mha)	2,599	2,552	2,598	2,603	2,671	2,287
Change in food use (%)*						
Due to policy	-	-3.5	-2.8	-2.8	-3.3	-4.8
Due to bioenergy	-	-1.4	-0.8	-0.7	-1.3	-1.4
Change in food price (%)*						
Due to policy	-	3.3	2.7	2.6	3.2	4.7
Due to bioenergy	-	2.6	1.4	1.3	2.4	2.5

* Changes are expressed relative to the relevant reference cases for each scenario in 2050.

5.1 The *Reference* and *Base Policy* Scenarios

We begin by analyzing the impact of the carbon price on energy production and use by comparing the *Reference* and *Base Policy* scenarios. Imposing a carbon price induces energy

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efficiency improvements and energy use reductions, resulting in global primary energy use of 573.6 EJ in 2050 (compared to 718.7 EJ in the *Reference* scenario) (**Figure 10a**). The carbon price also reduces energy from coal and oil, and promotes energy from low-carbon sources, especially biomass. Similar changes are observed for electricity (**Figure 10b**). In 2050, the *Base Policy* scenario shows 19% less electricity consumption and 73% less electricity from coal (relative to *Reference*). Biomass electricity and electricity produced as a co-product with biofuels reach a combined total of 11 EJ, or 9% of total production (compared to 0.9 EJ in the *Reference* scenario). Transportation fuels are also affected (**Figure 10c**). In 2050, the *Base Policy* total transportation fuel use is 10% less (relative to *Reference*), ethanol accounts for 93% of global private transportation fuel energy use, and from 2015–2050 the biofuels share of total transportation fuels rises from 3% to 38% (whereas in the *Reference* scenario, it rises to just 11%).

In the *Base Policy* case, greater use of biomass and other abatement options decrease total GHG emissions by 16% relative to *Reference* (see Table 5). *Base Policy* cumulative GHG emissions from 2015–2050 are 1.3 trillion metric tons. IPCC estimates (IPCC, 2013, Table SPM.10) indicate that this level of CO_2 emissions through 2050 corresponds with a global mean surface temperature increase of ~2 degrees Celsius (°C) relative to the 1861–1800 average. If annual emissions from 2051 to 2100 are held constant at the 2050 level, cumulative 2015–2100 CO_2 emissions are 3 trillion metric tons, which corresponds with a total increase of ~3°C. Net of climate benefits, the *Base Policy* carbon price reduces global welfare in 2050 by 2.5% relative to the *Reference* case, where welfare changes are measured as equivalent variation changes in consumption spending.

In the *Reference* scenario, driven by renewable fuel mandates in the EU and the US and the cost competitiveness of some biomass technologies, primary bioenergy rises from 8.5 EJ in 2015 to 49.5 EJ in 2050. Bioenergy production in 2050 includes bioheat, sugarcane, and LC ethanol. Corn ethanol and diesel from soybean and palm oil are produced only until 2025. The increase in biomass energy over time is mainly driven by increases in fossil fuel prices and cost reductions for LC ethanol.

In the *Base Policy*, primary bioenergy increases to 152.4 EJ in 2050 (predetermined by our ~150 EJ target), or 76.6 EJ of final energy (**Figures 11 & 12**). In this scenario, the ethanol blending constraint is binding from 2015 to 2025, which results in ethanol being upgraded to diesel in these years. Corn ethanol is produced in the US up until 2025, when it becomes uneconomical. After 2025, higher limits on ethanol in gasoline blends remove the need to upgrade ethanol to diesel, and in 2050 LC ethanol accounts for around 57% of total bioenergy consumption by energy content.[3]

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[3] Assuming LC ethanol plant capacity of 135 million gallons per year, LC ethanol production simulated in the *Base Policy* scenario requires a global average build rate of 36 new plants per year from 2015–2030, and 160 new plants per year from 2035–2050. For comparison, 31 first-generation ethanol plants were built in the US in 2009 and 30 in Brazil in 2008 (RFA, 2014; GAIN, 2013).
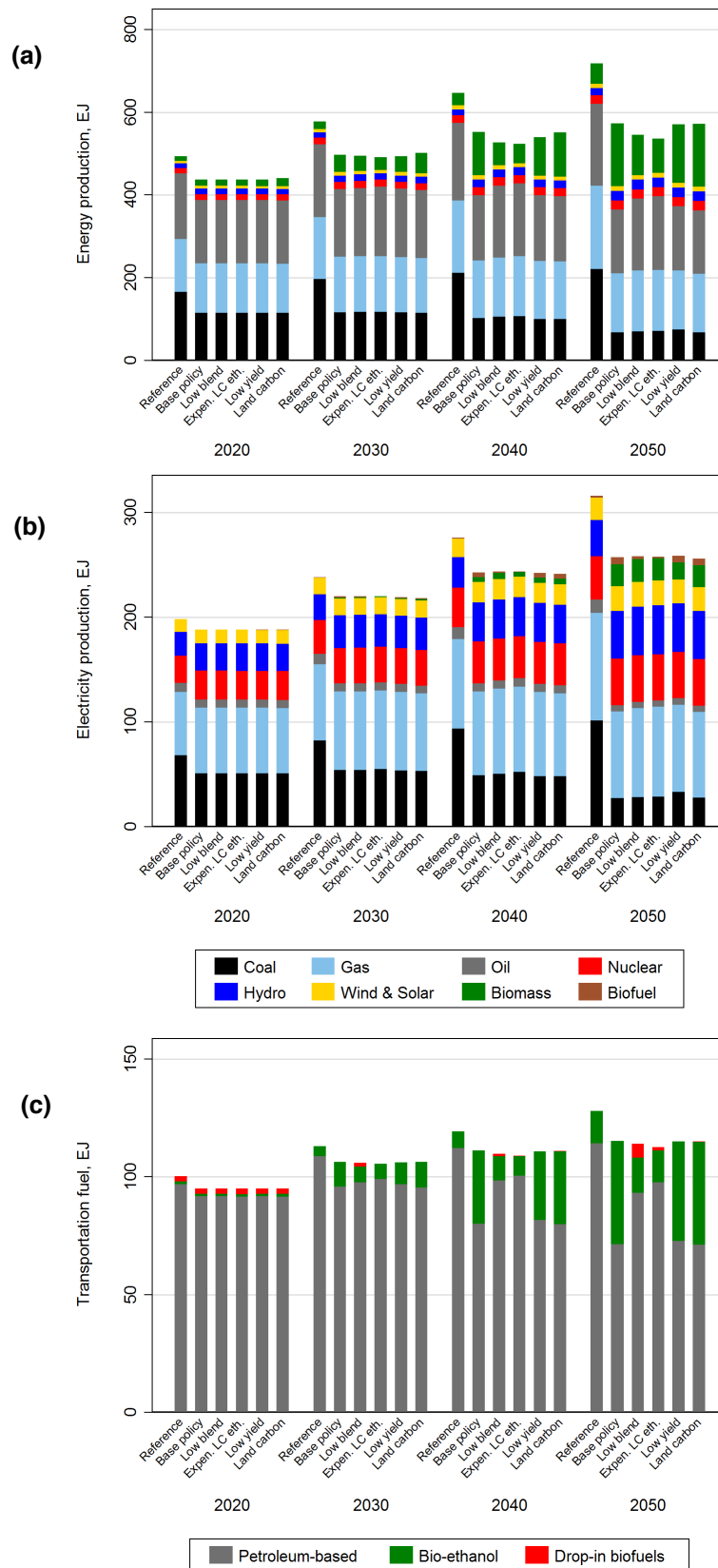
Figure 10. Global production of **(a)** Primary Energy, **(b)** Electricity, and **(c)** Transportation.

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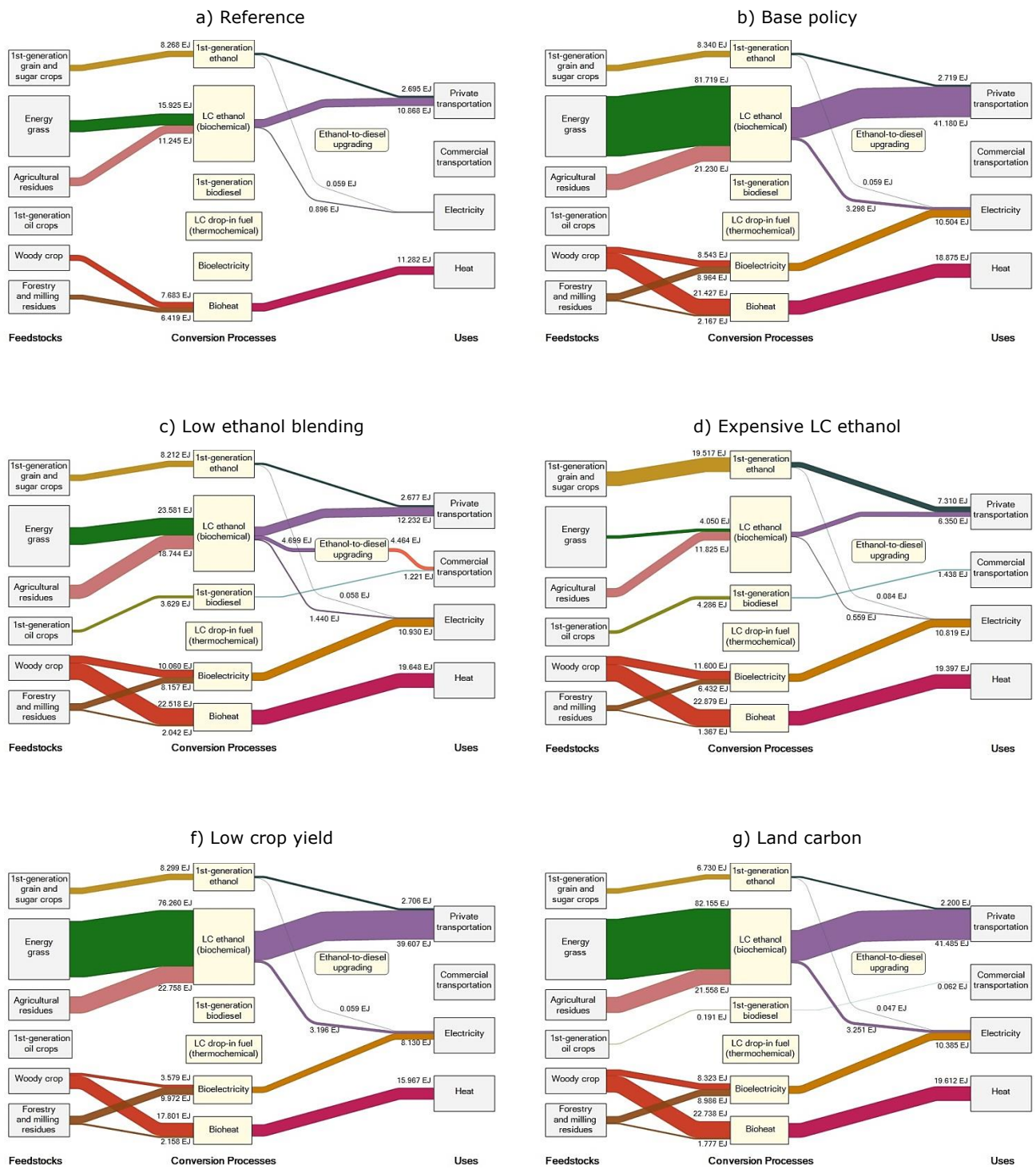
Figure 11. Global biomass production, energy conversion and end use in 2050, EJ.
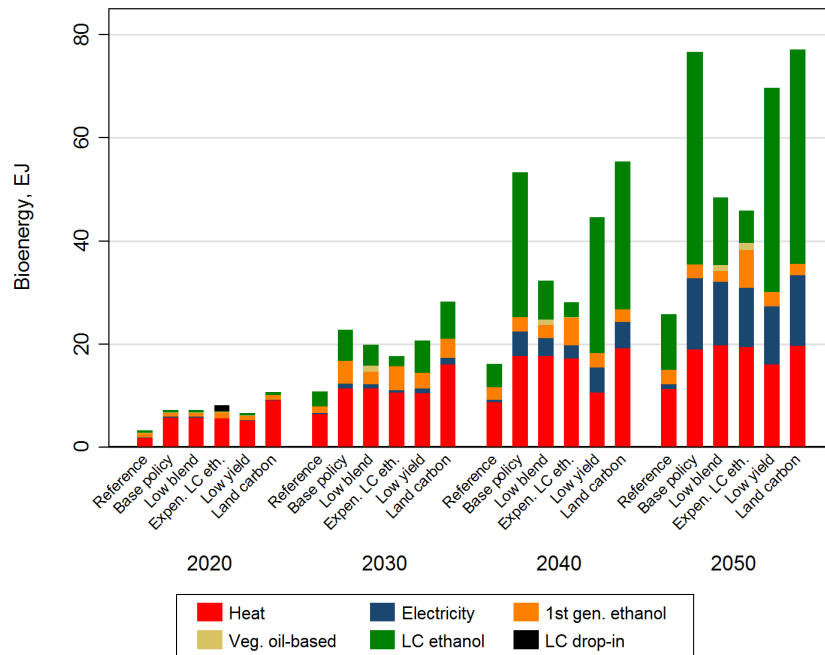
Figure 12. Global final bioenergy by energy type.

The carbon price induces other price changes that make LC ethanol the cheapest biofuel in most regions. Energy grass requires less energy-intensive inputs than first-generation crops, and thus is less affected by rising energy prices, and as LC ethanol has lower land costs per GEG than other biofuels, rising land prices also have a smaller impact on LC ethanol. Additionally, rising electricity prices will increase LC ethanol's co-product revenue.[4]

Other major sources of bioenergy production in the *Base Policy* scenario include bioheat and bioelectricity (produced from dedicated bioelectricity operations and as a co-product with biofuels). Bioelectricity production is driven by relatively large increases in the carbon-cost-inclusive price of coal. LC drop-in fuels are not produced due to their relatively high costs, and CCS is not economical in any year for any technology. When the carbon price is first introduced, most bioenergy is produced from the woody crop, but energy grass becomes the largest source of bioenergy by 2035 (**Figure 13**). By 2050, forestry and agricultural residues combined account for 15.6 EJ (or 20%) of final bioenergy.

The largest bioenergy producers in the *Base Policy* scenario are Africa (15.4 EJ of final bioenergy) and Brazil (11.1 EJ) (see **Figure 14**). Most bioenergy produced in Africa in 2050 is LC ethanol with electricity produced as a co-product. In Brazil, bioenergy production is split between LC and sugarcane ethanol (with electricity co-product) and bioheat. Other major bioenergy production regions include China, which produces LC ethanol and bioelectricity; Other Latin

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[4] With low energy-intensive inputs, LC drop-in fuels and sugarcane ethanol also benefit from rising electricity co-product revenue. However, LC drop-in fuels remain more expensive than LC ethanol. When the blend wall is binding, LC drop-in fuels are also more expensive than upgrading ethanol to diesel.
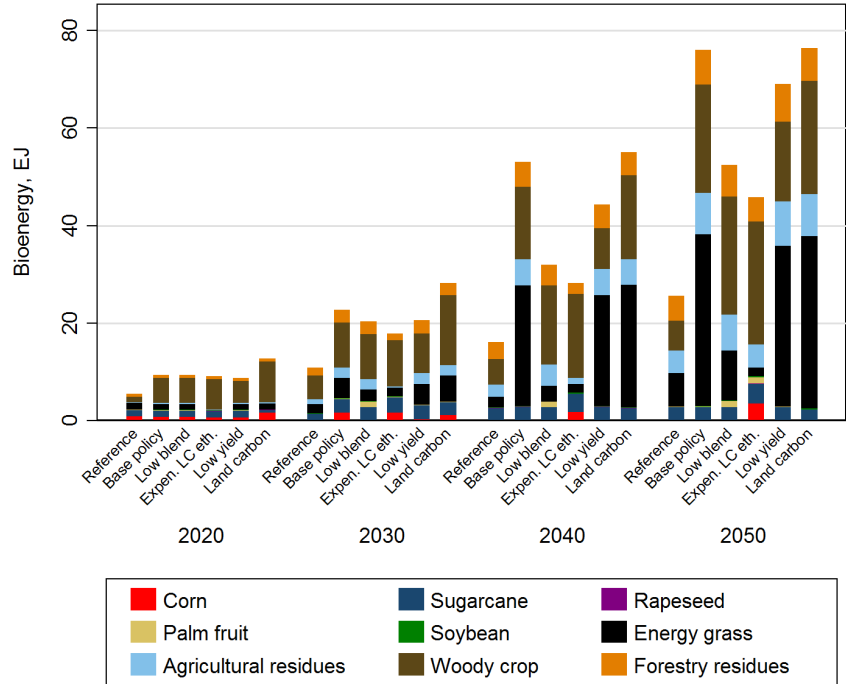
Figure 13. Global final bioenergy production by feedstock.
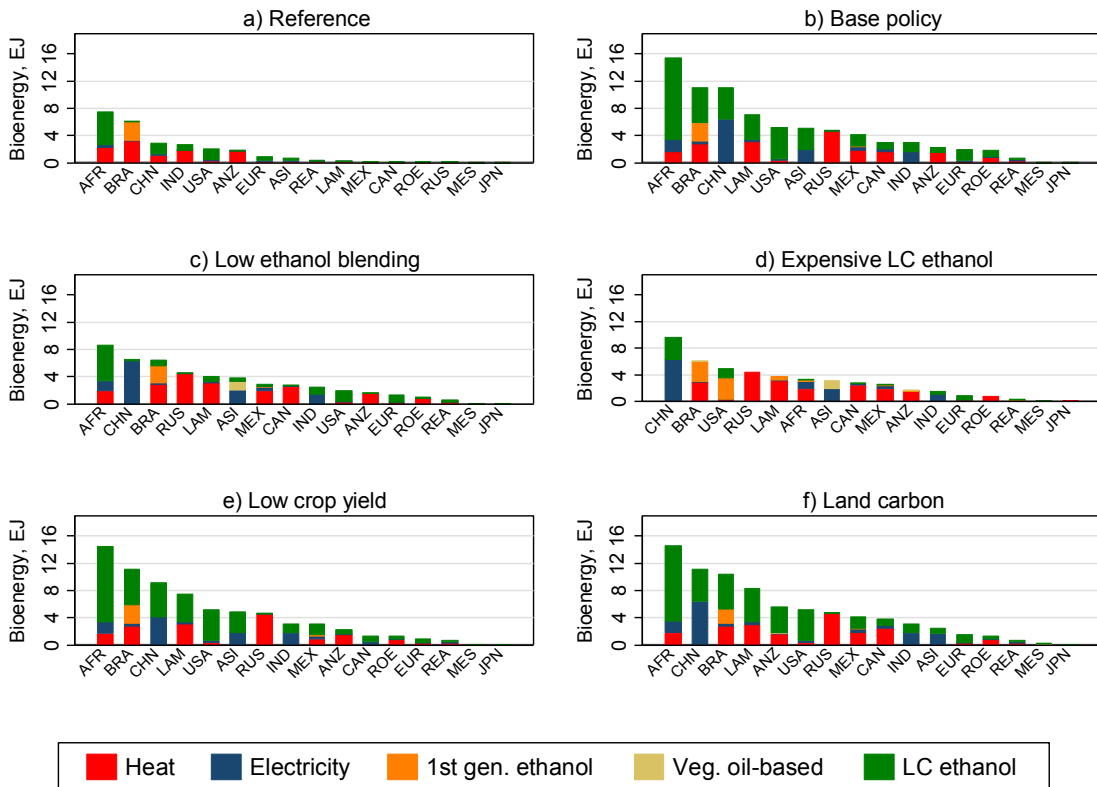
Figure 14. Regional final bioenergy by scenario in 2050.

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America, which primarily produces LC ethanol and bioheat; and the US, which mostly produces LC ethanol. Sugarcane ethanol, produced in Brazil and Mexico, is the only first-generation biofuel still produced in 2050.

The carbon price and bioenergy production induce changes in land use (see **Figures 15 & 16**). In 2050, in the *Reference* case, global land use includes 2,599 million hectares (Mha) for food crops and 64 Mha for bioenergy crops; in the *Base Policy* scenario, food crops use 2,552 Mha and bioenergy crops use 229 Mha. The additional bioenergy cropland in the *Base Policy* scenario comes at the expense of food crops, and also natural forestland—natural forest area is 196 Mha lower than in the *Reference* case due to deforestation, mainly in Africa (101 Mha), Other Latin America (62 Mha) and Brazil (29 Mha) (**Figure 17a**).
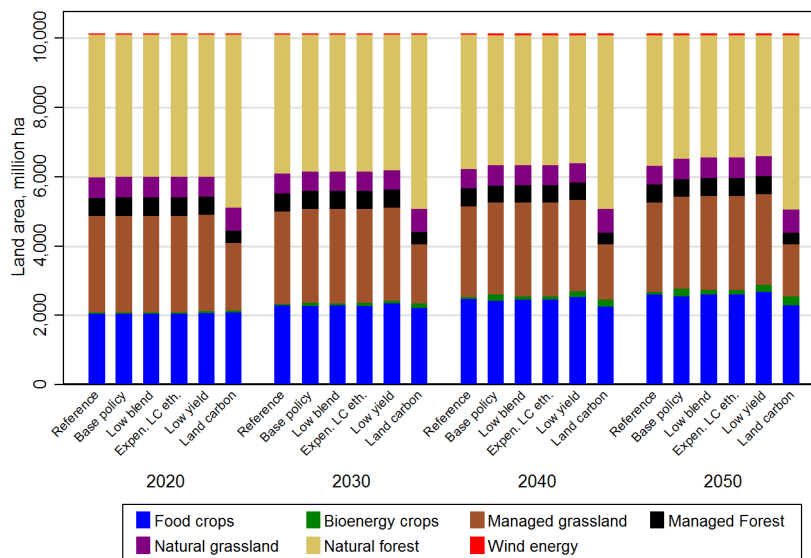
Figure 15. Global land use, million ha. *Note:* Land unsuitable for growing vegetation is not represented.
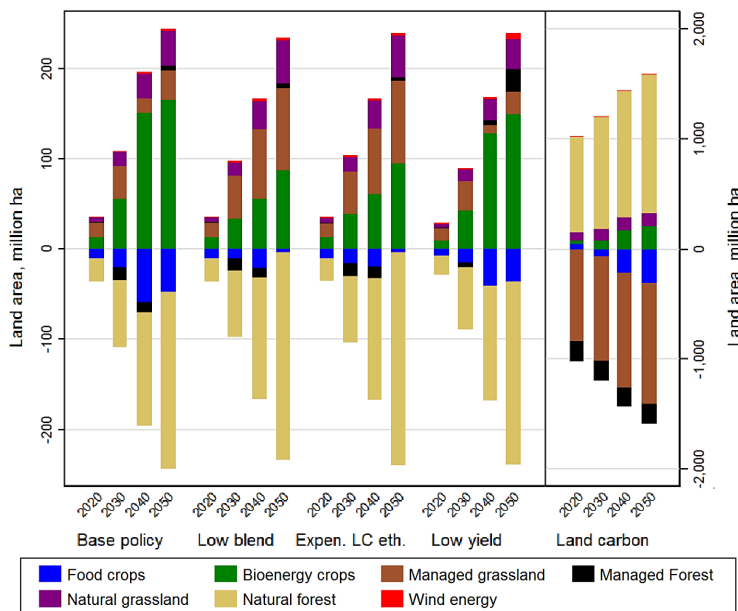
Figure 16. Global land-use change relative to the reference scenario, million ha.
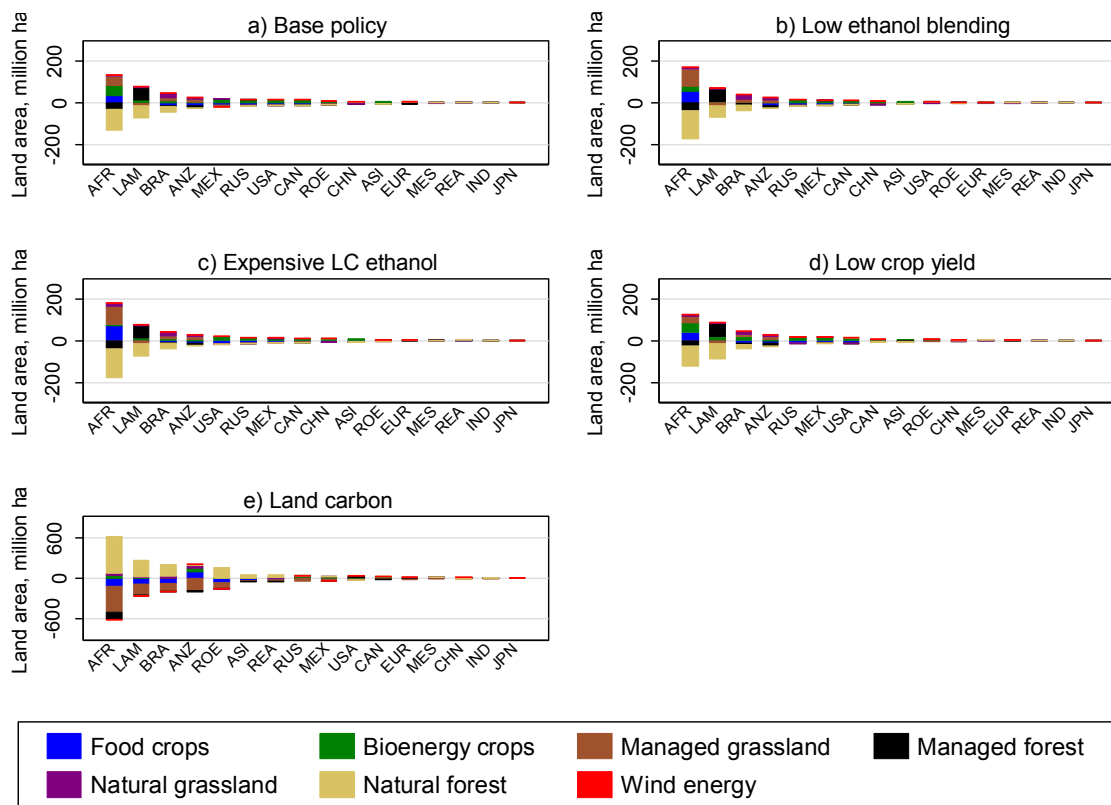
Figure 17. Regional land-use change relative to the *Reference* scenario in 2050, million ha.

Although global livestock production decreases, managed grassland (pasture) areas increase in the Base policy scenario relative to the *Reference* case due to a change in the regional composition of livestock production. The global change in managed grasslands is driven by a decrease in livestock production in Other Latin America and an increase in livestock production in Africa. Although pasture yields are higher in Other Latin America than Africa, the energy grass-to-pasture relative yield is also higher in this region. Following the theory of comparative advantage, this relative yield difference, *ceteris paribus*, promotes livestock production in Africa. As pasture yields are lower in Africa than in Other Latin America, livestock production decreases even though more land is allocated to pasture. There are also small increases in natural grassland in some regions, as this type of land is valued for its environmental services and the carbon price increases the relative cost of agricultural uses.

The impact of bioenergy on land-use change is influenced by at least three factors in our analysis. First, the scope for deforestation in the model reflects current trends and political constraints. Depending on how economic costs and incentives induced by a carbon price affect political and public opinion, there may be smaller or larger changes in land use. Second, some bioenergy feedstocks are sourced from forestry and agricultural residues. Third, improved efficiency both in growing crops and turning biomass into biofuel results in improvements in energy produced per ha of land. For example, in the US, the energy grass yield increases by 48% between 2015 and 2050, with 41 percentage points due to exogenous yield increases and the remainder due to a price-induced yield response. Combined with price-induced responses in

energy efficiency when converting grass into biofuel, each ha produces 51% more fuel in 2050 (1,757 GEGs per ha) than in 2015 (1,166 GEGs per ha).

Food use and prices are also affected (see Table 5).[5] The carbon price decreases real incomes and the production of bioenergy drives up land prices. As a result, relative to the *Reference* case, in 2050 the *Base Policy* global food price increases by 3.3% and food use decreases by 3.5%. The reduction in food use is partially driven by a substitution effect, including using more other inputs so that food is used more efficiently (e.g., reducing waste); therefore, food use reduction percentages given do not solely represent reduction in calories consumed. We isolate the impact of bioenergy on food consumption and prices by imposing the carbon price when bioenergy technologies are unavailable, then compare the results to outcomes in the *Base Policy* case. This comparison indicates that bioenergy production alone increases food prices by 2.6% and decreases food consumption by 1.4%.

5.2 The *Low Ethanol Blending* Scenario

In this scenario, we impose tighter blend wall constraints to restrict the use of LC ethanol. Relative to the *Base Policy* case, this scenario decreases total bioenergy production, increases CO_2e emissions, increases petroleum-based fuel use in transportation, and improves (net of climate benefits) welfare. A smaller decrease in welfare occurs, because tightening the blend wall constraint reduces changes in the economy relative to the *Reference* case, which by assumption was the optimal economic outcome (subject to prevailing constraints).[6]

Bioheat and dedicated bioelectricity production increase relative to the *Base Policy* case, although there is a decrease in total biomass electricity due to reduced production of electricity as a LC ethanol co-product. Ethanol-to-diesel upgrading and diesel from oil crops remain through 2050 due to the tighter blend wall constraints. In 2050, 23% of global ethanol production is upgraded to diesel, which results in 4.4 EJ of diesel from ethanol, and 1.2 EJ of palm oil diesel is produced in Dynamic Asia. As in the *Base Policy* case, LC drop-in fuels are never produced. In the *Low Ethanol Blending* scenario, all regions produce less final bioenergy relative to *Base Policy*, with the largest decrease occurring in Africa.

Less bioenergy production in the *Low Ethanol Blending* scenario reduces the amount of land used for energy crops. Changes in bioenergy crops and the regional composition of bioenergy drive differences in land-use change between the *Base Policy* and *Low Ethanol Blending* scenarios. Interestingly, although there is less land used for bioenergy crops in the *Low Ethanol*

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[5]As our model, like all general equilibrium models, only resolves relative prices, we estimate food price changes using the relationship $\dot{\Delta}C = \epsilon\dot{\Delta}I + \eta\dot{\Delta}P$, where $\dot{\Delta}$ denotes percentage change, C is food consumption, I is income, P is the food price, and ϵ and η are, respectively, the price and income elasticity of demand for food.

[6] The opposite would be true under a cap on emissions rather than a fixed emissions price. That is, tightening the ethanol blending constraints under an emissions cap would increase the carbon price and ultimately result in a larger decrease in welfare.

Blending scenario, less land is also allocated to natural forests than in the *Base Policy* case. This is driven by linkages between food and bioenergy markets and interactions among regions. Specifically, relative to the *Base Policy* case and due to the tighter constraint on using fuel from the energy grass, China allocates more land to woody energy crops. As the woody crop yield in this region is less than that for the energy grass, more land is allocated to energy crops and less to food crops, which results in increased imports of food. A large share of these imports is sourced from Africa, where more land is allocated to food crops at the expense of natural forests due to relatively low political barriers to deforestation. This result indicates that, due to international agricultural trade, growing energy crops will reduce natural forest areas in regions with the lowest constraints to deforestation, regardless of the location of bioenergy production.

5.3 The *Expensive LC Ethanol* Scenario

In this scenario, we increase the cost of LC ethanol production. Similarly to *Low Ethanol Blending*, this change reduces total bioenergy production, increases CO_2e emissions, and increases the use of petroleum-based fuels relative to the *Base Policy* case. The higher cost of LC ethanol also increases production of first-generation ethanol relative to other cases. In 2050, global ethanol production is 3.4 EJ from corn (mainly in the US) and 3.8 EJ from sugarcane (principally in Brazil), whereas global LC ethanol production is just 6.3 EJ (compared to 41.2 EJ in the *Base Policy* case). The blend wall is binding between 2015 and 2025, which induces production of LC drop-in fuels (1.4 EJ in 2025) and ethanol-to-diesel upgrading (0.9 EJ in 2025). From 2030 onward, the blend wall is not binding and LC drop-in and ethanol upgrading technologies do not operate.

Total bioenergy production in Africa falls by 78% relative to the *Base Policy* case, as increasing the cost of LC ethanol reduces production of this fuel (both for the domestic market and for export) and there is a large difference in energy yields for the energy grass and those for first-generation bioenergy crops in this region. China is the largest bioenergy producer in this scenario. Brazil and the US are also relatively large bioenergy producers due to their production of first-generation ethanol.

Similar to the *Low Ethanol Blending* scenario, less land is allocated to natural forests than in the *Base Policy* case due to increased production of food crops in Africa for export to China. Changes in food prices and use when LC ethanol is expensive are also smaller than in the *Base Policy* case.

5.4 The *Low Crop Yield* Scenario

In the *Low Crop Yield* scenario, the exogenous increase in crop yields is 0.75% per year (compared to 1% in all other scenarios). LC ethanol, bioheat and bioelectricity continue to be the major forms of bioenergy, but less total bioenergy is produced than in the *Base Policy* case. Compared to the *Low Ethanol Blending* and *Expensive LC Ethanol* scenarios, there is more total bioenergy and LC ethanol, but less first-generation ethanol. Driven by changes in total bioenergy production, CO_2e emissions in the *Low Crop Yield* scenario are greater than those in the *Base*

Policy case, but less than emissions in the *Low Ethanol Blending* and *Expensive LC Ethanol* scenarios.

Although, relative to the *Base Policy* scenario, less land is used for bioenergy crops, less land is also allocated to natural forests in this scenario. This is because more land is used for food crops when yields are lower in both the *Reference* case and when there is a carbon price. For example, in 2050 at the global level, 2,599 Mha of land are used for food crops in the *Reference* scenario when yields increase by 1% per year, and 2,707 Mha are allocated to food crops in the this scenario when yields increase by 0.75% per year. As the amount of land used for bioenergy in the *Low Crop Yield* scenario is similar to the *Base Policy* case, changes in food prices (3.2%) and consumption (-3.4%) are also similar.

5.5 The *Land Carbon* Scenario

In this scenario, we price emissions from land use and land-use change to provide incentives for reforestation. However, soil carbon credits for some bioenergy crops counteract reforestation incentives, and bioenergy production in the *Land Carbon* scenario remains similar to that in the *Base Policy* case. Bioheat and bioelectricity increase while biofuels decrease, a change attributed to two related mechanisms. First, feedstock costs as a proportion of total costs for bioheat and bioelectricity are larger than those for biofuels, so decreasing (gross of carbon credits) feedstock costs has a larger impact on bioheat and bioelectricity. Second, although slightly more soil carbon is sequestered per ha of energy grass than woody crop, as woody crop yields are less than those for energy grass, woody crop provides more soil carbon credits per ton than energy grass. Ultimately, as woody crops are used for bioheat and bioelectricity but not for biofuels produced in the *Land Carbon* scenario, these forces result in larger cost decreases for bioheat and bioelectricity when land-use emissions are priced.

Pricing carbon from land-use change results in global reforestation of 800 Mha between 2010 and 2050—a significant increase from the *Base Policy* and *Reference* cases (1,459 Mha and 1,263 Mha, respectively). Regions with the largest increases in natural forest area relative to the *Base Policy scenario* are Africa (relative increase of 646 Mha in 2050, or 344 Mha between 2010–2050), Other Latin America (315 Mha, 151 Mha), and Brazil (203 Mha, 118 Mha).

Although there is reforestation, the marginal impact of bioenergy in the *Land Carbon* scenario—calculated by comparing results from a similar policy scenario without bioenergy production—is to reduce global natural forest area. Due to soil carbon credits, bioenergy production also reduces global land used for food crops by more than in the *Base Policy* scenario. As a result, changes in food consumption (-4.8%) and the food price (4.7%) are relatively high in this scenario.

Reforestation in the *Land Carbon* scenario significantly reduces GHG emissions compared to other scenarios. In 2050, CO_2e emissions are 37,381 million metric tons (MMt), compared to 74,140 MMt in the *Base Policy* case, with cumulative CO_2 emissions from 2015–2050 of 0.5 trillion metric tons. Estimates from IPCC (2013, Table SPM.10) indicate that these cumulative emissions will increase the global mean surface temperature by ~1.7°C relative to the 1861–1800

average. Assuming that annual emissions from 2051 to 2100 are constant at the 2050 level, cumulative emissions through 2100 would increase the global annual mean surface temperature by ~2.5°C relative to the same average.

As the carbon price is applied to more activities than in the *Base Policy* scenario, the welfare decrease in the *Land Carbon* scenario is greater as well.[7]

6. CONCLUSIONS

We have developed and deployed a detailed representation of bioenergy in a global economy-wide model of economic activity, energy production and GHG emissions. The model was used to explore the role of biomass in energy production under a global carbon price that induced ~150 EJ of primary bioenergy production by 2050. The required carbon price was $15/tCO_2$ in 2015 and rose to $59/tCO_2$ in 2050.

If cost reductions follow those in a recent business survey and the blend wall is eliminated by 2030, LC ethanol will account for 57% of final bioenergy production in 2050. When the blend wall constraint was tightened or LC ethanol costs were increased, bioelectricity and bioheat were the major forms of bioenergy. Under higher LC ethanol costs, first-generation technologies accounted for 58% of total biofuel production. Lower crop yields reduced the amount of bioenergy produced, but did not have a large impact on the composition of bioenergy. Pricing emissions from land-use change did not significantly decrease the amount of bioenergy produced due to soil carbon credits for some bioenergy crops.

In all cases considered, there was a limited role for drop-in biofuels, as they were often more expensive than LC and first-generation ethanol and, when the blend wall was binding, ethanol upgraded to diesel.

With a carbon price applied to all GHGs except those from land-use change, less land was allocated to food crops and, in particular, natural forests than in the absence of a carbon price. Decreases in natural forestland were largest in Africa (which has the lowest political barriers to deforestation) in favor of bioenergy production, or food production for export to regions that produce large quantities of bioenergy. This outcome indicates that regardless of the location of production, incentivizing bioenergy production will lead to deforestation in unprotected areas and calls for a global solution to land-use change issues. However, the impact of bioenergy production on land-use change in our analysis was moderated by (1) the availability of forestry and agricultural residues as feedstocks for bioenergy, (2) the extension of current political deforestation constraints into the future, and (3) improvements in crop yields and energy efficiency when converting biomass to energy.

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[7] Global CO_2e emissions in 2050 are 45,586 MMt in the *Land Carbon* scenario when bioenergy technologies are not available, so most of the decrease in emissions relative to the *Reference* case is due to reforestation.

Pricing emissions from land-use change resulted in reforestation, with a decrease in food crops and managed grassland relative to when land-use emissions were not priced. In addition to incentivizing reforestation, pricing emissions from land-use change resulted in soil carbon credits for some bioenergy crops. The net effect was that the quantity of land allocated to bioenergy crops when land-use emissions were priced was similar to when they were not.

In 2050 relative to a reference case, food prices increased by between 2.6% and 3.3% when land-use change emissions were not priced and 4.7% when these emissions were priced. Decomposing these changes into various components revealed that the independent effect of growing biomass to produce energy increased food prices by between 1.3% and 2.6%. Food use decreased by between 2.8% and 4.8% of which between 0.7% and 1.4% was due to bioenergy production.

In terms of mitigating climate change, our results indicated that, if emissions from land-use change are not priced, cumulative CO_2 emissions through 2050 will increase the global mean surface temperature by ~2°C relative to the 1861–1880 average. If the carbon price is also applied to land-use emissions, cumulative CO_2 emissions through 2050 would increase the global mean surface temperature by ~1.7°C relative to the same average.

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