The feasibility, costs, and environmental implications of large-scale biomass energy*

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ABSTRACT

What are the feasibility, costs, and environmental implications of large-scale bioenegry? 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 $25 per metric ton in 2015 to $99 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 (138 EJ), oil (171 EJ), and gas (106 EJ). With this policy, 2050 emissions are 42% 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 52% 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 the 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 barriers to deforestation. In 2050, the combination of carbon price and bioenergy production increases food prices by 3.2%–5.2%, with bioenergy accounting for 1.3%–3.5%.

1. Introduction

There has been strong interest in bioenergy for several decades. A substantial industry of sugar ethanol was developed in Brazil dating to the 1970s in an effort to limit the impact of high crude oil prices on the economy (Tyner, 2008). The U.S. ethanol industry, now the largest in the world with Brazil a fading second (RFA, 2014), has had various motivations (Gardner and Tyner, 2007). Originally, corn ethanol was supported by agriculture because it supported farm incomes (while producing renewable energy and limiting dependence on imported petroleum) (Kane and Reilly, 1989). Its value as a supply of renewable energy has long been questioned by analysis suggesting the net energy of ethanol production could be negative, using as much fossil energy to produce it as the energy content of the fuel itself (Farrell et al., 2006). With significant increase in ethanol use in the early 2000s as an oxygenate in gasoline, replacing methyl tertiary butyl ether, its value had little to do with the energy it used or created. Then, with the renewable fuel standard (RFS2) in the United States and renewable mandates in Europe, the focus on ethanol, and bioenergy more generally, became explicitly a question of its effects on greenhouse gas emissions. Both the U.S. Environmental Protection Agency (EPA) and the European Commission created rules to favor fuels and fuel pathways that had lower greenhouse gas (GHG) emissions (EC, 2015; USEPA, 2015). While ethanol and biofuels have generally received the most attention and have grown in use rapidly over the last decade, even in the United States, most biomass is used for in heat and power, largely in the pulp and paper industry (USEIA, 2014).

While the several decades of interest in bioenergy and rapid expansion of biofuels in the United States and Europe over the past decade have been the source of much analysis, modern commercial biomass energy remains a small source of energy. Biomass energy is estimated to contribute 10% of global energy use but two-thirds of that is in residential use mainly in developing countries. The 18 EJ of industrial biomass energy, including that used to produce biofuels in 2009 compares with 106 EJ of natural gas, 138 EJ of coal, and 171 EJ of oil

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

Regions and factors	Sectors
Regions	*Energy sectors*
United States (USA)	Coal
Canada (CAN)	Crude oil
Mexico (MEX)	*Conventional crude oil; oil from shale, sand*
Japan (JPN)	Refined oil
Australia-New Zealand (ANZ)	*From crude oil, first- and second-generation biofuels*
European Union (EUR)	Natural gas
Rest of Europe and Central Asia (ROE)	*Conventional gas; gas from shale, sandstone, coal*
Russia (RUS)	Electricity
China (CHN)	*Coal, gas, refined oil, hydro, nuclear, wind, solar, biomass with and without CCS, natural gas combined cycle,*
India (IND)	*integrated gasification combined cycle, advanced coal, and gas with and without CCS*
Dynamic Asia (ASI)	*Agriculture*
Rest of East Asia (REA)	Crops
Brazil (BRA)	*Food crops; biofuel crops (corn, wheat, energy beet, soybean, rapeseed, sugarcane, oil palms, represent. energy*
Other Latin America (LAM)	*grass, represent. woody crop)*
Africa (AFR)	Livestock
Middle East (MES)	Forestry
Factors	*Non-energy sectors*
Capital	Crops
Labor	Livestock
Land	Forestry
Crop land, managed forest land, natural forest land, managed	Energy-intensive industry
grassland, natural grassland, other land	Other industry
Resources	Services
For coal; crude oil; gas; shale oil; shale gas; hydro, nuclear,	Commercial transportation
wind, and solar electricity	Household transport
	Conventional, hybrid, and plug-in electric vehicles

(Vakkilainen et al., 2013). Much of the analysis related to current polices has represented in detail existing technologies and the impact of relatively small changes in production (e.g., Kane and Reilly, 1989; Taheripour and Tyner, 2014). Another thread of research has looked at the large-scale potential of biomass as a major alternative to fossil fuels. These studies indicate an estimated technical potential for bioenergy of 300 and 500 EJ year in 2020 and 2050, respectively, and deployment of 100 to 300 EJ (Berndes et al., 2003; Chum et al., 2011). For example, Rahdar et al. (2014) examined competition for biomass between bioelectricity and biofuels in the United States 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. Calvin et al. (2014) examine the role of bioenergy under a carbon price but do not fully integrate land, energy, and agricultural markets.[1]

In this paper, we investigate the following: (1) Given the multiple pathways with which biomass can be used to produce energy, how will pathways change over time and across regions, and would certain pathways ultimately prevail? (2) What are the GHG implications of expanding bioenergy when accounting for the potential need to expand cropland or apply nitrogen fertilizer? (3) Where will bioenergy feedstocks be grown? (4) How will large-scale bioenergy production affect food prices? (5) Will land use limitation policy, intended to protect forested land with large carbon stocks, also limit bioenergy expansion by increasing land prices?

We contribute to the existing literature by evaluating the role of bioenergy under a combination of current and additional policy incentives that would scale up the industry to about 150 EJ, the same order as existing oil, gas, and coal energy use. Our analysis employs a global model of economic activity, including, energy, agriculture, and land markets that is augmented to represent bioenergy in detail. We are thus able to illustrate competition among (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 (LC) 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. We explicitly represent bioenergy co-products (e.g., distillers' dry grains and surplus electricity), international trade in biofuels, land use change with explicit representation of conversion costs, 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. Hence, compared with previous investigations, we are able to simulate a transition from current use of first-generation biofuels stimulated by a mix of policies in the United States, Europe, and Brazil to a 150 EJ (primary energy) industry in 2015, with a specific transition path.

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. A global model of the economy, energy, agriculture, and land

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,

[1] Several partial equilibrium studies are also relevant to our analysis. Using a mathematical programming model of the agricultural and forest sectors in the US, McCarl et al. (2000) examine the competitiveness of biomass-based electricity generation. The authors find that, under existing policies, improved production methods for short-rotation woody crops are needed for biomass to be competitive with coal. McCarl and Schneider (2001) assess the economic and technical potential for agricultural and forestry emissions mitigation in the U.S. under various carbon prices. They find that the optimal responses vary regionally and include soil-based strategies, biofuels, and afforestation. Using a global agricultural model to estimate emissions from land-use change, Searchinger et al. (2008) conclude that U.S. biofuel production increases GHG emissions. Lauri et al. (2014) employ a global partial equilibrium model of the forestry and agricultural sectors estimate woody biomass feedstock supply curves.

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 and Walmsley, 2008), population forecasts from the United Nations Population Division (UN, 2011), and energy data from the International Energy Agency (IEA, 2006, 2012). 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, and 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.

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).[2]

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. Fig. 1 provides an overview of bioenergy feedstocks, technologies and uses included in the model, which are described in detail below.

3.1. Biofuels

The current version of the EPPA model includes a single, aggregate crop production sector, which includes all crops grown for food, feed and other uses. We augment this representation by including separate production activities for each crop grown for bioenergy purposes and production functions for each bioenergy conversion technology. First-generation biofuel pathways added to the model include ethanol from corn, sugarcane, sugar beet, and wheat, and diesel from palm fruit, soybean, and rapeseed/canola. As these crops are also grown for food and other purposes, their production for non-biofuel uses continues to be captured within the aggregate crops sector, and their production for bioenergy purposes is included in each relevant bioenergy crop activity.

Two 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 Fig. 2, the 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 material composite (e.g., fertilizer) and between the resource-intensive bundle and the capital-labor aggregate. The model also includes compounding exogenous yield improvements of 1% per year for all crops (including food crops), which is consistent with estimates by Ray et al. (2013). 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.[3]

For the energy grass, we assign yields in the United States 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 U.S. 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 United States, and McLaughlin and Kszos (2005) observed yields from 18 field sites in 13 states ranging from 9.9 to 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 U.S. yield of 16.8 ODT/ha for the representative energy grass. To calculate energy

[2] Population and GDP in the reference case and income and price elasticities for food demand in the EPPA model are included in the supplementary materials for this paper.

[3] 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.

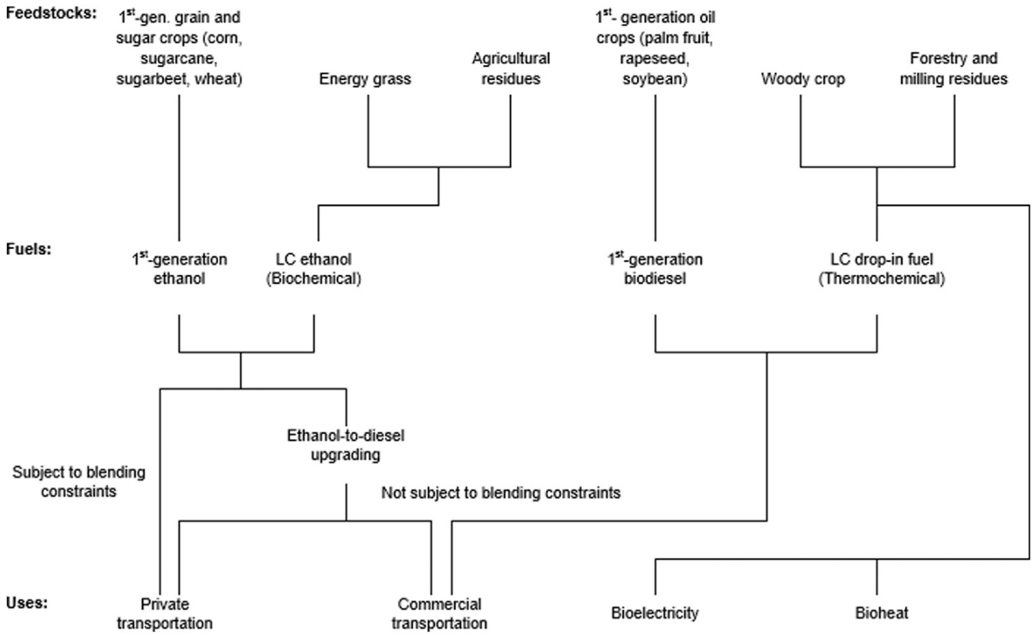

Fig. 1. Bioenergy feedstocks, fuels, and uses in the extended EPPA model.

grass yields for other regions, we multiply the U.S. yield by net primary productivity for C3–C4 grasslands estimated by the TEM in each region divided by that in the United States. Energy grass yields for Brazil and Other Latin America (listed in Table 2) are higher than yields typically estimated for energy grasses in the United States 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 United States 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).

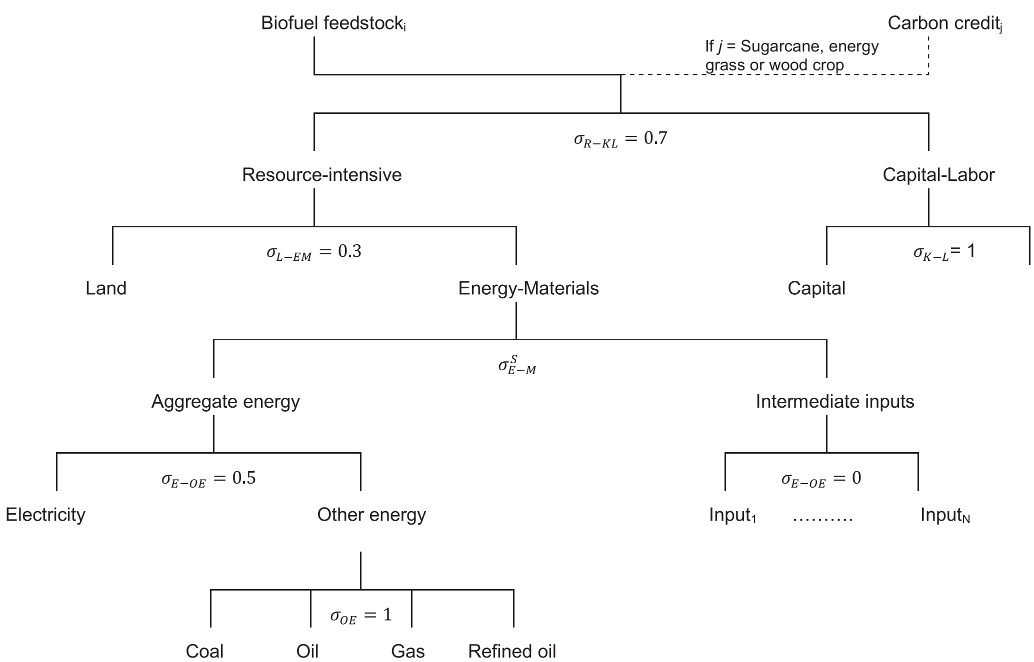

Fig. 2. Bioenergy crop production (j = corn, sugarcane, sugar beet, wheat, palm fruit, rapeseed, soybean, energy grass, woody crop).

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 United States are based on a literature survey. Yields for these crops in other regions are calculated by applying yield adjust factors to U.S. yields calculated using the TEM for the energy grass and Brown (2000) for the woody crop.

For soil carbon accumulation, we assume that sugarcane, energy grass, and woody crop accumulate, respectively, 1.8, 3.7, 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.

As shown in Fig. 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}) equal to zero, so a fixed quantity of feedstock is needed per GEG of fuel. For second-generation pathways, $\sigma_{KLI-C} = 0.2$, 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 IREA [International Renewable Energy Agency] (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.

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

In Fig. 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 U.S.-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[4] 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, and 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. Fig. 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 United States. Crop residues are the largest source of residues in all regions except Russia.

[4] 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.

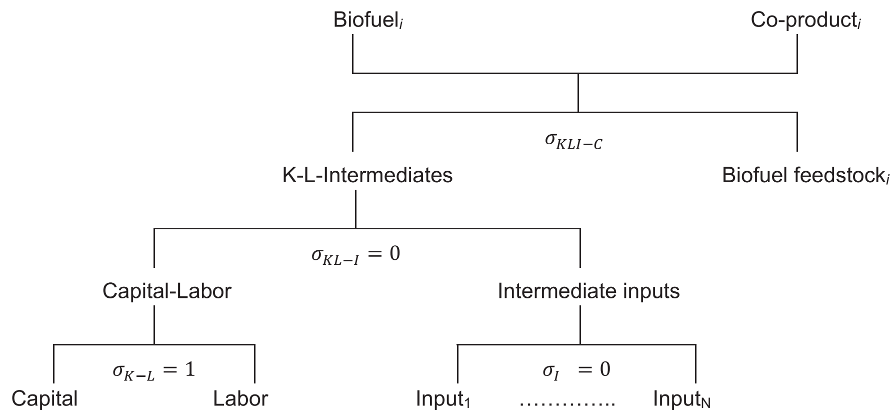

Fig. 3. Biofuel production (i = corn ethanol, sugarcane ethanol, sugar beet ethanol, wheat ethanol, palm oil diesel, rapeseed diesel, soybean diesel, LC ethanol, LC drop-in fuel). Note: $\sigma_{KLI-C} = 0$ for first-generation biofuel and $\sigma_{KLI-C} = 0.2$ for second-generation biofuels.

Residue collection and transportation costs are explicitly included in the production of collected biomass, as outlined in Fig. 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 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 $\delta_R = 0.1$.

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 Fig. 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}), which allows us to represent historical relationships between changes in land use and land rents. As noted by Gurgel et al. (2007, p. 15), "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} 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.

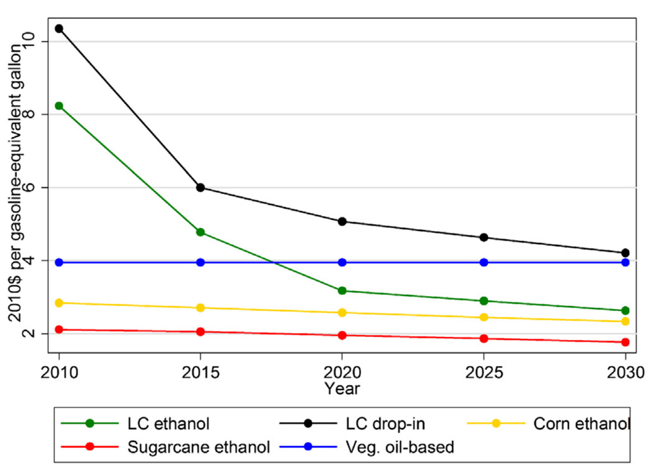

Fig. 4. Benchmark biofuel costs in the United States (for corn and LC ethanol and vegetable oil-based fuels) and Brazil (for sugarcane ethanol), 2010 dollars per gasoline-equivalent gallon.

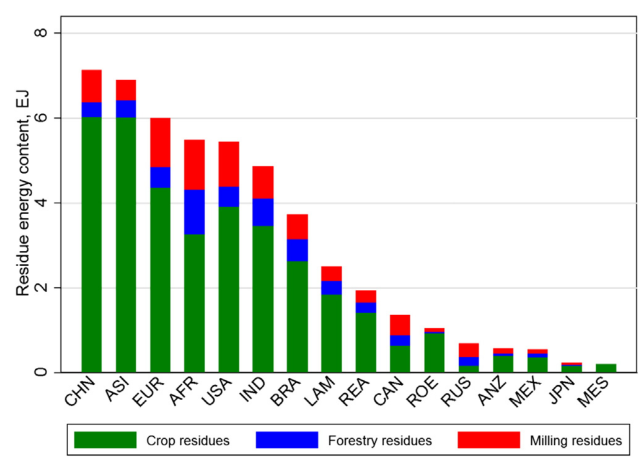

Fig. 5. Residue biomass potential by type and region in 2004 (EJ). *Source:* Authors' aggregation of estimates from Gregg and Smith (2010).

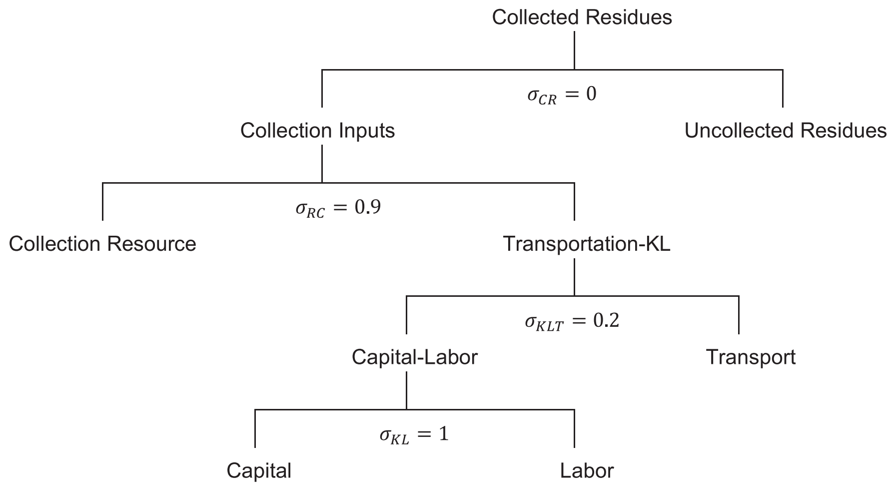

Fig. 6. Production of collected biomass residues.

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 United States and estimates of how these policies may evolve in the future. To capture the EU policy, we impose minimum energy 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 onward. For the United States, 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 Fig. 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 a (set exogenously; $0 < a < 1$) permits for each GEG of fuel sold. Under such a system, a 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 a. For the United States, we include a separate permit system for each fuel type mandated.

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 Fig. 9. In most scenarios, 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 toward 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 toward 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 Fig. 8. Specifically, each GEG of ethanol requires an ethanol permit, and λ permits are

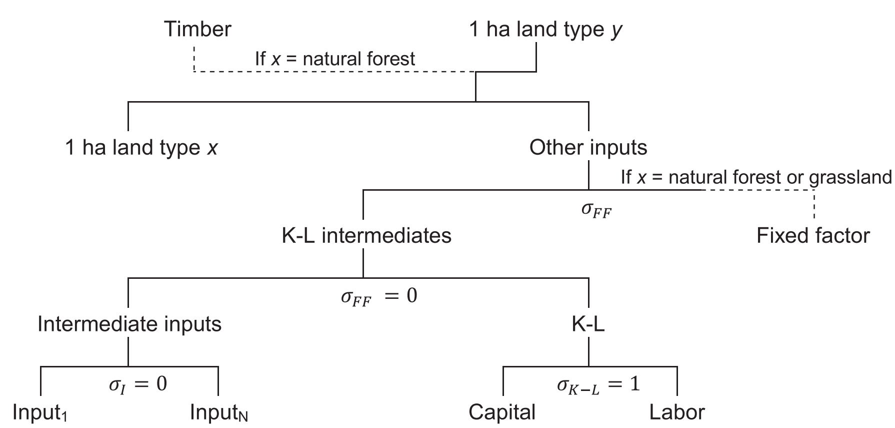

Fig. 7. Land conversion in the EPPA model. Note: Values for σ_{FF} vary by region and are assigned so that the model represents observed relationships between changes in land prices and the conversion of natural areas, as calculated by Gurgel et al. (2007, Table 5).

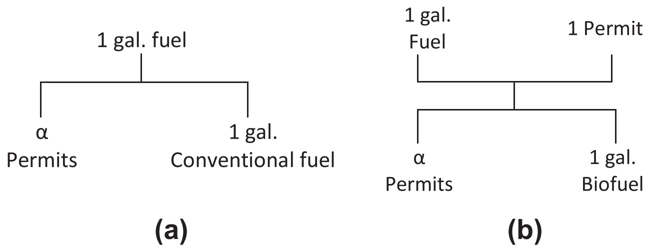

Fig. 8. Production and blending of renewable fuel permits into (a) Conventional fuel and (b) Biofuels.

"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.

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

To address key uncertainties about bioenergy outcomes noted in the introduction, we design scenarios that differ with respect to costs for new pathways, the development of infrastructure and technologies concerning the blend wall, future crop yields, and land use policies. Specifically, we simulate a reference scenario to be used as a benchmark for five additional scenarios that implement a global climate policy under alternative 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 United States; however, it does not include the EU Emissions Trading Scheme.

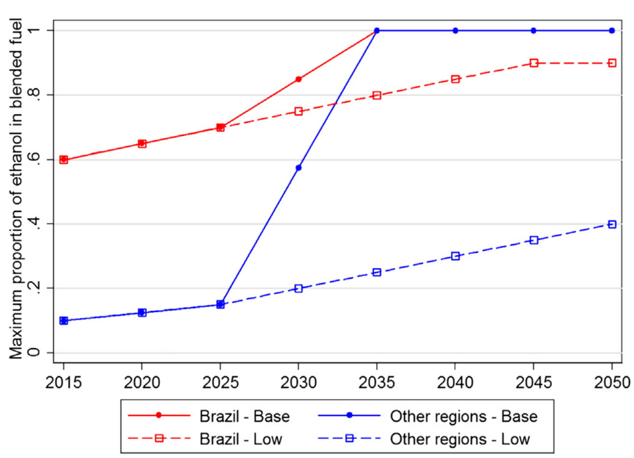

Fig. 9. Maximum proportion of ethanol in gasoline-ethanol fuel blends by volume.

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 United States
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 change, including changes in emissions due to soil carbon accumulation

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 carbon price 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.[5] 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 \$25 (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.

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 Fig. 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 those from soil carbon accumulation.[6]

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

5 This policy is chosen to create conditions favorable for bioenergy rather than to represent a likely outcome of policy negotiations. That is, our goal is to examine the potential of bioenergy and associated impacts, not to evaluate a current or proposed policy.

6 See Kriegler et al. (2014) for a discussion of obstacles associated with regulating emissions from land-use change.

Table 5
Summary of global results in 2050.

	Reference	Base policy	Low ethanol blending	Expensive LC ethanol	Low crop yield	Land carbon
Welfare change (%)*	–	−3.5	−3.1	−2.9	−3.4	−4.2
CO_2e emissions (MMt)	74,131	43,180	44,466	45,828	43,124	35,627
Primary bioenergy (EJ)	28.2	142.6	99.5	72.7	136.5	150.9
Final bioenergy (EJ)	14.5	68.4	50.0	38.6	64.6	75.7
Bioenergy land (Mha)	13	158	97	76	160	361
Natural Forest land (Mha)	3,994	3,828	3,817	3,815	3,775	4,883
Food crop land (Mha)	1,765	1,634	1,674	1,681	1,726	1,609
Change in food use (%)*						
Due to policy	–	−4.5	−3.5	−3.7	−4.3	−5.6
Due to bioenergy	–	−1.7	−0.7	−0.9	−1.3	−1.9
Change in food price (%)*						
Due to policy	–	4.3	3.5	3.2	4.1	5.2
Due to bioenergy	–	3.2	1.3	1.7	2.7	3.5

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

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 (and bioenergy mandates are not enforced). 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 Figs. 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) \$25/tCO_2 in 2015, rising to \$98.7/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.

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 efficiency improvements and energy use reductions, resulting in global primary energy use of 515.6 EJ in 2050 (compared to 699.73 EJ in the *Reference* scenario) (Fig. 10a). The carbon price also reduces energy from coal and oil and promotes energy from low-carbon sources, including biomass. Similar changes are observed for electricity (Fig. 10b). In 2050, the *Base Policy* scenario shows 22% less electricity consumption and 81% less electricity from coal (relative to *Reference*). Biomass electricity and electricity produced as a co-product with biofuels reach a combined total of 14 EJ, or 11% of total production (compared to 0.6 EJ in the *Reference* scenario). Transportation fuels are also affected (Fig. 10c). In 2050, the *Base Policy* total transportation fuel use is 14% less (relative to *Reference*), ethanol accounts for 97% of global private transportation fuel energy use, and from 2015 to 2050, the biofuels share of total transportation fuels rises from 2% to 42% (whereas in the *Reference* scenario, it rises to just 6%).

In the *Base Policy* case, greater use of biomass and other abatement options decrease total GHG emissions by 42% relative to *Reference* (see Table 5). Net of climate benefits, the *Base Policy* carbon price reduces global welfare in 2050 by 3.5% 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 United States and the cost competitiveness of some biomass technologies, primary bioenergy rises from 7.3 EJ in 2015 to 28.2 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 142.6 EJ in 2050 (predetermined by our ~150 EJ target), or 68.4 EJ of final energy (Figs. 11 and 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 United States 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.[7] This result is consistent with findings from Calvin et al. (2014), who find that second-generation biofuels are the dominant source of bioenergy under certain policy assumptions.

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.[8]

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

[7] 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 to 2030, and 160 new plants per year from 2035 to 2050. For comparison, 31 first-generation ethanol plants were built in the US in 2009 and 30 in Brazil in 2008 (GAIN, 2013; RFA, 2014).

[8] 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.

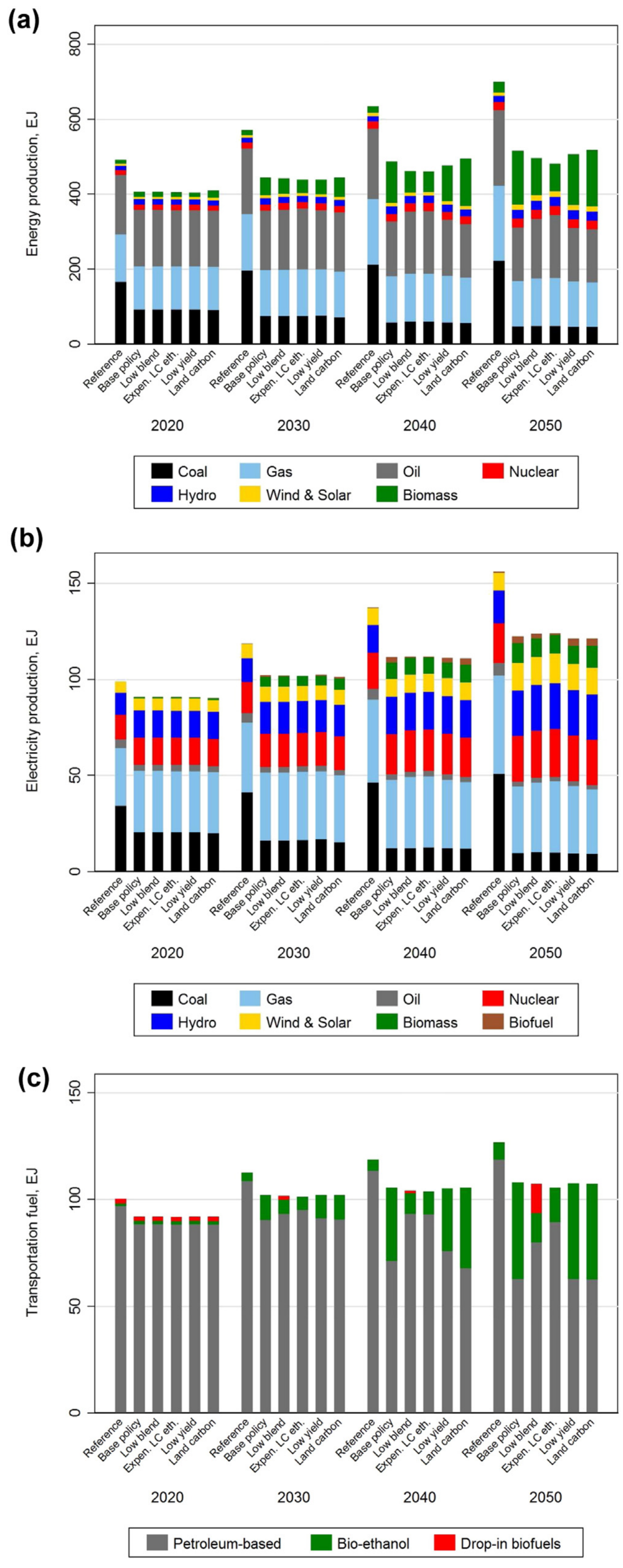

Fig. 10. Global production of (a) primary energy, (b) electricity, and (c) transportation.

source of bioenergy after 2030 (Fig. 13). By 2050, forestry and agricultural residues combined account for 21.8 EJ (or 32%) of final bioenergy.

The largest bioenergy producers in the *Base Policy* scenario are Africa (13.2 EJ of final bioenergy) and Brazil (12.1 EJ) (see Fig. 14).[9] 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; Russia, which primarily produces bioheat; and the United States, which mostly produces LC ethanol. Sugarcane ethanol, produced in Brazil, is the only first-generation biofuel still produced in 2050.

The carbon price and bioenergy production induce changes in land use (see Figs. 15 and 16). In 2050, in the *Reference* case, global land use includes 1,765 million hectares (Mha) for food crops and 12.6 Mha for bioenergy crops; in the *Base Policy* scenario, food crops use 1,634 Mha and bioenergy crops use 158 Mha. The additional bioenergy cropland in the *Base Policy* scenario comes at the expense of food crops, and also natural forestland—natural forest area in 2050 is 166 Mha lower than in the *Reference* case, mainly due to deforestation in Africa (86 Mha), Other Latin America (63 Mha), and Brazil (19 Mha) (Fig. 17a).

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 United States, the energy grass yield increases by 60% 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 60% more fuel in 2050 (1,873 GEGs per ha) than in 2015 (1,166 GEGs per ha).

Food use and prices are also affected (see Table 5) through at least two channels: (1) the carbon price increases production costs throughout the economy, which decreases real incomes, and (2) bioenergy production drives up land prices. As a result, relative to the *Reference* case, in 2050, the *Base Policy* global food price increases by 4.3% and food use decreases by 4.5%.[10] For comparison, in the *Reference* case, global food prices increase by 7.2% between 2015 and 2050. The reduction in food use is partially driven by a substitution effect, including using more other inputs so that food is used more

[9] Gurgel et al. (2007) and Melillo et al. (2009) also find that Africa and Latin America are major bioenergy producers when GHG emissions are constrained.

[10] 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 the price and the income elasticity of demand for food, respectively.

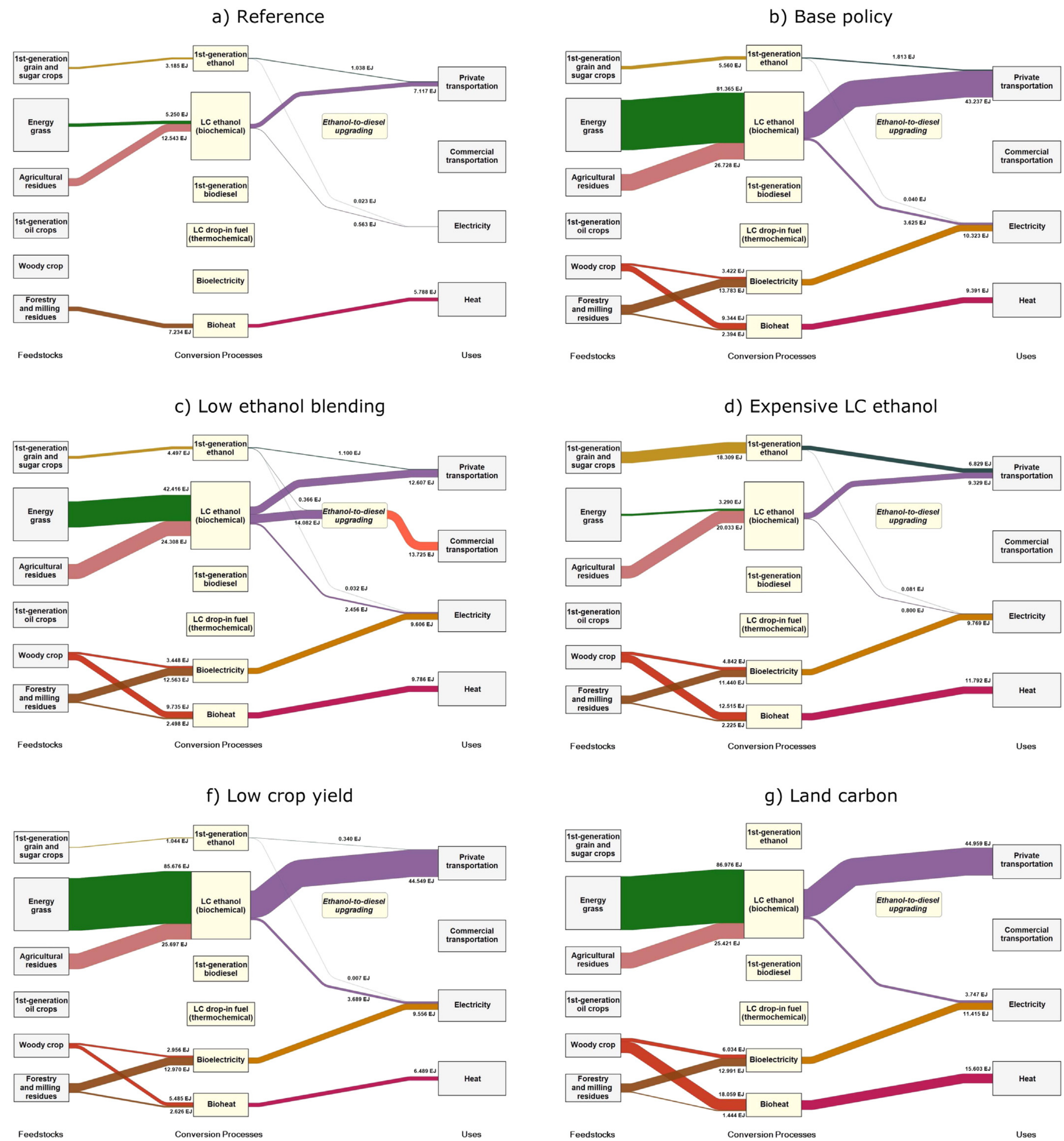

Fig. 11. Global biomass production, energy conversion and end use in 2050, EJ.

efficiently (e.g., reducing waste). Therefore, although the model does not track calories, food-use reduction percentages given do not solely represent reductions 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 3.2% and decreases food consumption by 1.7%.

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

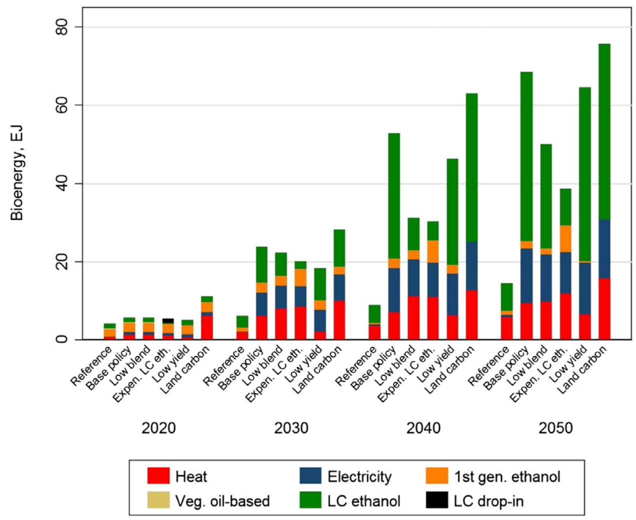

Fig. 12. Global final bioenergy by energy type.

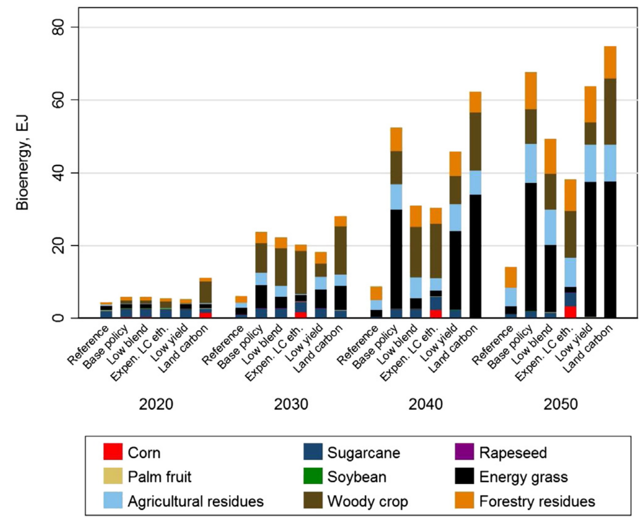

Fig. 13. Global final bioenergy production by feedstock.

economy relative to the *Reference* case, which by assumption was the optimal economic outcome (subject to prevailing constraints).[11]

Bioheat and dedicated bioelectricity production increase relative to the *Base Policy* case, although there is a decrease in total biomass electricity due to the reduced production of electricity as a LC ethanol co-product. Ethanol-to-diesel upgrading remains through 2050 due to the tighter blend wall constraints. In 2050, 34% of global ethanol production is upgraded to diesel, which results in 13.7 EJ of diesel from ethanol. 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 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 the production of first-generation ethanol relative to other cases. In 2050, global ethanol production is 3.1 EJ from corn (mainly in the United States) and 3.7 EJ from sugarcane (principally in Brazil), whereas global LC ethanol production is just 9.3 EJ (compared to 43.2 EJ in the *Base Policy* case). The blend wall is binding between 2015 and 2025, which induces the production of LC drop-in fuels (1.3 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 the 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 United States 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 the 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, 1,765 Mha of land are used for food crops in the *Reference* scenario when yields increase by 1% per year, and 1,855 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 (4.1%) and consumption (-4.3%) are also similar.

[11] 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.

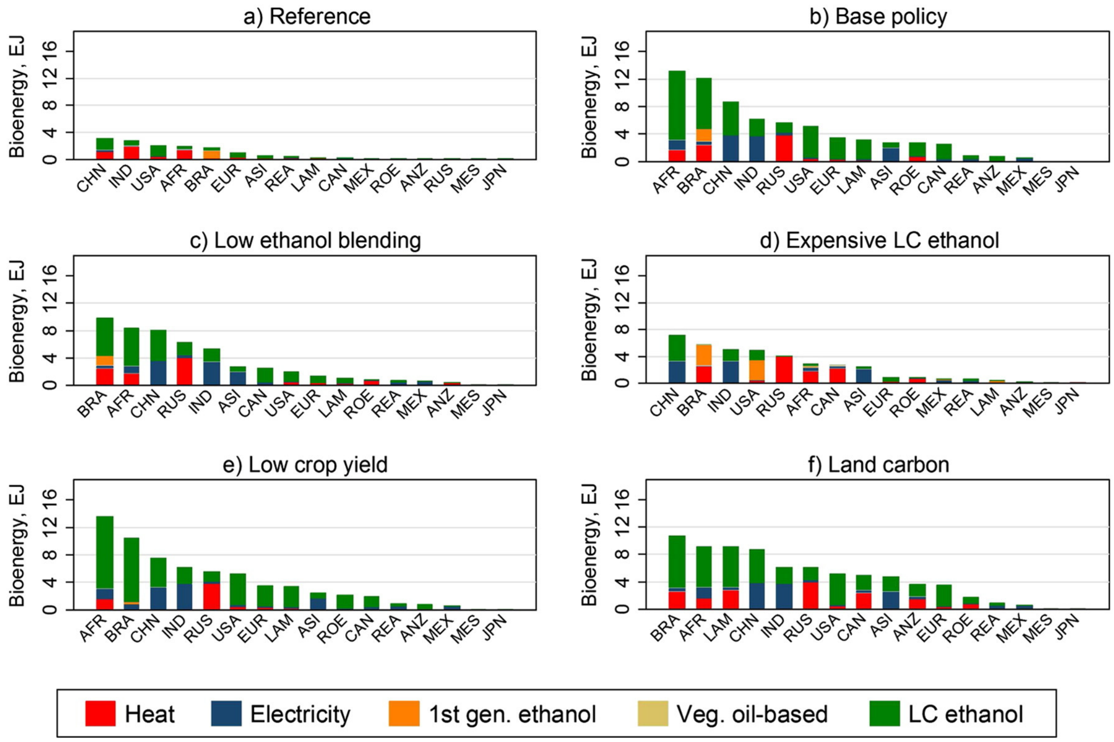

Fig. 14. Regional final bioenergy by scenario in 2050.

5.5. The Land Carbon scenario

In this scenario, we price emissions from land use and land-use change to provide incentives to protect existing natural forests and 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

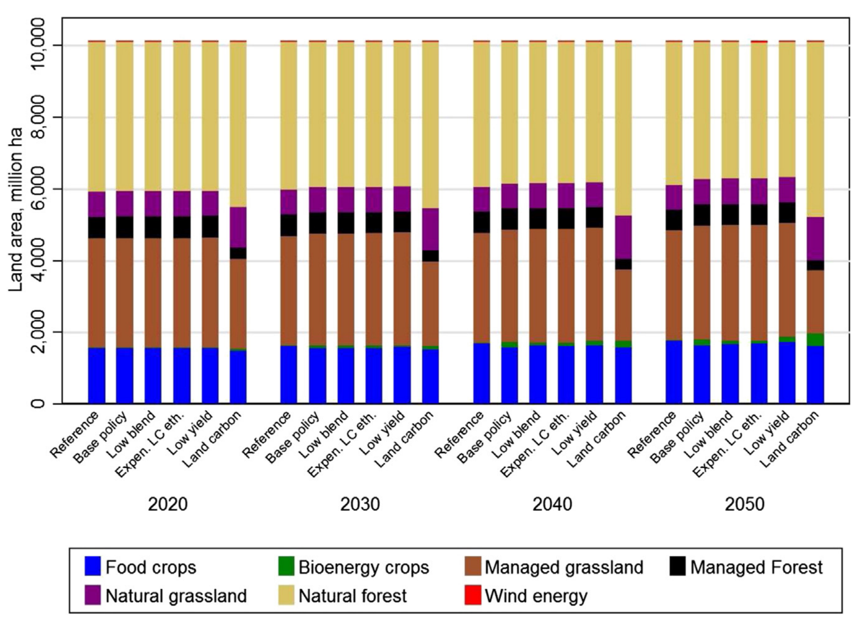

Fig. 15. Global land use, million ha. *Note:* Land unsuitable for growing vegetation is not represented.

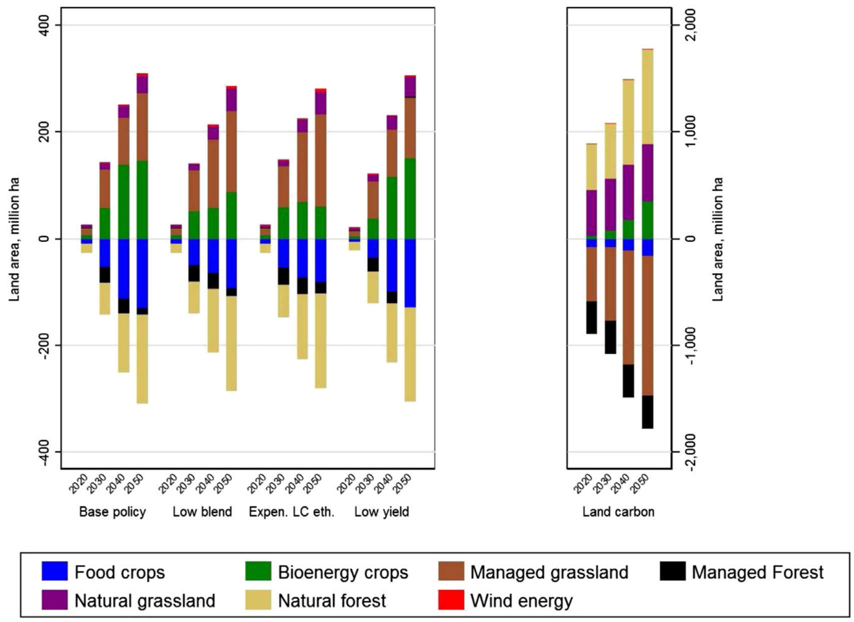

Fig. 16. Global land-use change relative to the *Reference* scenario, million ha.

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 661 Mha between 2010 and 2050, and there is 1,056 Mha more natural forest land in 2050 than in the *Base Policy*. Regions with the largest increases in natural forest area relative to the *Base Policy* scenario are Africa (712 Mha in 2050) and Other Latin America (160 Mha in 2050).

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 (-5.6%) and the food price (5.2%) 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

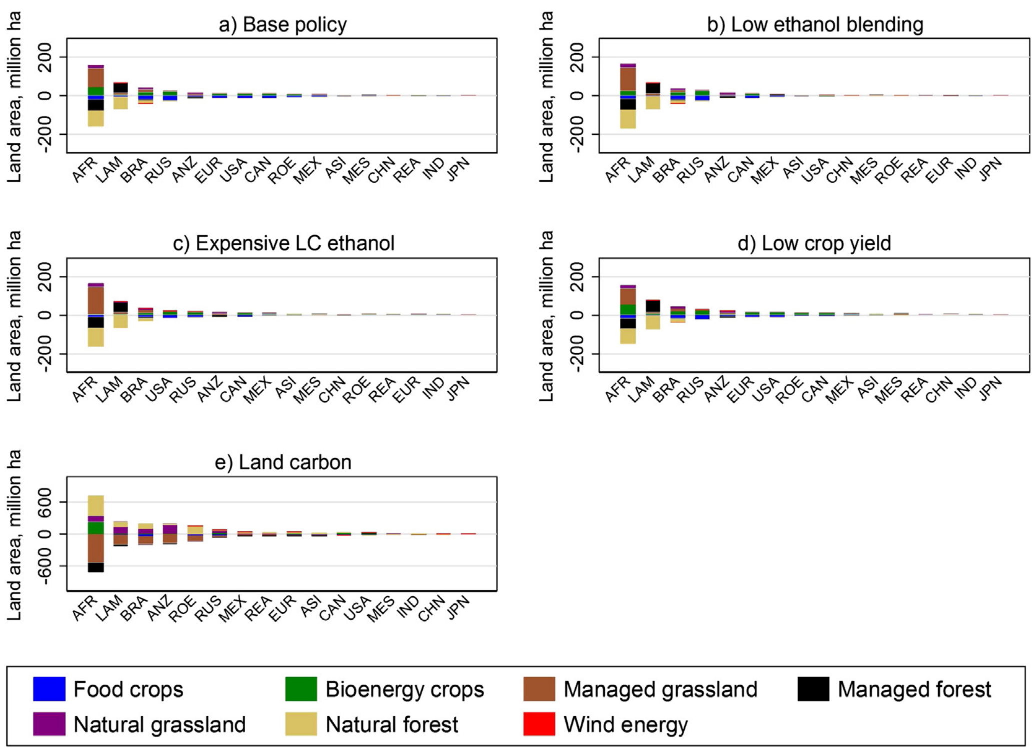

Fig. 17. Regional land-use change relative to the *Reference* scenario in 2050, million ha.

35,627 million metric tons (MMt), compared to 43,180 MMt in the *Base Policy* case. 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.

6. Discussion and implications

In our simulations, we created a policy scenario where primary energy from biomass reaches ~150 EJ by 2050, on the order of oil, gas, or coal today. This level appears technically achievable, agreeing with previous literature that concluded that an industry of 100 to 300 EJ was feasible in the 2050 time horizon. Our results provide insights into three important aspects of bioenergy: (1) changes in food prices and consumption, (2) technology pathway choices, and (3) land-use change impacts.

There has been much concern that even the current, relatively small level of bioenergy production, is a threat to food prices and food supply. This has focused attention on forms of biomass energy that supposedly would not compete with food production. What would constitute such biomass sources is not always agreed. While dedicated woody biomass or perennial grass crops are not directly used for human food, neither is most of the corn crop in the United States that has been diverted to ethanol production. Moreover, the co-products of corn ethanol or soybean oil can be used as animal feed and so the actual diversion of feed from livestock is considerably less than the acreage of the crop going to the ethanol plant. Whereas a dedicated biomass crop may generate a higher energy return per hectare, none of the crop ends up as animal feed, and so the direct accounting of energy per hectare is a misleading calculation. In addition, even dedicated biomass crops compete for land with food and feed crops, and the bid up of land prices would still affect food crops and food prices. Thus, the more important medium- and long-run concern is that on land prices because that will ripple through and affect all crops. We do not see the level of biomass supply strongly affecting food prices, the increase are on order of 1.3% to 3.5% compared to a baseline with limited biomass energy.

Two factors explain this result. First, our analysis is relevant to the medium- to long-term where the agriculture system has the opportunity to adjust. This is a considerably different situation than that which existed in 2007–2010, when the large increase in corn ethanol came as a surprise in an already tight market where there were coincidentally other disruptions, and policy interventions by some large exporters to restrict exports aggravated the market response. Second, and relatedly, markets can adjust on several margins: yields can expand, activities can be intensified on existing crop and pasture land, more land can be converted from other uses to provide traditional food, feed and forest supplies, and demand can adjust.

In terms of competition for food and feed crops, the use of crop and forest residues would clearly not compete, and, in fact, with enough demand for the residue and a positive price for it, the supply of crops and forest products might actually be stimulated if their profitability increased due to revenue from residues. However, the design of a policy to limit bioenergy to use of waste has always been troubling to us: If the economics were to push up the value of waste derived energy, it would create economic incentives to "produce" waste, by utilizing less of the forest harvest for wood products and more for energy, or similarly growing a corn crop that maximized "residue" rather than grain yield. We find, however, relatively little demand for forest or agriculture residue because the cost of collecting and transporting the residue makes this "free" source of biomass more expensive than purpose grown crops.

Regarding bioenergy technology pathways, it appears that, at current costs, bioheat, bioelectricity, and some first-generation biofuels are to compete with conventional energy under moderate carbon prices. Significant penetration of LC ethanol relies on cost-reducing advances in technologies for this pathway. Higher energy yields for LC feedstocks compared to many first-generation crops and co-production of electricity means that the large-scale production of LC ethanol is possible if cost reductions are realized. In our simulations, there was limited scope for thermochemical (LC drop-in) biofuels, as they were more expensive than LC and first-generation ethanol. Furthermore, when the blend wall was binding, ethanol upgraded to diesel was often cheaper than thermochemical fuels.

Turning to deforestation, we found that absent a price on land-use change emissions, decreases in natural forest areas 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. That is, as agricultural markets are linked via international trade, incentivizing bioenergy will lead to deforestation in unprotected areas, regardless of the location of bioenergy production. This suggests that promoting bioenergy based on the location of production or even the type of bioenergy, as in many renewable energy policies, is a poor instrument to prevent emissions from land use change. Instead, the issue should be addressed directly by protecting forested areas or pricing emissions from land-use change.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.eneco.2015.06.016.

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