The Feasibility, Costs, and Environmental Implications of Large-scale Biomass Energy

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Joint Program on the Science & Policy of Global Change

Massachusetts Institute of Technology

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Motivation

- Several governments have implemented policies to promote bioenergy

- Large-scale bioenergy and/or afforestation is required to prevent large temperature increases

Approach

- Develop a detailed representation of bioenergy in the MIT Economic Projection and Policy Analysis (EPPA) model

  - A global applied general equilibrium model that links greenhouse gas emissions to economic activity (16 regions, 14 sectors)

- Simulated conditions favorable for bioenergy (and other low-carbon energy) using a carbon price

Regions in the EPPA model
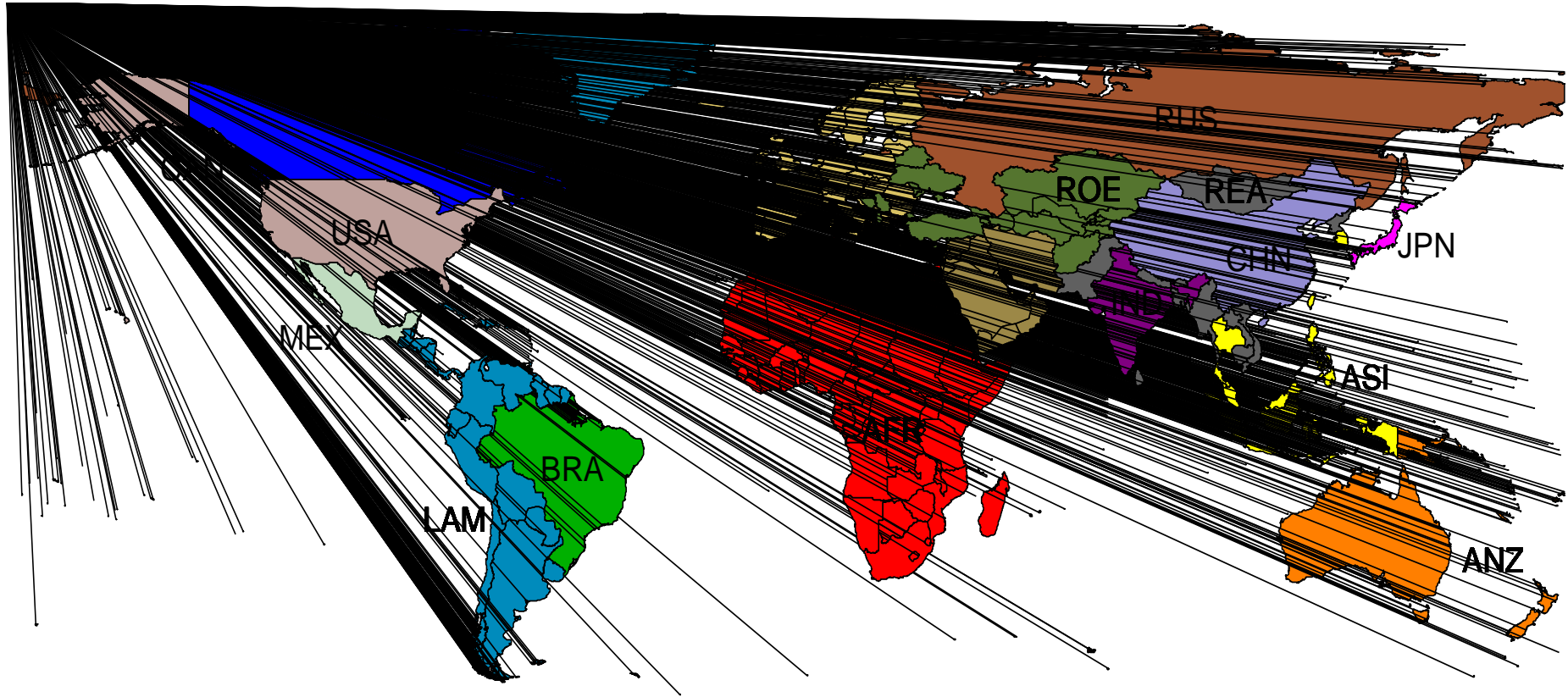
Bioenergy pathways considered in the EPPA model (for each region)
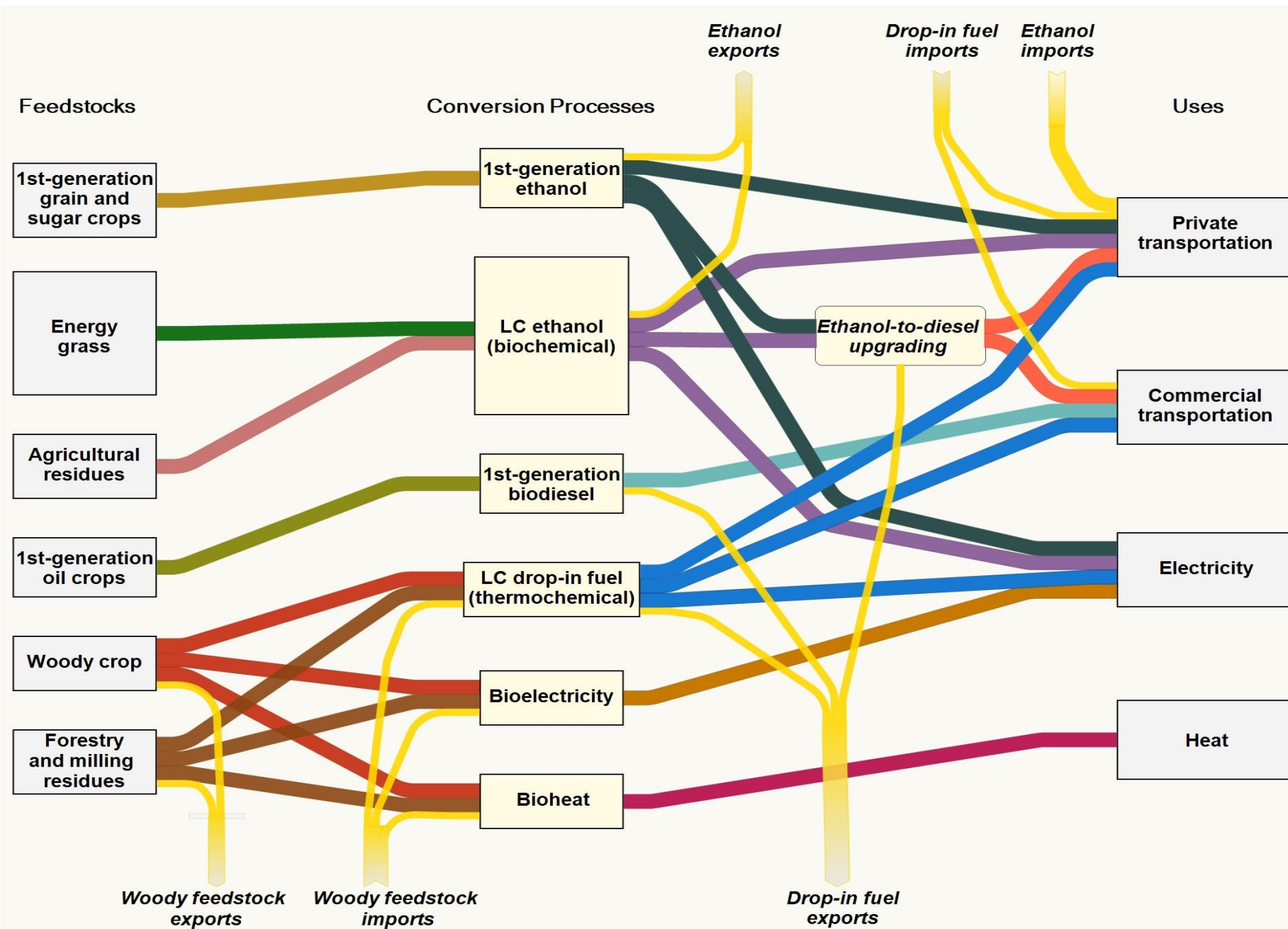
Production costs per gasoline-equivalent gallon, 2010 USD
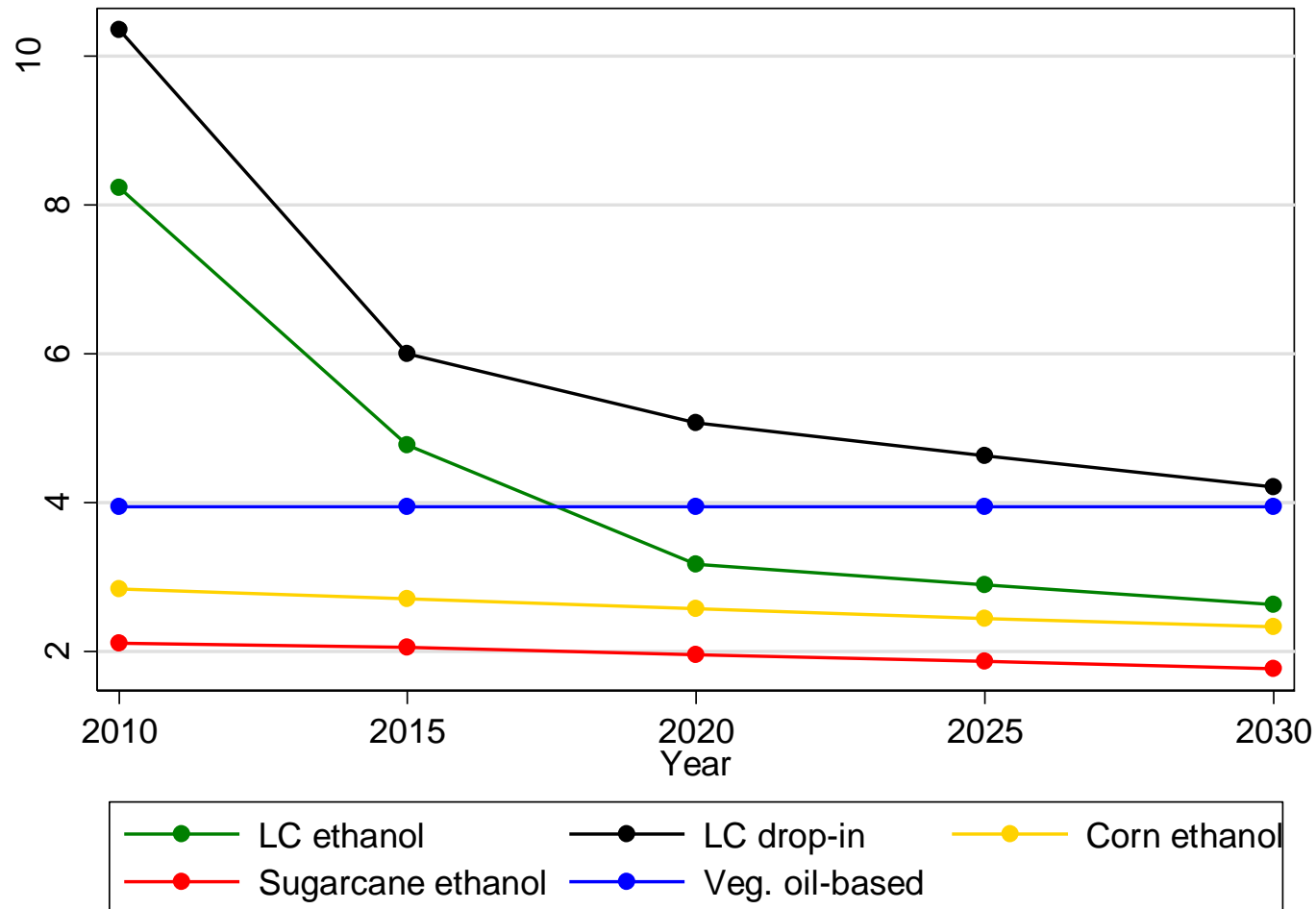
- Costs for corn ethanol, soybean diesel and LC fuels in the US at constant input prices, and sugarcane ethanol in Brazil
  - Costs across regions vary depending on crop yields and land costs

Design of scenarios

- Goal is to investigate a large-scale contribution of biomass to global energy demand

- Biomass energy (and other low-carbon energy) production is induced with a global price on GHG emissions

  - Goal of ~150 exajoules (EJ) of modern primary bioenergy ($\rightarrow$ ~75 EJ of final bioenergy) by 2050

  - Required carbon price was $25/tCO2e in 2015, rising by 4% per year to $99/tCO2e in 2050

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Scenarios

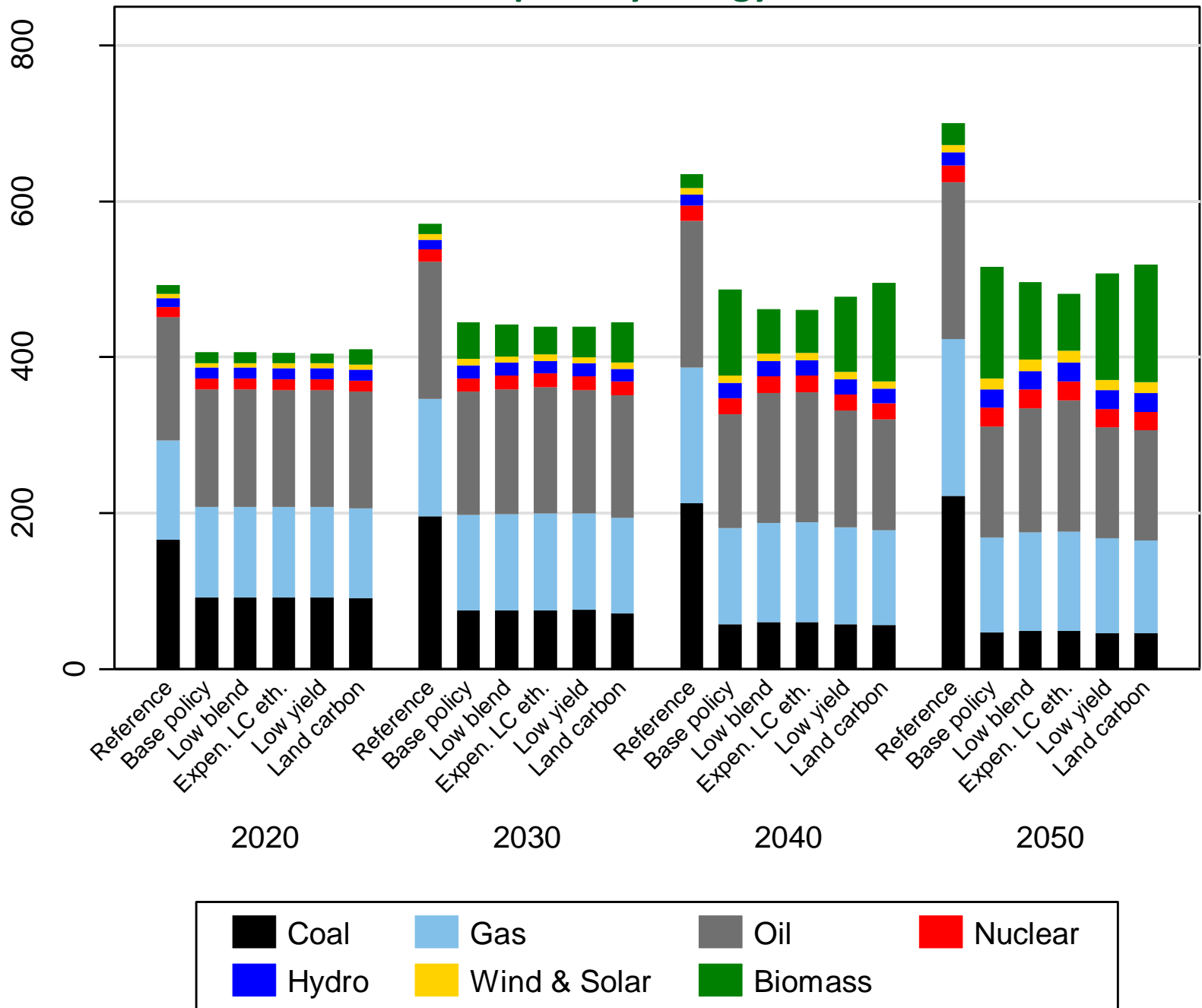| Name	Description
Reference	'Business as usual' assumptions about economic, population and productivity growth and extension of renewable fuel mandates in the EU and the US
Base policy	Global carbon price on all GHG emissions except those from land-use change of $25/tCO2e in 2015 and rising by 4% per year to $99/tCO2e in 2050
Low ethanol blending	Global carbon price simulated in the Base policy with tighter ethanol blending constraints
Expensive LC ethanol	Global carbon price simulated in the Base policy with 50% more expensive LC ethanol costs
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

Global primary energy

Legend:
- **Coal** (black)
- **Gas** (light blue)
- **Oil** (grey)
- **Nuclear** (red)
- **Hydro** (blue)
- **Wind & Solar** (yellow)
- **Biomass** (green)

Scenarios (for each of 2020, 2030, 2040, 2050): Reference, Base policy, Low blend, Expen. LC eth., Low yield, Land carbon

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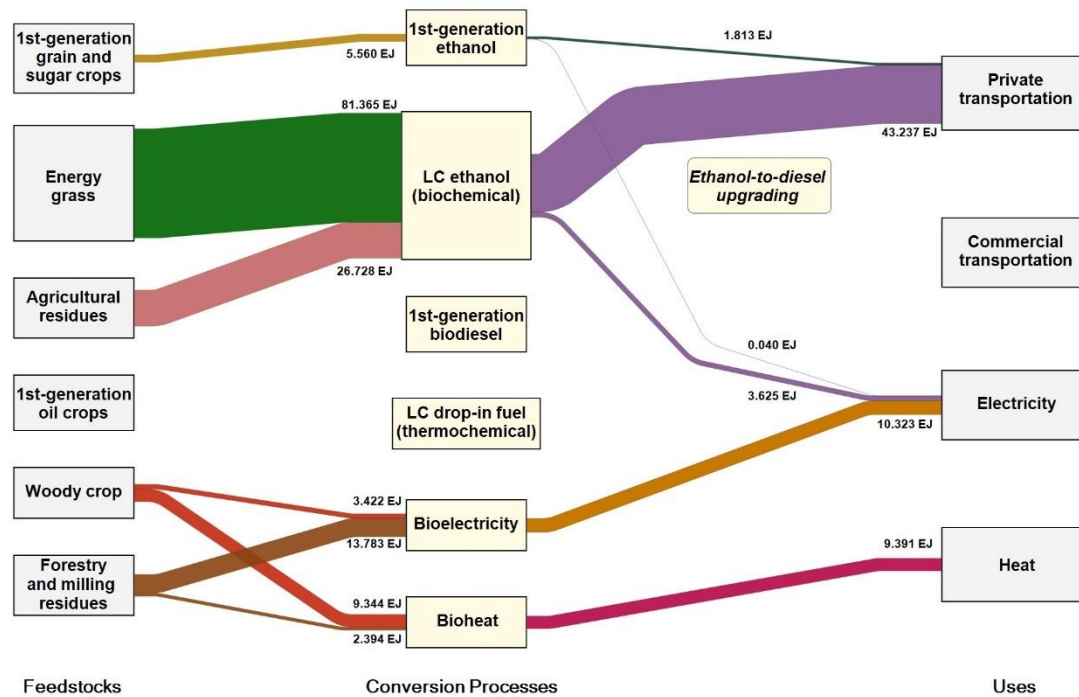
Global bioenergy in the Base policy scenario in 2050
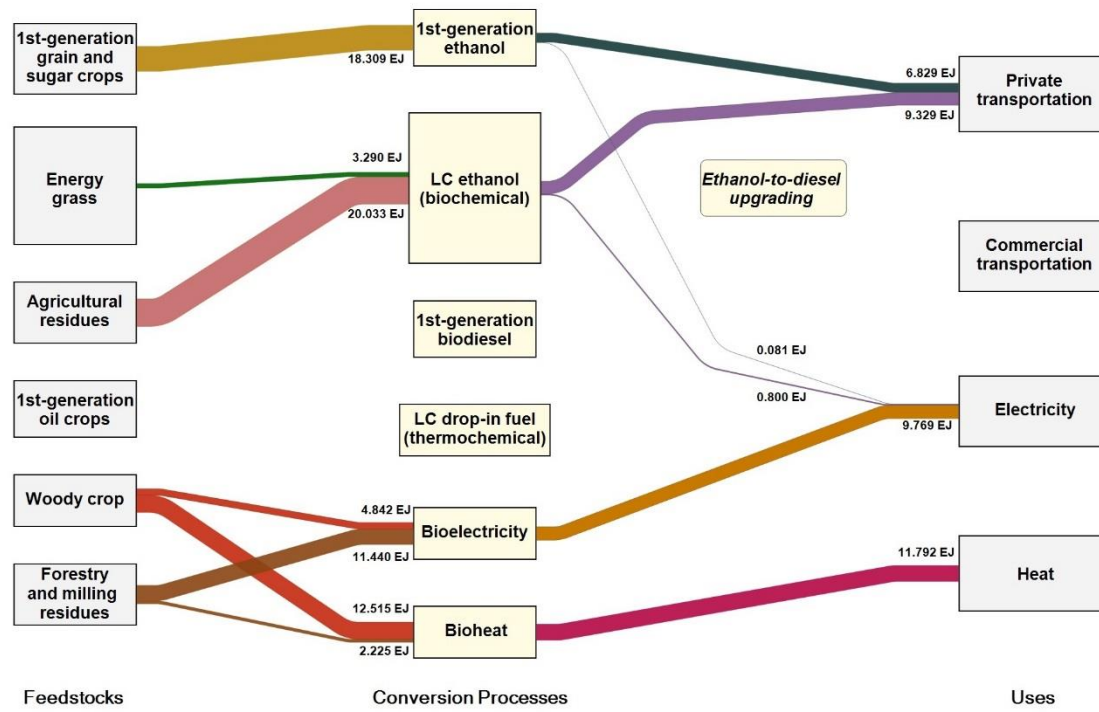
Global bioenergy in the Expensive LC ethanol scenario in 2050

Global land use

Legend:
- Food crops (blue)
- Bioenergy crops (green)
- Managed grassland (brown)
- Managed Forest (black)
- Natural grassland (purple)
- Natural forest (tan)
- Wind energy (red)
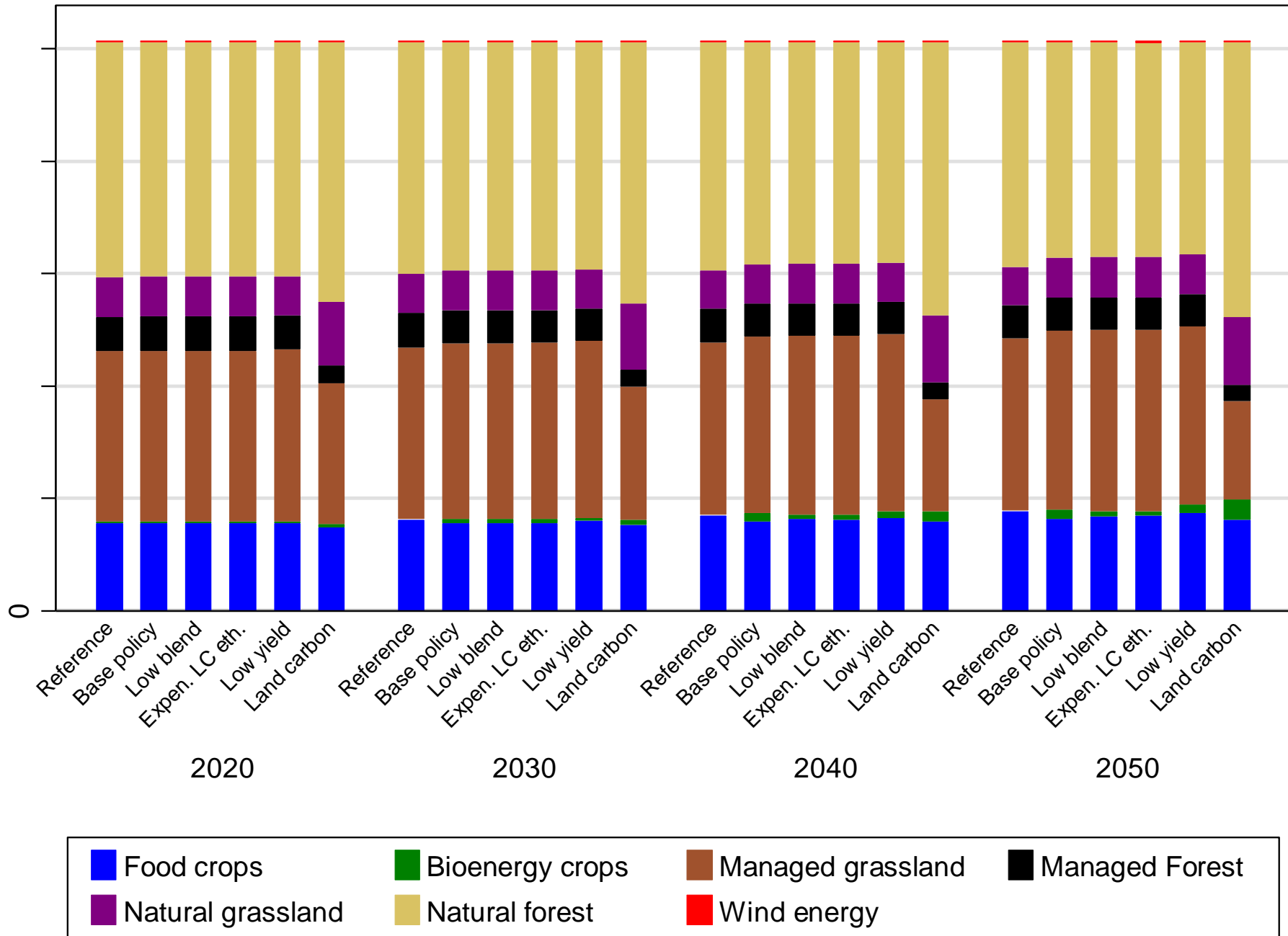
Note: 'Other land' is not represented.

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Global land-use change

Legend:
- Food crops (blue)
- Bioenergy crops (green)
- Managed grassland (brown)
- Managed Forest (black)
- Natural grassland (purple)
- Natural forest (tan)
- Wind energy (red)

X-axis groups: Base policy, Low blend, Expen. LC eth., Low yield, Land carbon
Each group shows years: 2020, 2030, 2040, 2050

Left Y-axis: Land area, million ha (−400 to 400)
Right Y-axis: Land area, million ha (−2,000 to 2,000)

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Regional land-use change relative to the reference scenario, 2050

a) Base policy

b) Low ethanol blending

c) Expensive LC ethanol

d) Low crop yield

e) Land carbon

Legend:
- Food crops
- Bioenergy crops
- Managed grassland
- Managed forest
- Natural grassland
- Natural forest
- Wind energy

Other global results in 2050

	Reference	Base policy	Low blending	Expensive LC eth.	Low 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
N. 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, % change relative to Reference						
Total	-	-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 % change relative to Reference						
Total	-	4.3	3.5	3.2	4.1	5.2
Due to bioenergy	-	3.2	1.3	1.7	2.7	3.5

Conclusions

- The impact of bioenergy production on food prices is limited by:

  - Price-induced improvements in crop yields and conversion efficiency, reduced food wastage and incentives to collect more residues

- Penetration of LC biofuels rely on large reductions in costs for these technologies, otherwise first generation biofuels remain in the fuel mix, and bioelectricty and bioheat are the major forms of bioenegry

- Regardless of the location of bioenergy production, deforestation is largest in regions with the lowest barriers to conversion of natural areas

  - Policies that specify life-cycle emissions reduction factors based on the location of bioenergy production (or even the type of bioenergy) are unlikely to be successful

Backup slides

The Economic Projection and Policy Analysis (EPPA5) model

- Global, recursive dynamic applied general equilibrium model

- Detailed representation of energy production and GHG emissions

- 16 regions and 14 broad sectors with multiple ways to produce some commodities (e.g., electricity)

- Advanced energy technologies and energy sources compete with conventional energy

- Represents six land types and land-use change: crop land, managed forest, natural forest, managed grassland, natural grassland, and other land
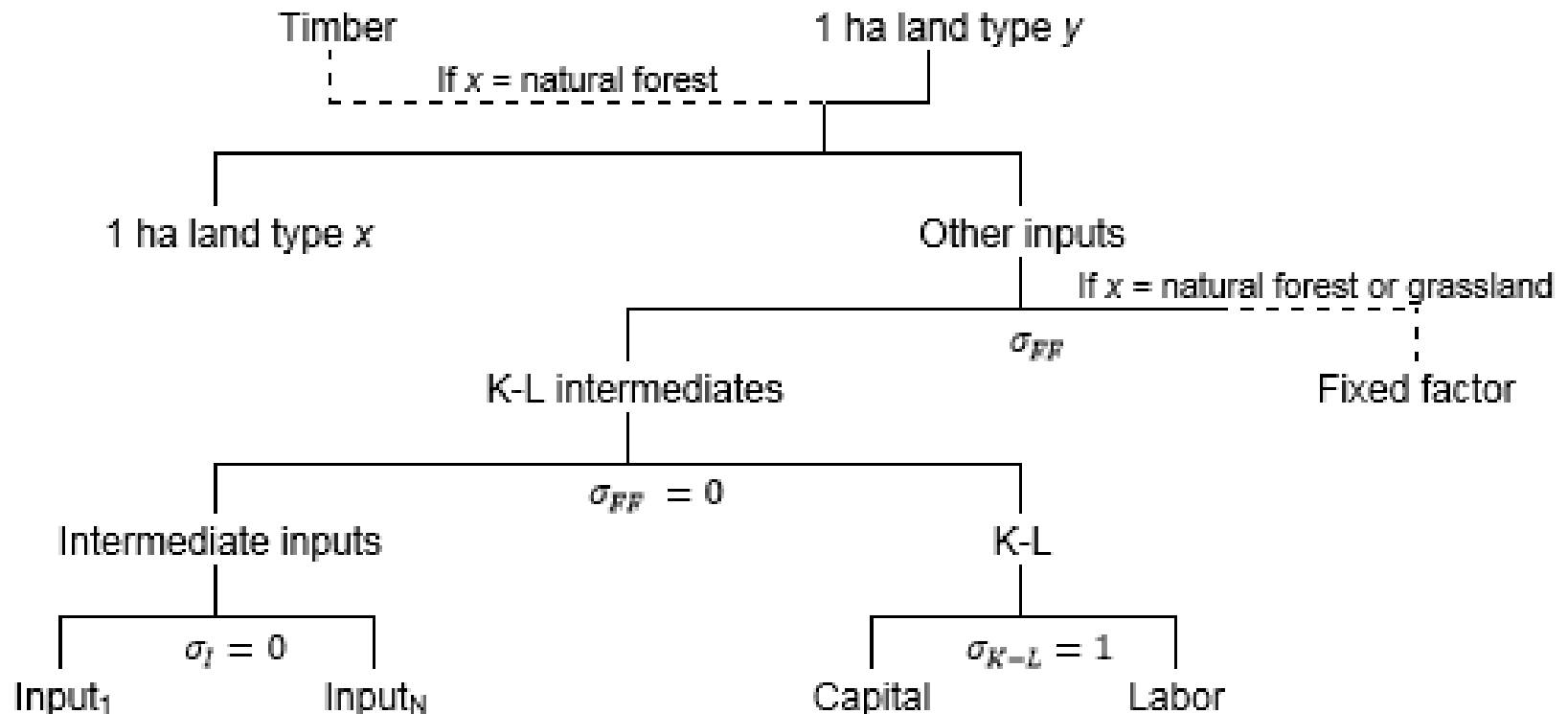
Note: *x*, *y* = crop land, managed forest land, natural forest land, managed grassland, natural grassland

The Economic Projection and Policy Analysis (EPPA) model

Factors/primary inputs and sectors in the EPPA for model

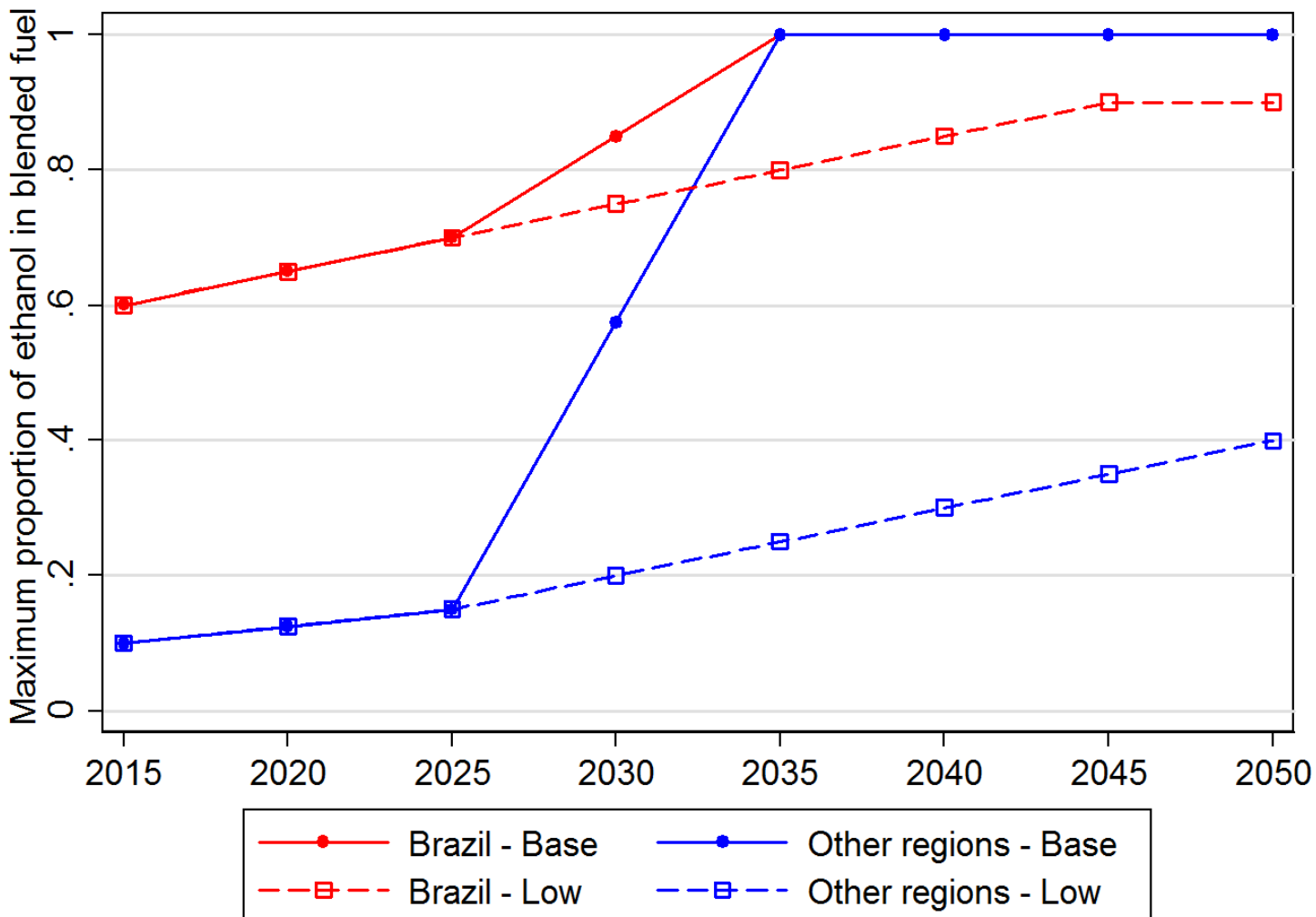| Factors/Primary inputs	Sectors

Capital
Labor
Land
    Crop land, managed forest, natural forest, managed grassland, natural grassland, other land
Resources
    For coal; crude oil; gas; shale oil; shale gas; hydro, nuclear, wind and solar electricity
	Crops
	Livestock
	Forestry
	Food
	Coal
	Crude Oil
	    Conventional and tight oil, oil sands, oil shale
	Refined Oil
	    From crude oil, first generation biofuels, cellulosic biofuels
	Gas
	    Conventional gas, shale gas, tight gas, coal-bed methane, synthetic gas from coal
	Electricity
	    Coal, gas, refined oil, hydro, nuclear, wind, solar, biomass, natural gas combined cycle, integrated gasification combined cycle, advanced coal and gas with CCS
	Energy Intensive Industry
	Other Industry
	Services
	Other Commercial Transportation
	Household Transportation
	    ICE vehicles, hybrid vehicles, plug-in electric vehicles

Table 2. Bioenergy crop yields, wet metric tons per hectare per year (unless stated otherwise).
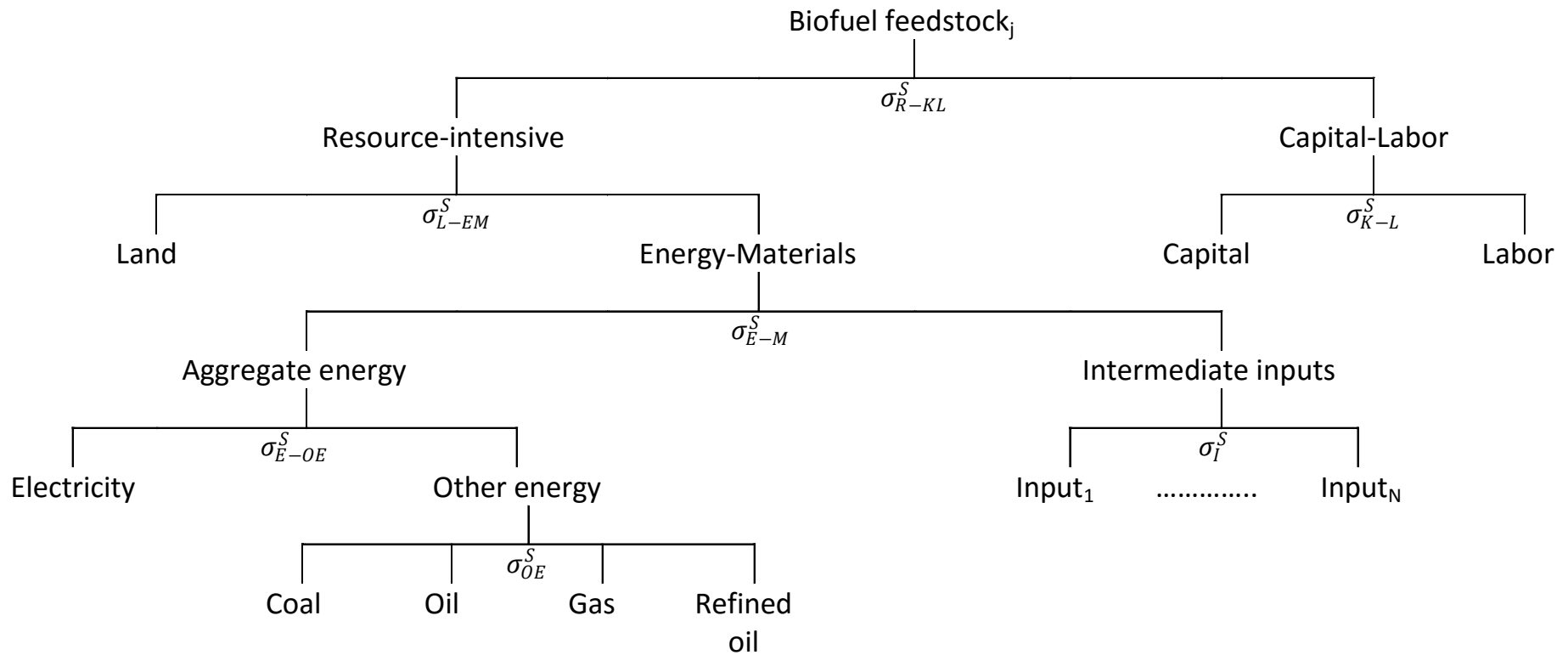
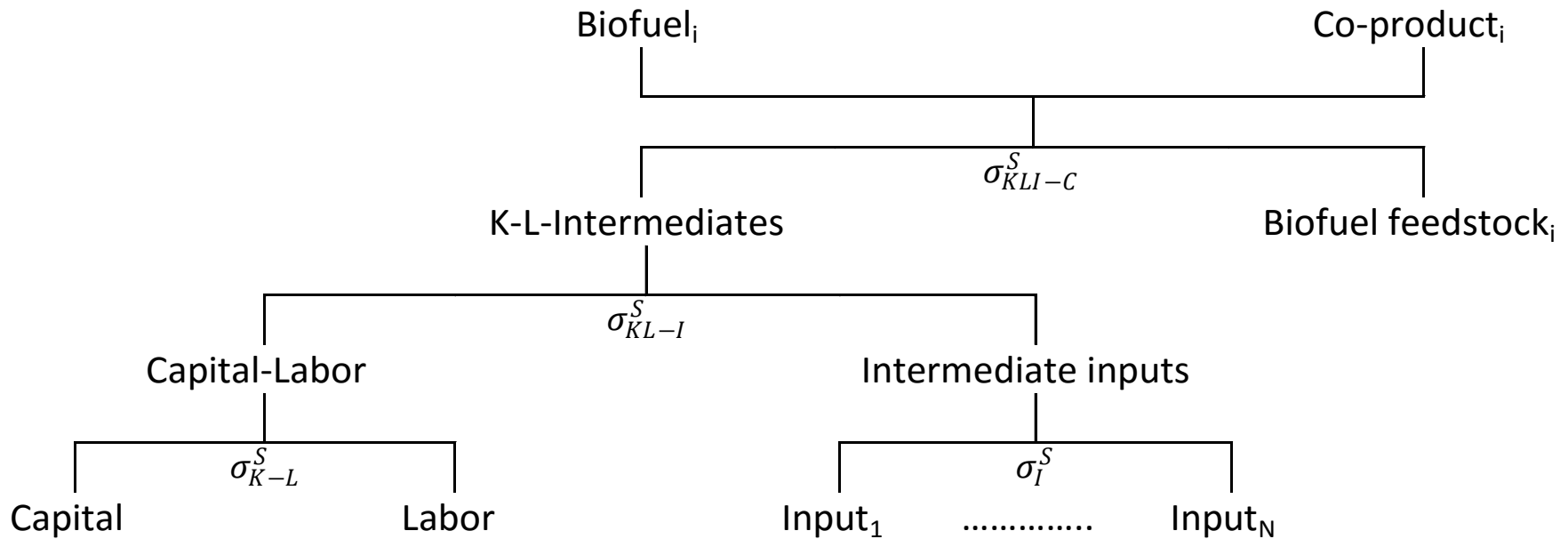|	USA	CAN	MEX	BRA	LAM	EUR	RUS	ROE	CHN	IND	JPN	ASI	REA	ANZ	MES	AFR
Corn	9.5	8.5	3.2	3.8	5.9	5.0	2.9	4.8	5.2	2.3	2.6	3.4	3.6	6.2	7.0	1.7
Rapeseed	1.4	1.5	1.3	1.3	2.2	2.5	1.2	1.3	1.9	1.1	1.2	1.2	0.9	1.0	2.1	1.2
Soybean	2.8	2.3	1.4	2.8	2.9	1.4	0.9	1.4	1.5	1.2	1.6	1.4	1.4	2.4	2.4	1.0
Sugar beet	63.2	55.2	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.

The Economic Projection and Policy Analysis (EPPA)

Maximum proportion of ethanol in blended fuel by volume in the Low ethanol blending (Low) and other scenarios (Base)

Biofuel feedstock$_j$

σ^S_{R-KL}

Resource-intensive

Capital-Labor

σ^S_{L-EM}

Land

Energy-Materials

σ^S_{K-L}

Capital

Labor

σ^S_{E-M}

Aggregate energy

Intermediate inputs

σ^S_{E-OE}

Electricity

Other energy

σ^S_I

Input$_1$ .... Input$_N$

σ^S_{OE}

Coal   Oil   Gas   Refined oil

Biofuel crop production (j = corn, sugarcane, sugar beet, wheat, palm fruit, rapeseed, soybeans, energy grass, woody crop)

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Biofuel$_i$ Co-product$_i$

$$\sigma^S_{KLI-C}$$

K-L-Intermediates   Biofuel feedstock$_i$

$$\sigma^S_{KL-I}$$

Capital-Labor   Intermediate inputs

$$\sigma^S_{K-L}$$ $$\sigma^S_I$$

Capital   Labor   Input$_1$ …………..   Input$_N$

Biofuel production (*i* = corn ethanol, sugarcane ethanol, sugar beet ethanol, wheat ethanol, palm oil diesel, rapeseed diesel, soybeans diesel, LC ethanol, LC drop-in fuel)
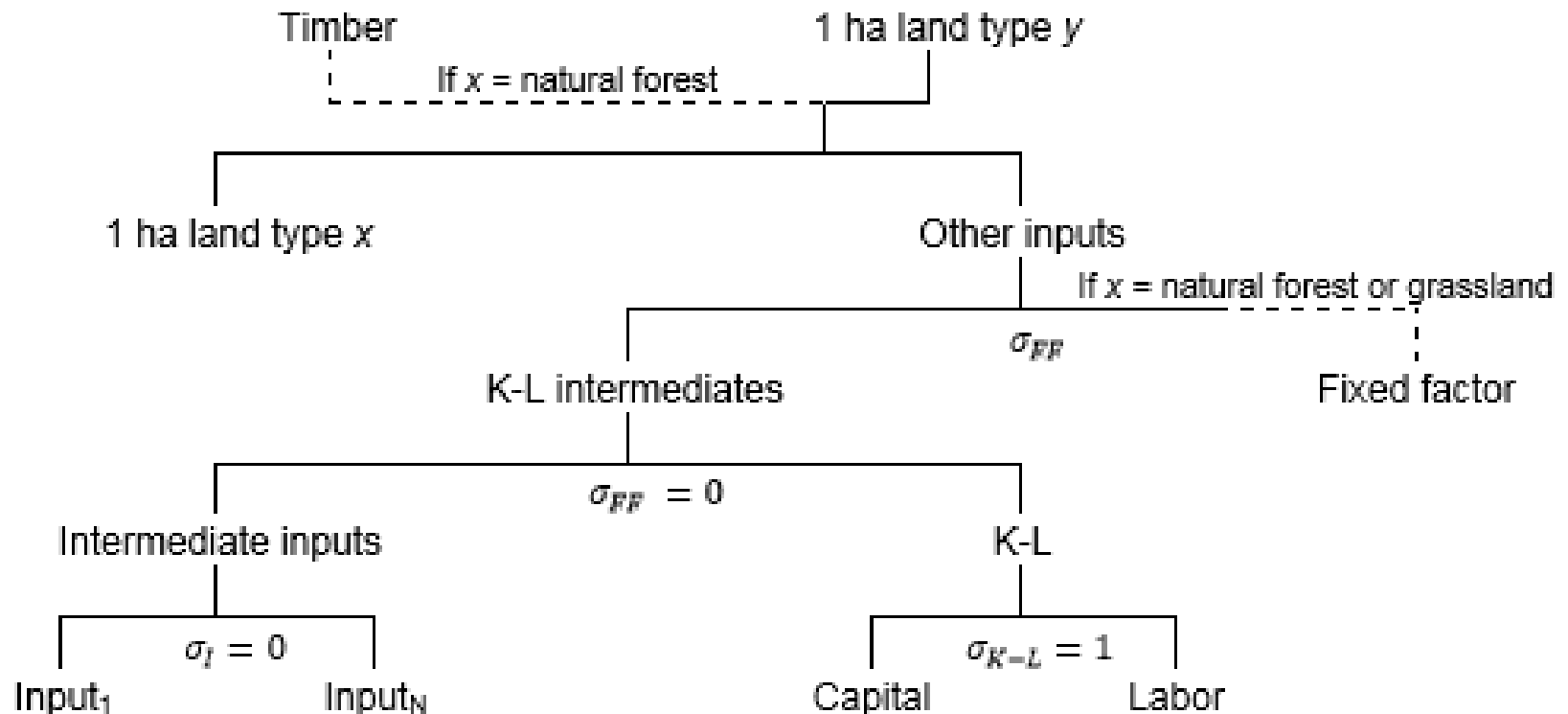
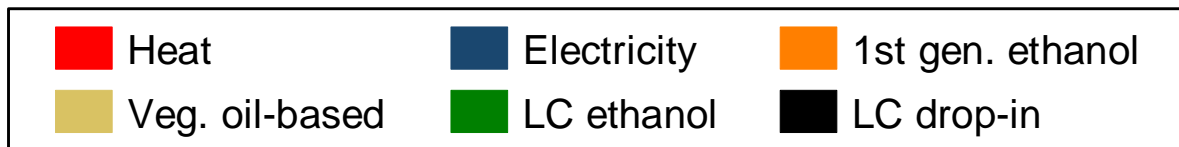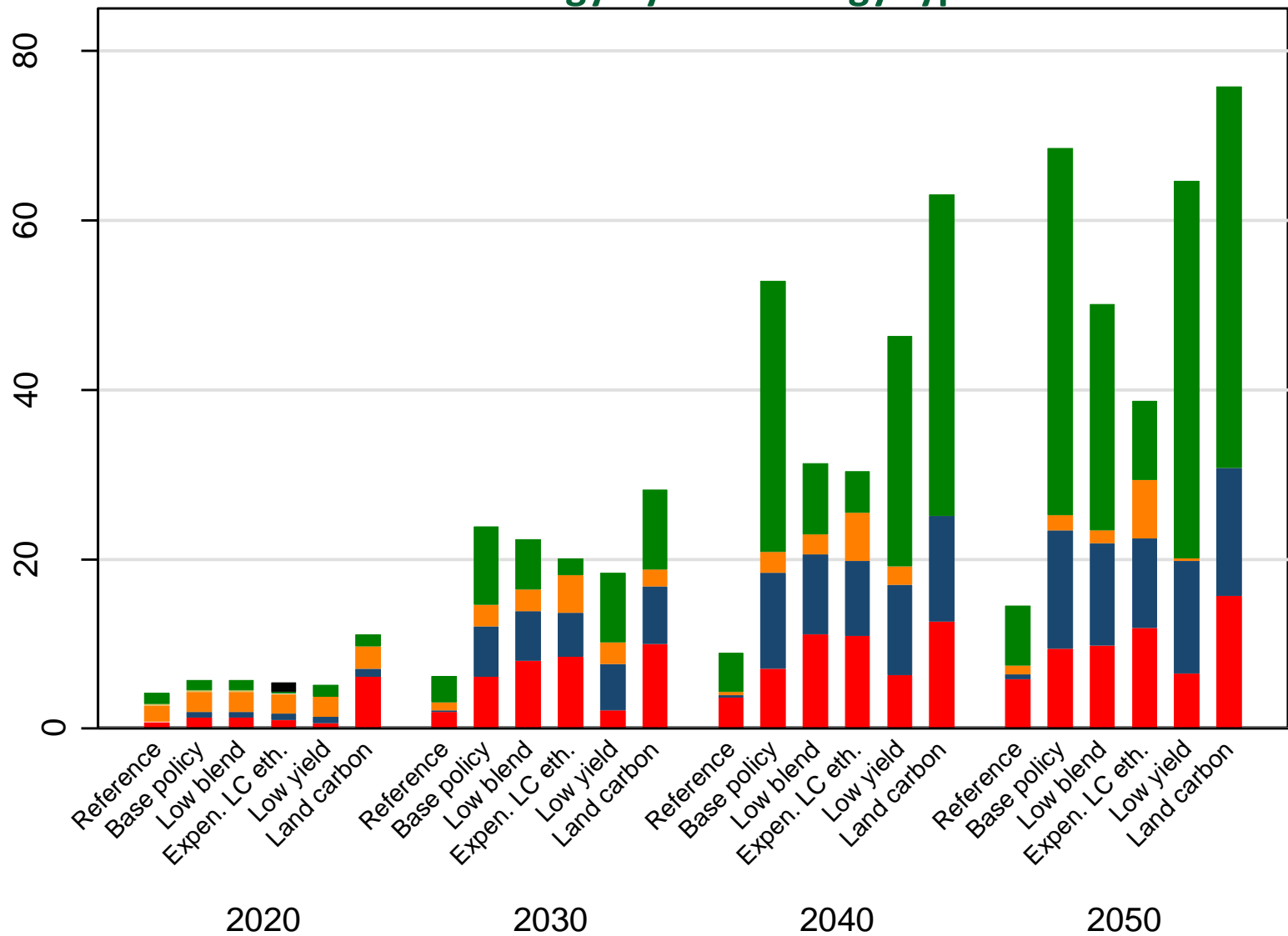GLOBAL CHANGE

Land-use change

Note: *x*, *y* = crop land, managed forest land, natural forest land, managed grassland, natural grassland

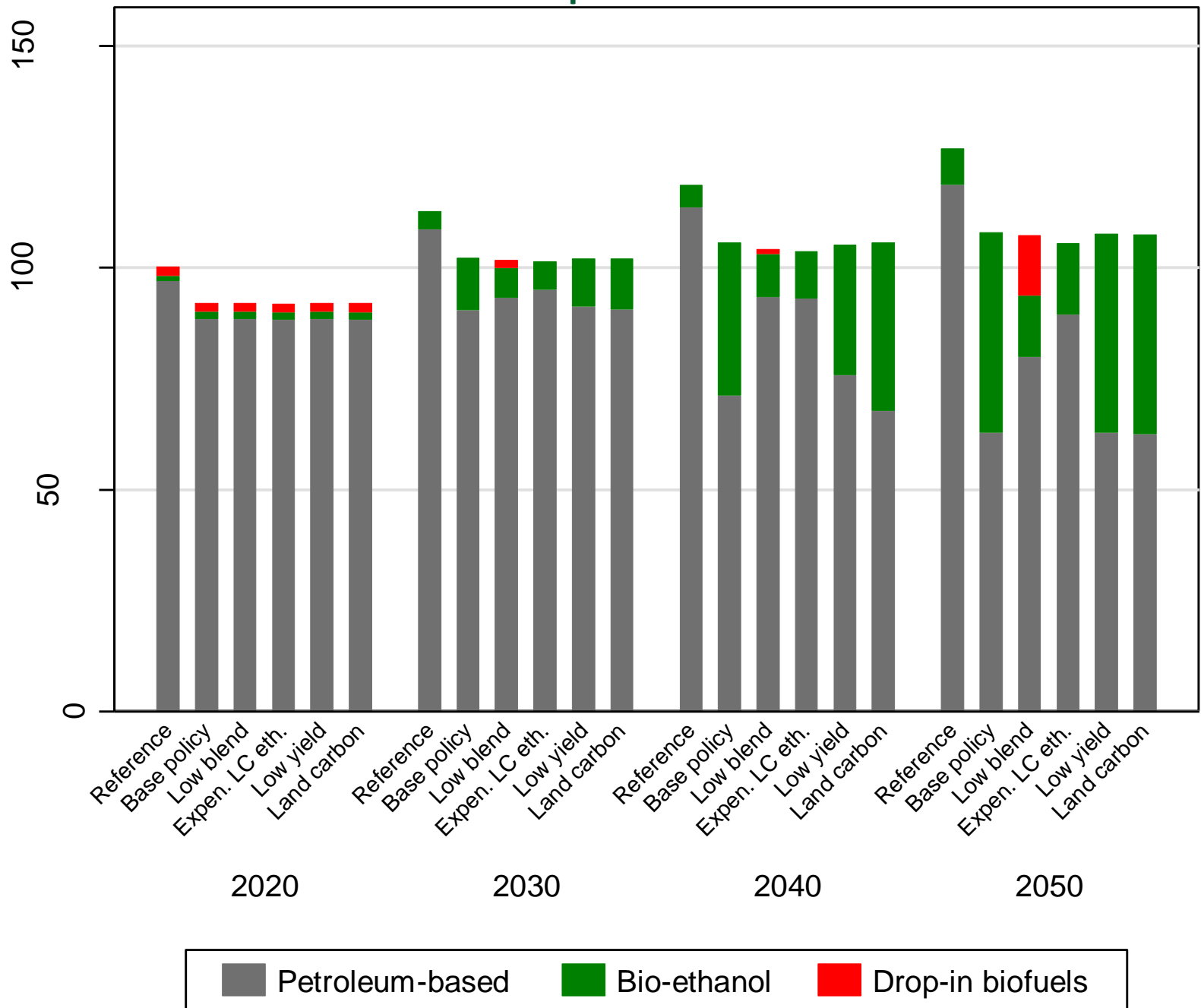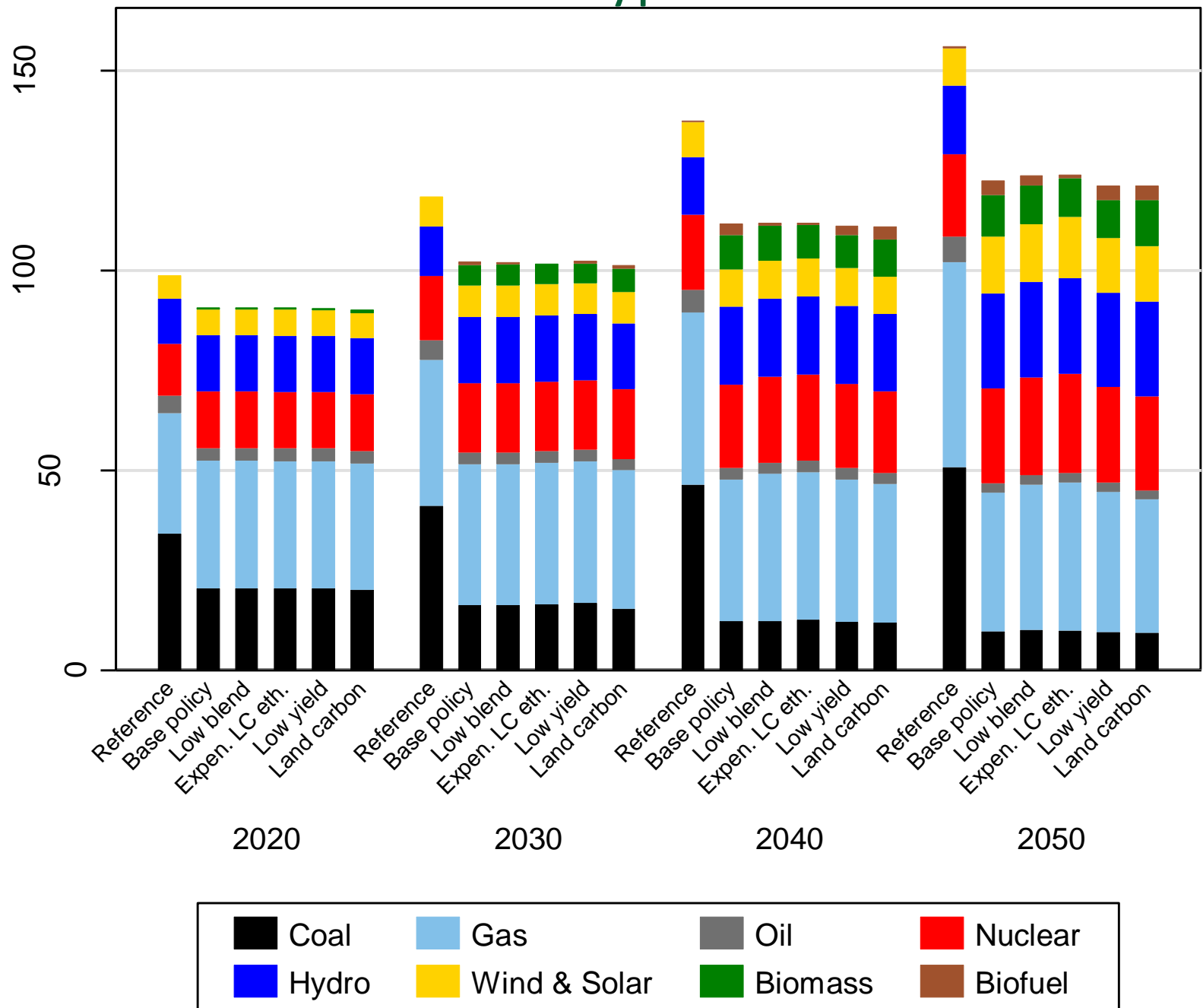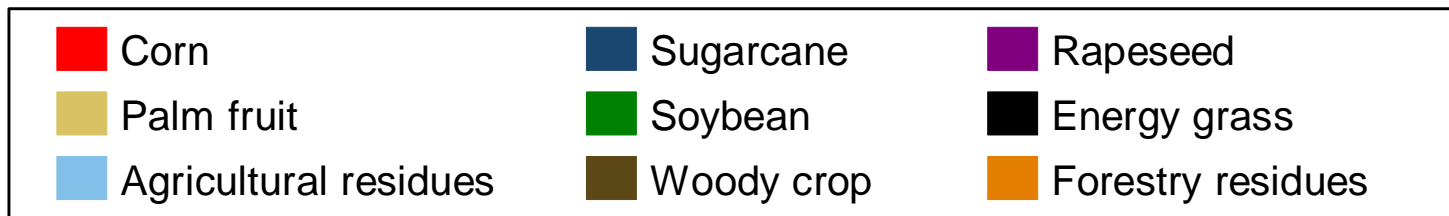# Conversion of natural forests to managed areas

Land Rents [$/ha]

Conversion of natural forests with 'tight' regulatory constraints

Conversion of natural forests with 'loose' regulatory constraints

Conversion of natural forests [ha]
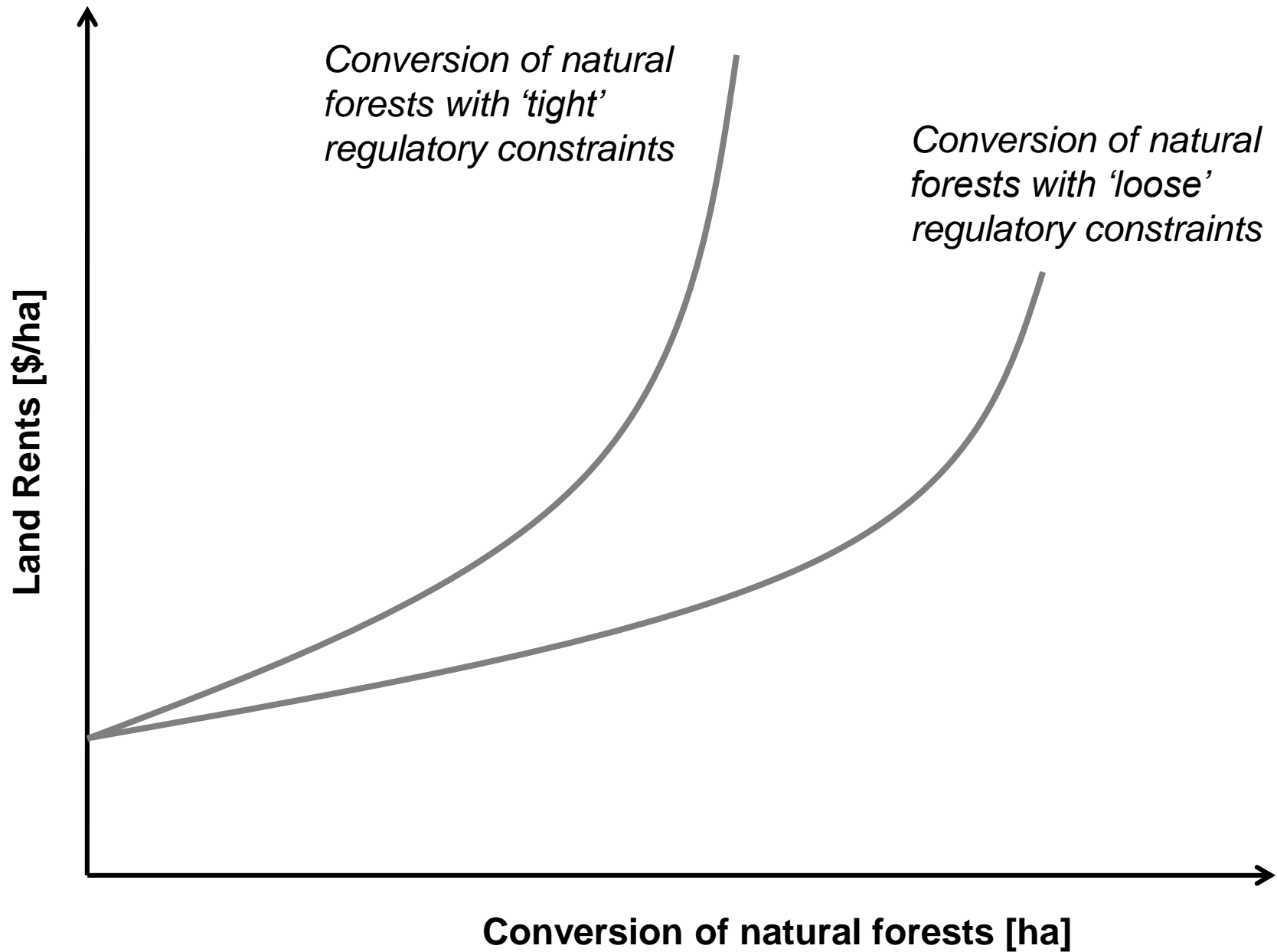
Global bioenergy by final energy type

Legend: Heat, Electricity, 1st gen. ethanol, Veg. oil-based, LC ethanol, LC drop-in

Global transportation fuel

Legend: Petroleum-based, Bio-ethanol, Drop-in biofuels

X-axis groups: 2020, 2030, 2040, 2050

Scenarios per group: Reference, Base policy, Low blend, Expen. LC eth., Low yield, Land carbon

Global electricity production

Legend: Coal, Gas, Oil, Nuclear, Hydro, Wind & Solar, Biomass, Biofuel

Categories (for years 2020, 2030, 2040, 2050): Reference, Base policy, Low blend, Expen. LC eth., Low yield, Land carbon

Global final bioenergy by feedstock

Legend:
- Corn
- Sugarcane
- Rapeseed
- Palm fruit
- Soybean
- Energy grass
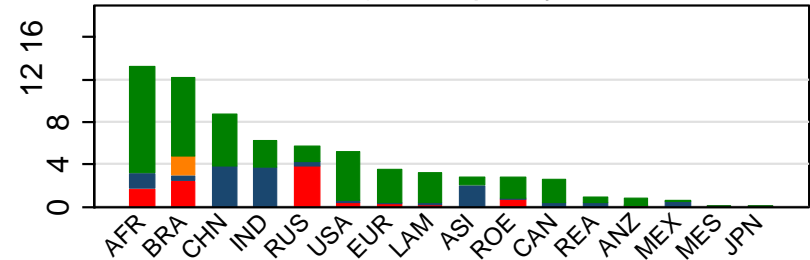- Agricultural residues
- Woody crop
- Forestry residues
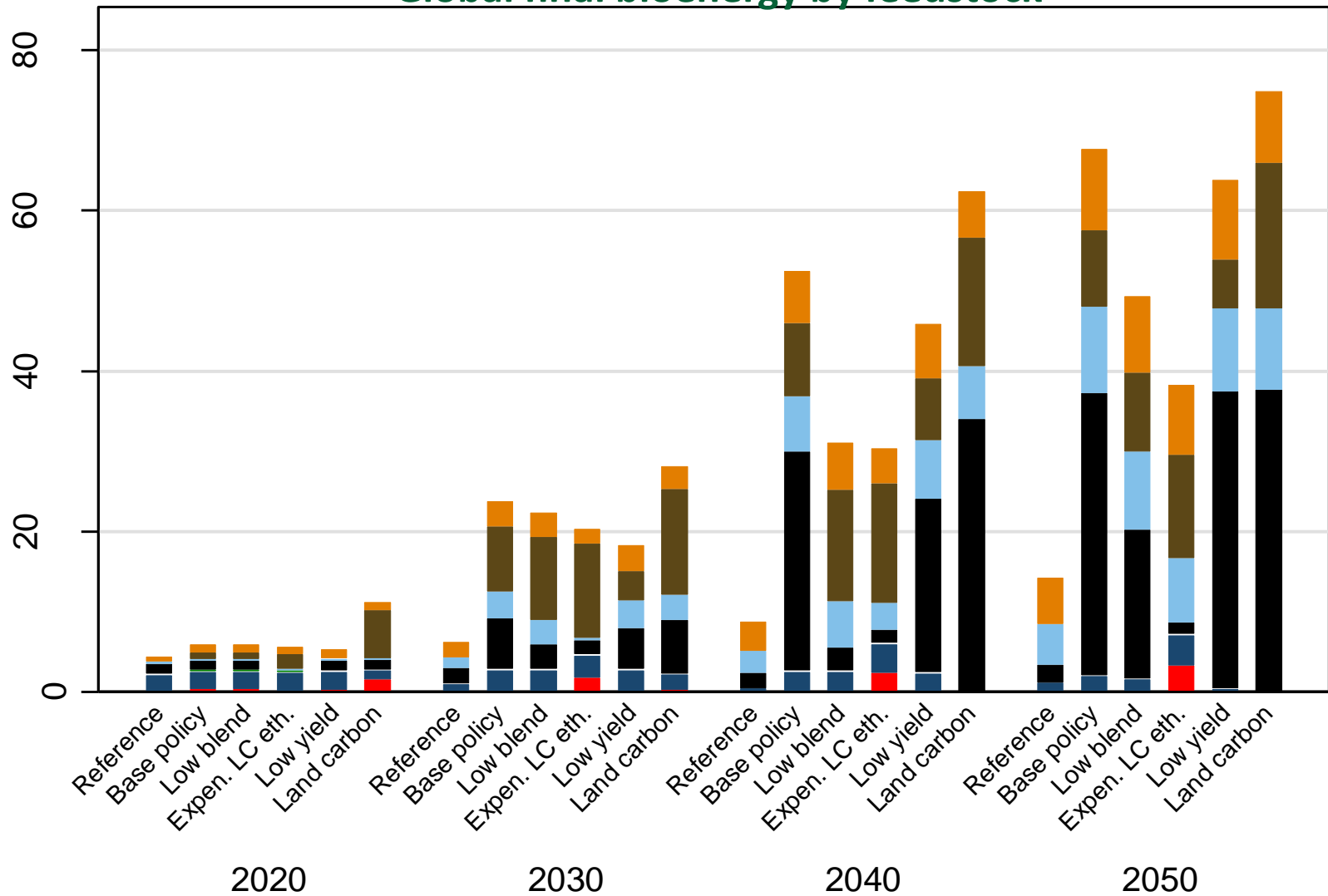
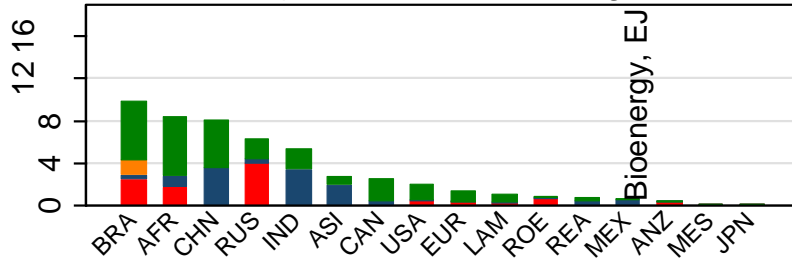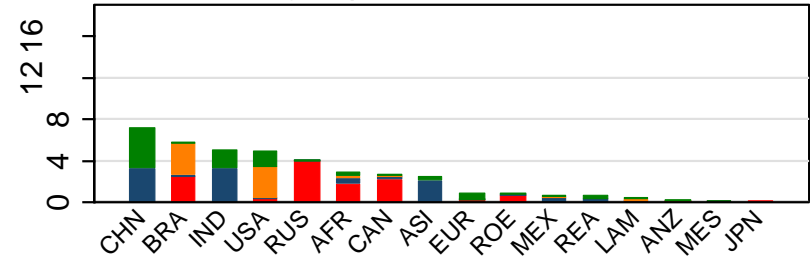# Global bioenergy by region in 2050
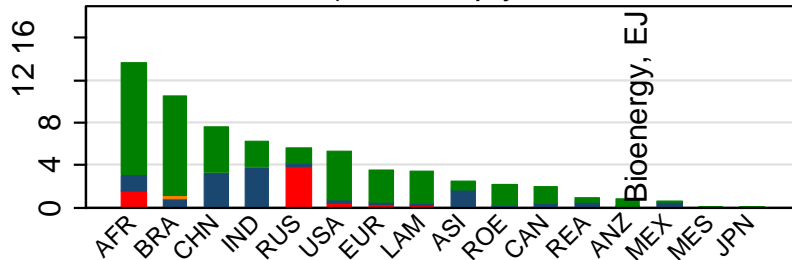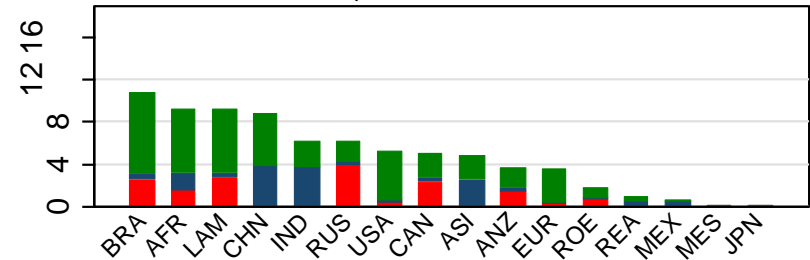

a) Reference
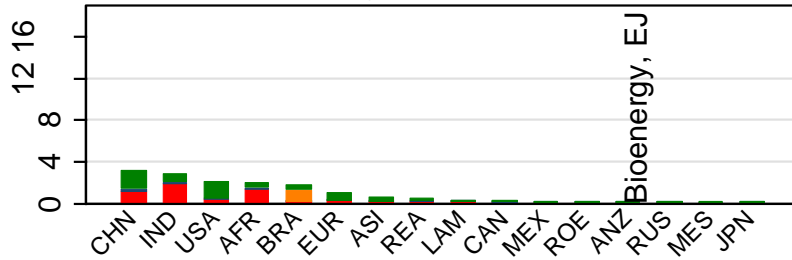
b) Base policy

c) Low ethanol blending

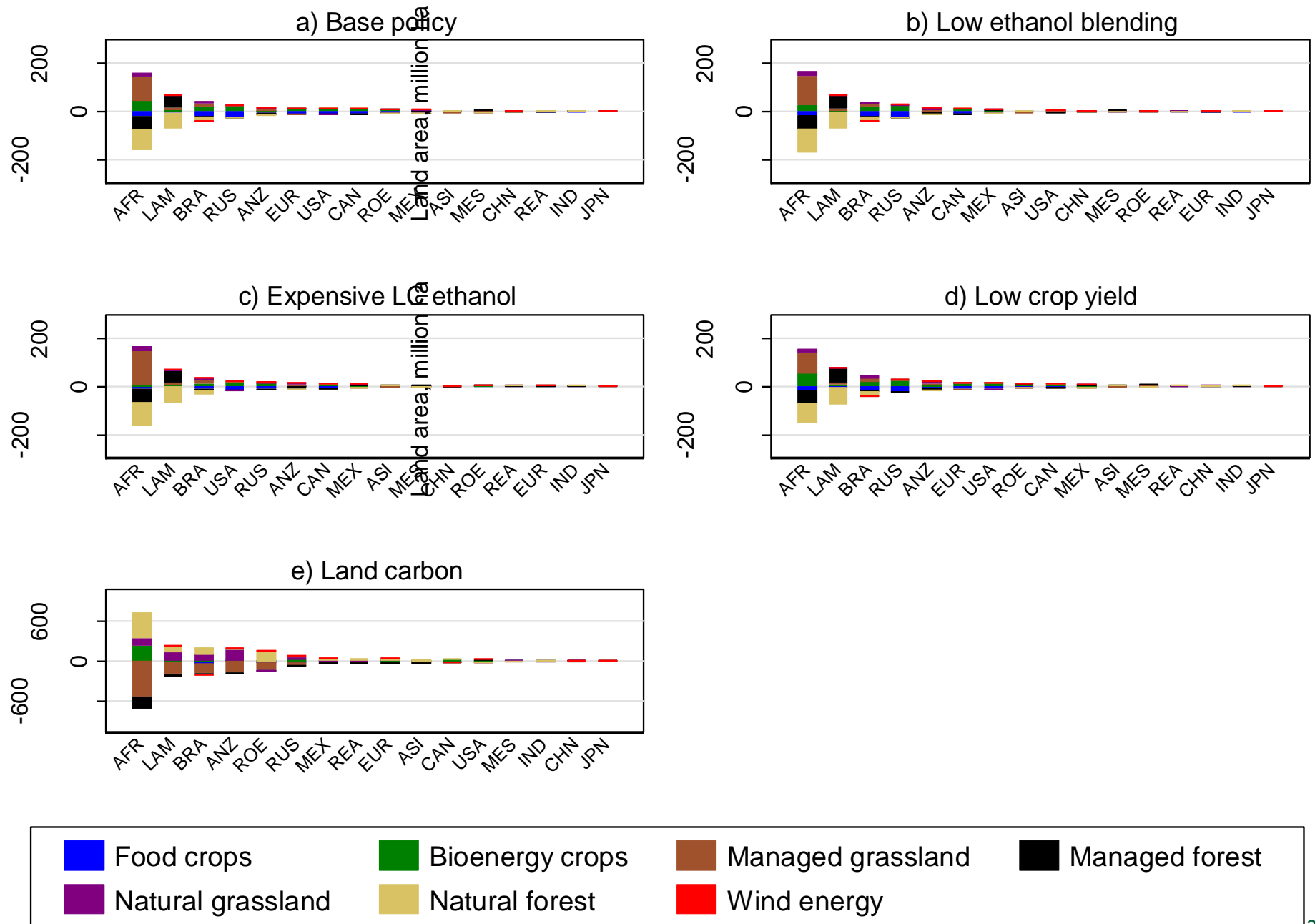d) Expensive LC ethanol

e) Low crop yield

f) Land carbon

Legend: Heat | Electricity | 1st gen. ethanol | Veg. oil-based | LC ethanol

Regional land-use change relative to the reference scenario, 2050

a) Base policy
b) Low ethanol blending
c) Expensive LC ethanol
d) Low crop yield
e) Land carbon

Legend:
- Food crops
- Bioenergy crops
- Managed grassland
- Managed forest
- Natural grassland
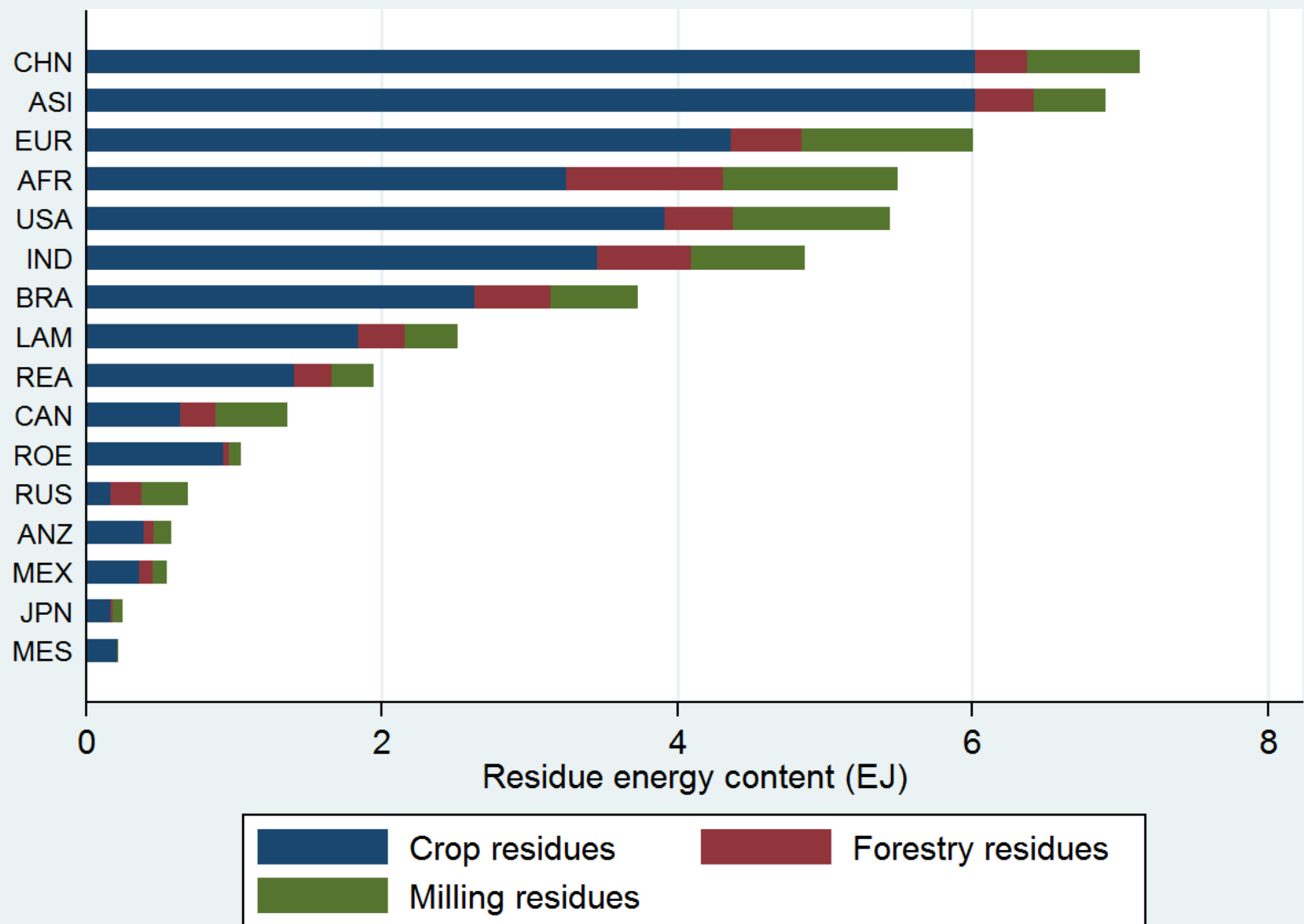- Natural forest
- Wind energy

Bioenergy land-use impacts

The impact of bioenergy on land-use change is influenced by at least three factors

1. The scope for deforestation in the model reflects current trends and political constraints

2. Some bioenergy feedstocks are sourced from forestry and agricultural residues (~30% of bioenergy is produced using residues)

3. Improved efficiency both in growing crops and turning biomass into biofuel results in improvements in energy yields

   – 60% increase in energy yield for energy grass in the US between 2015 and 2050 (1,166 → 1,873 gasoline-equivalent gallons per ha)
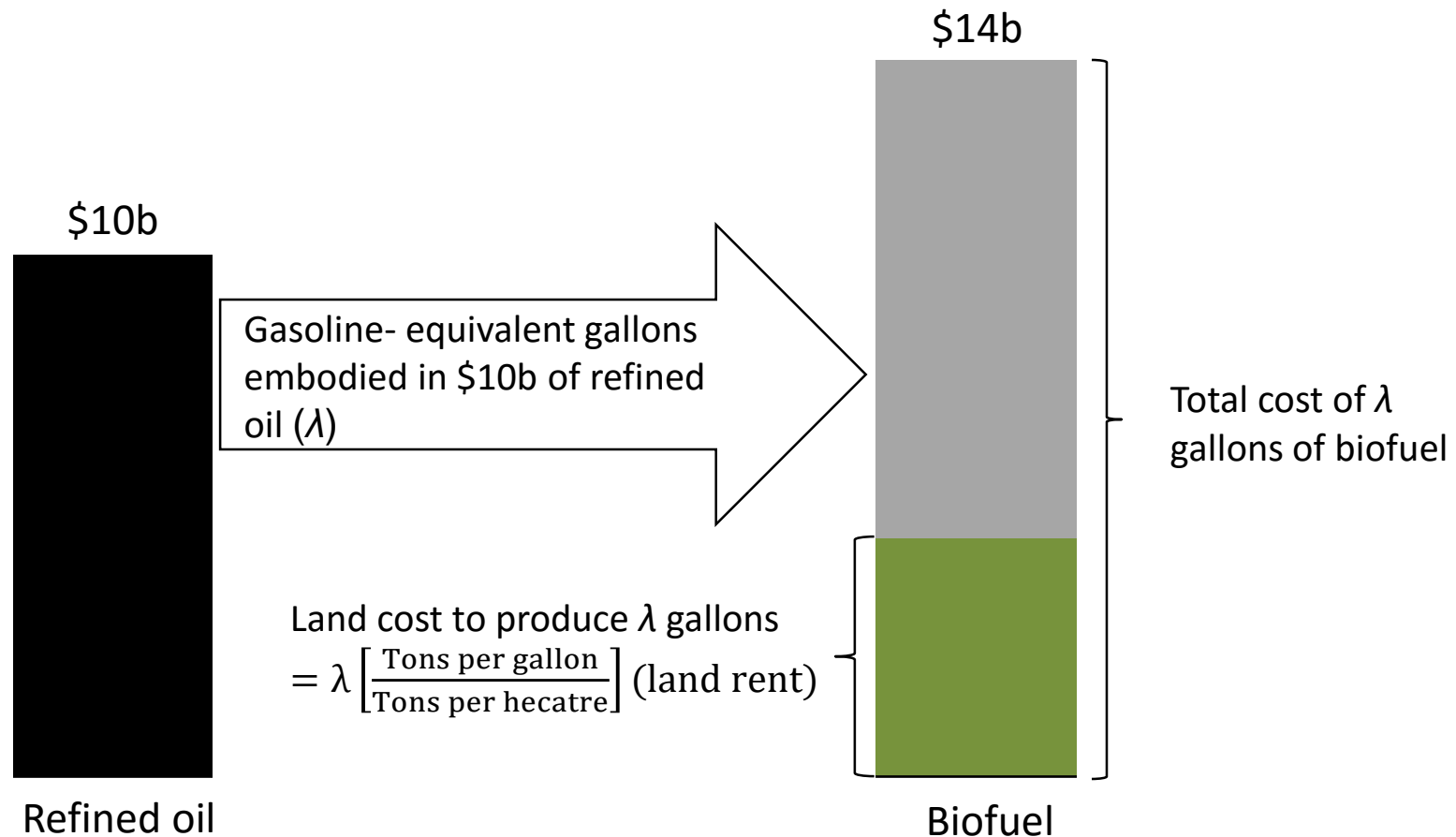
Interesting results

- Less bioenergy production can be associated with more deforestation

  1. Low crop yield scenario
     - More land is needed for food crops

  2. Low blending and Expensive LC ethanol scenarios
     - More (low yield) wood crops and less (high yield) energy grass in China → more land allocated to bioenergy and less to food crops
     - More food production in Africa for export to China

- Irrespective of the location of bioenergy production, natural forest loss is greatest in regions with the lowest political barriers to deforestation

- Pricing emissions from land-use change can increase bioenergy production (due to soil carbon credits) AND result in afforestation

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Residue biomass potential by type and region in 2004 (EJ)

Source: Gregg, J.S. and S.J. Smith, 2010: Global and regional potential for bioenergy from agricultural and forestry residues, *Mitigation and Adaptation Strategies for Global Change*, 15, 241-262.

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Biofuel values and physical quantities

$10b

Refined oil

Gasoline- equivalent gallons embodied in $10b of refined oil ($\lambda$)

$14b

Total cost of λ gallons of biofuel

Land cost to produce λ gallons
$$= \lambda \left[\frac{\text{Tons per gallon}}{\text{Tons per hecatre}} \right] (\text{land rent})$$

Biofuel

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Biofuel values and physical quantities