Overview of the Global Change Assessment Model (GCAM)

The JGCRI GCAM Team
GCAM Annual Meeting

Joint Global Change Research Institute, College Park, MD

November 8th, 2017

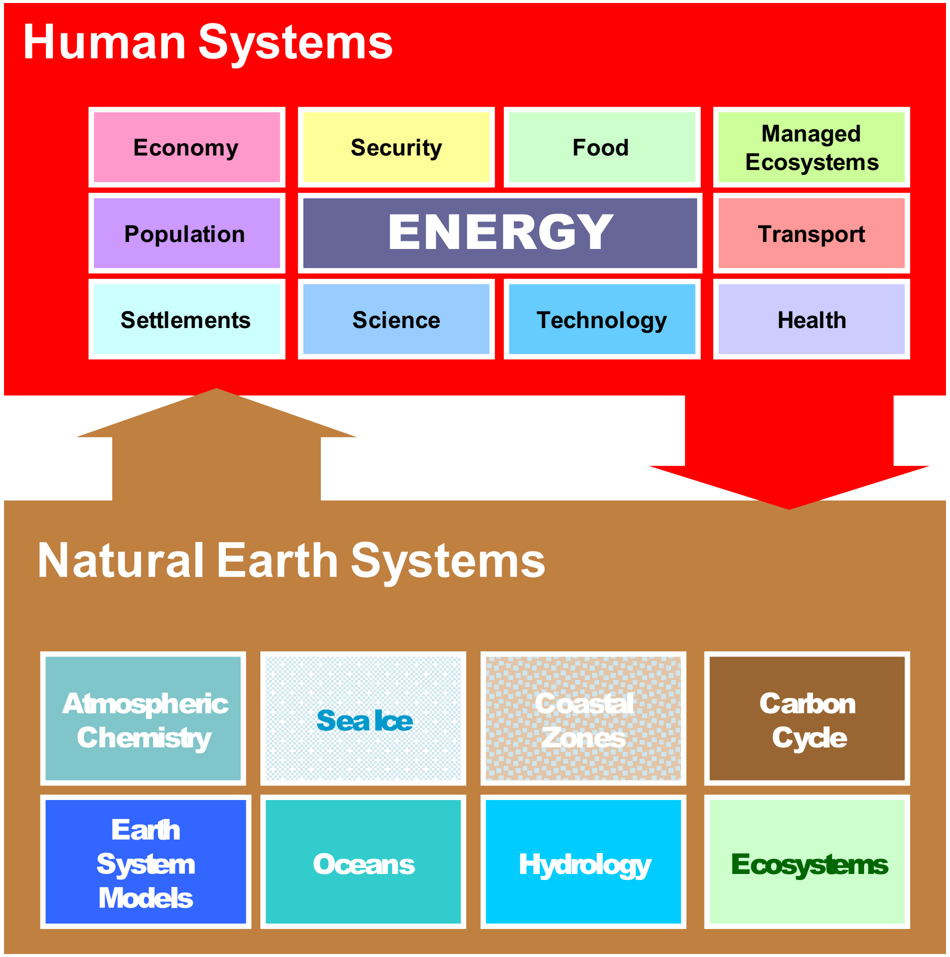
Outline

- Brief introduction to Integrated Models of Human and Natural System Interactions
- Overview of GCAM
- Detailed information on GCAM's
  - Socioeconomics,
  - Energy,
  - Agriculture and land use,
  - Modeling policies,
  - Emissions,
  - Earth System modeling
- Discussion

Introduction to Complex Integrated Assessment (IA) Models

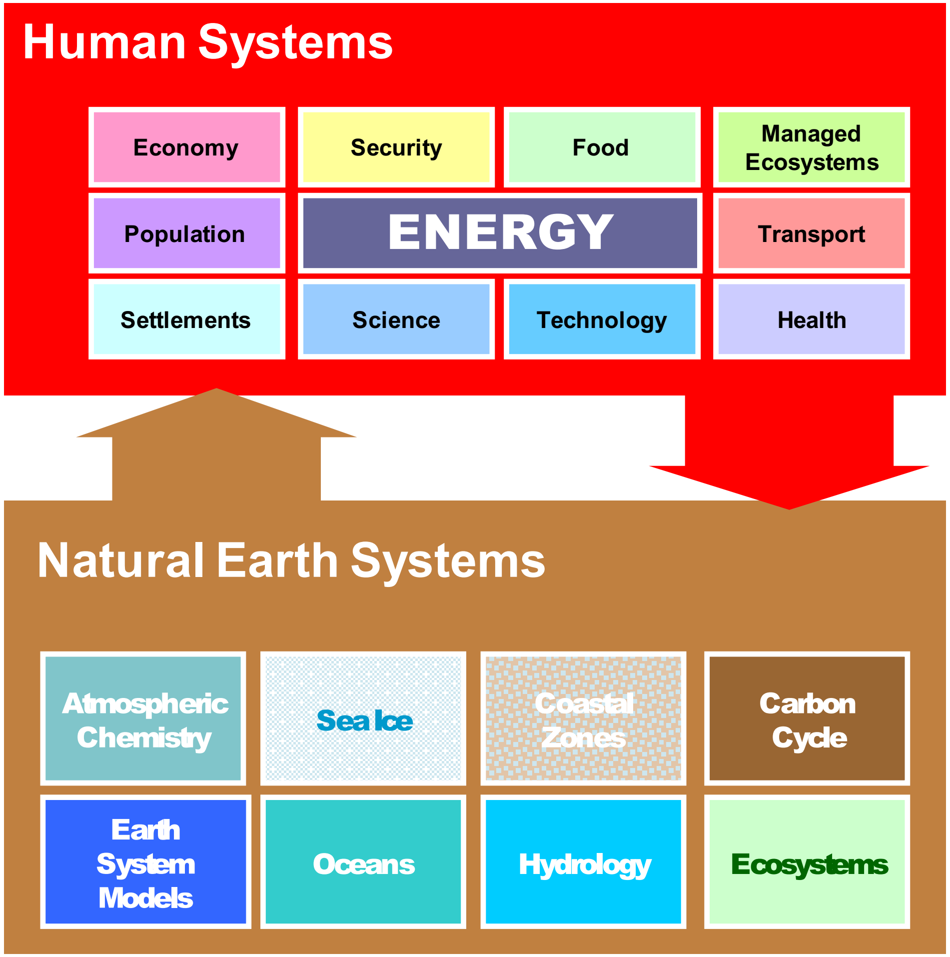
Integrated Assessment Models are all about …… integration

- Designed to capture dynamic interactions between complex and highly nonlinear human and natural systems.
- Current focus is on energy-water-land-economy-climate, typically with a global scope.
- Provide insights that unavailable from disciplinary research alone
- They are not substitutes for higher-fidelity disciplinary models



Integrated Assessment Models have multiple uses

- Used in tandem with other models and data to increase our understanding of human and natural system interactions.
- Provide natural science and other researchers with information about human systems such as emissions, land use and land cover.
- Support national, international, regional, and private-sector decisions.

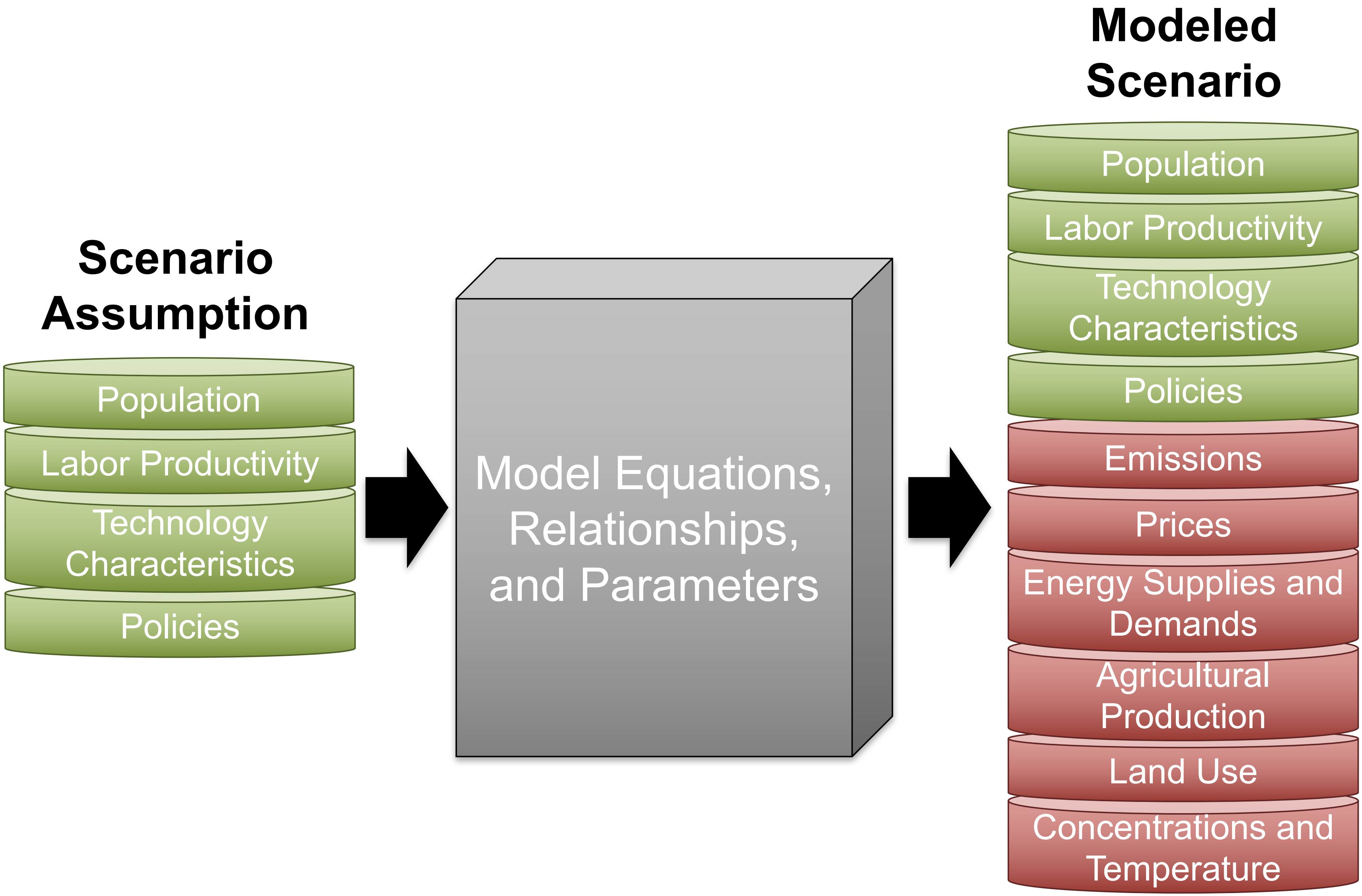


The Global Change Assessment Model (GCAM) is a “Complex” IA Model

Complex Models and Modeling Teams

Model	Home Institution
AIM Asia Integrated Model	National Institutes for Environmental Studies, Tsukuba Japan
GCAM Global Change Assessment Model	Joint Global Change Research Institute, PNNL, College Park, MD
IGSM Integrated Global System Model	Joint Program, MIT, Cambridge, MA
IMAGE The Integrated Model to Assess the Global Environment	PBL Netherlands Environmental Assessment Agency, Bildhoven, The Netherlands
MESSAGE Model for Energy Supply Strategy Alternatives and their General Environmental Impact	International Institute for Applied Systems Analysis; Laxenburg, Austria
REMIND Regionalized Model of Investments and Technological Development	Potsdam Institute for Climate Impacts Research; Potsdam, Germany

Integrated Assessment Models Produce Conditional Forecasts of an Uncertain Future

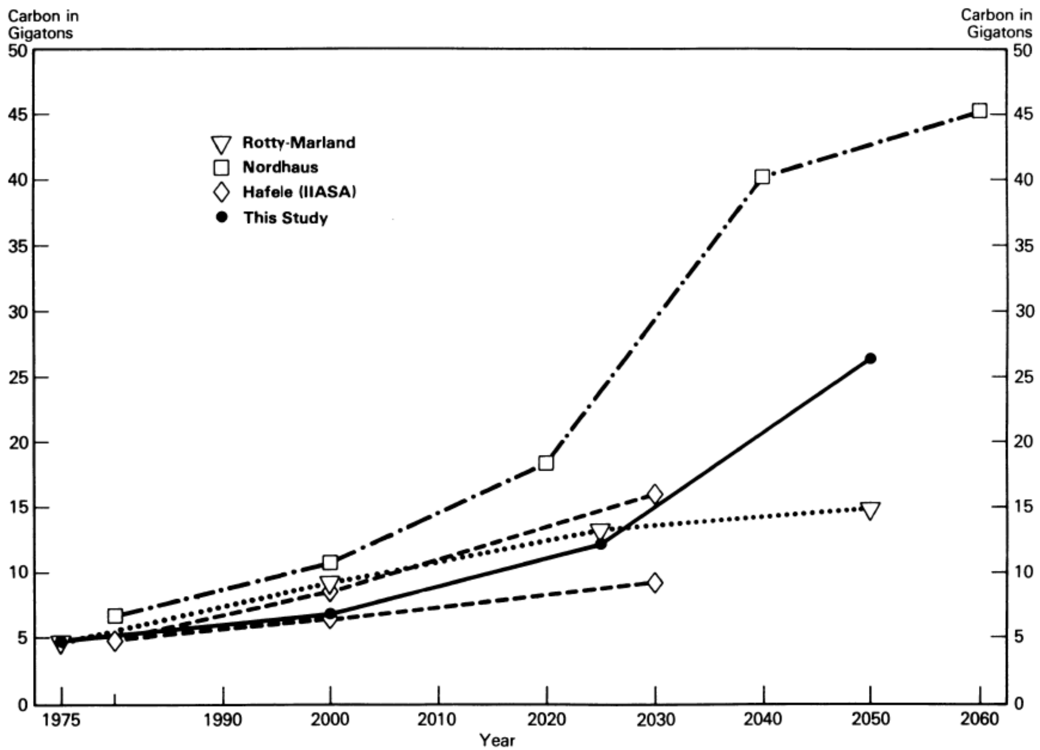


Integrated Assessment Research and Model Development is Problem Driven

energy-economy-climate

1980s

Projections of emissions and concentrations



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ENERGY-ECONOMY-climate

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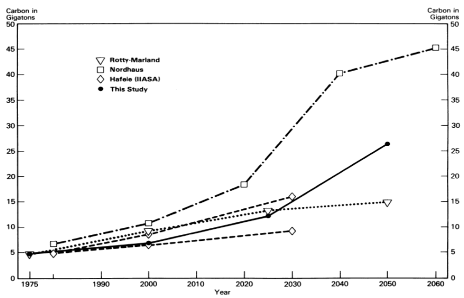
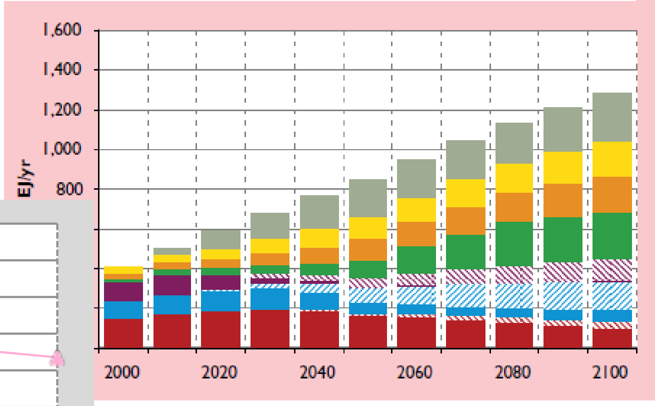
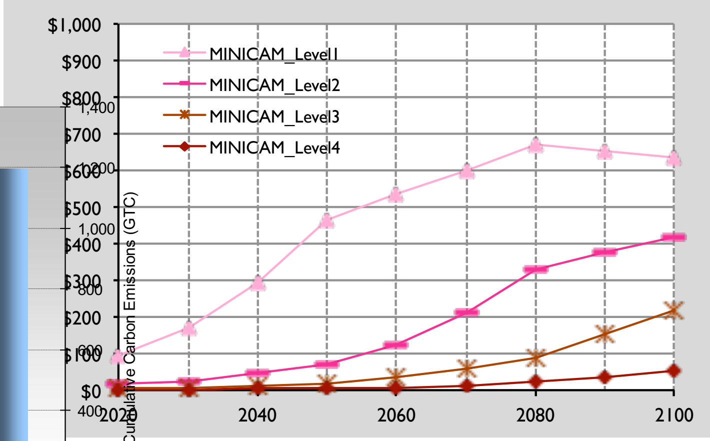


1990's through 2000's
Energy, Technology, and Mitigation

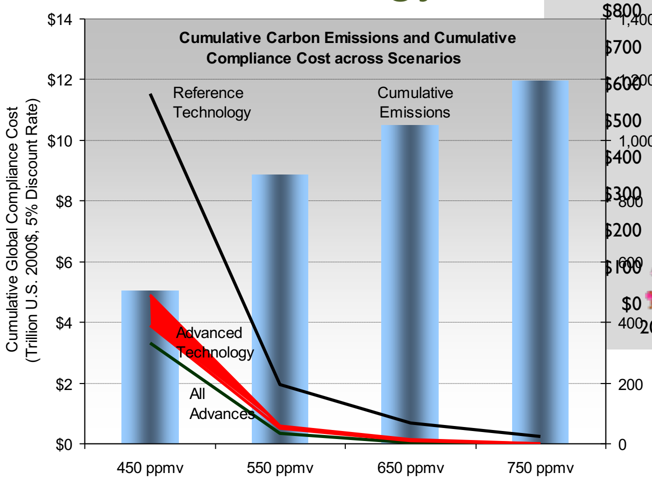
Energy Systems



Carbon Prices



Value of Technology



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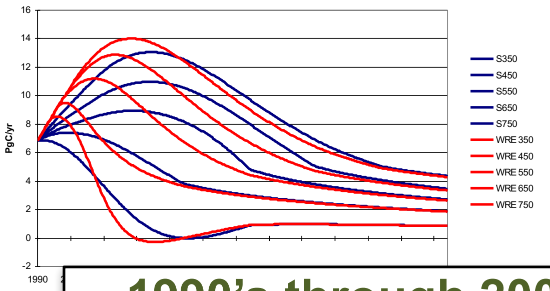
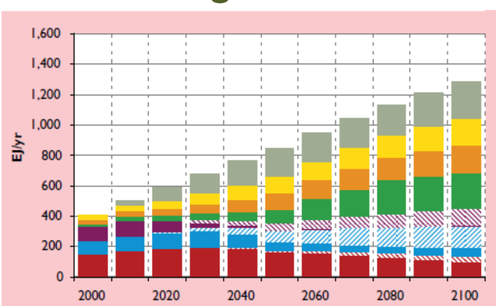


1990's through 2000's

Energy, Technology, and Mitigation

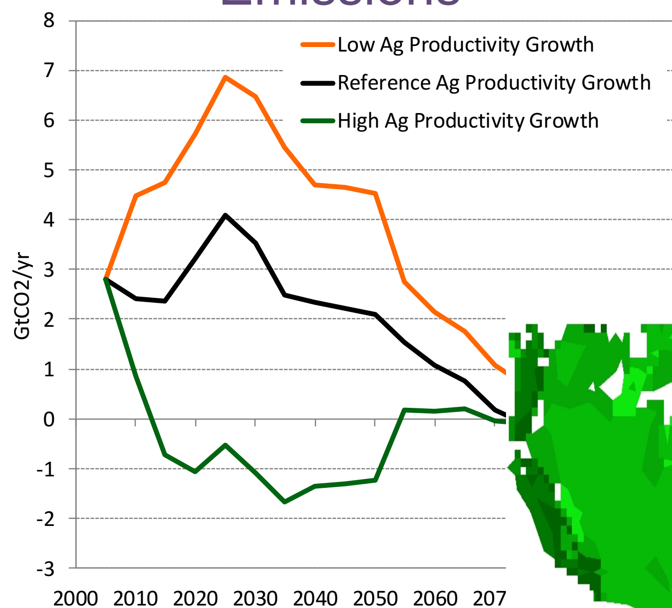


ENERGY-ECONOMY-land-climate

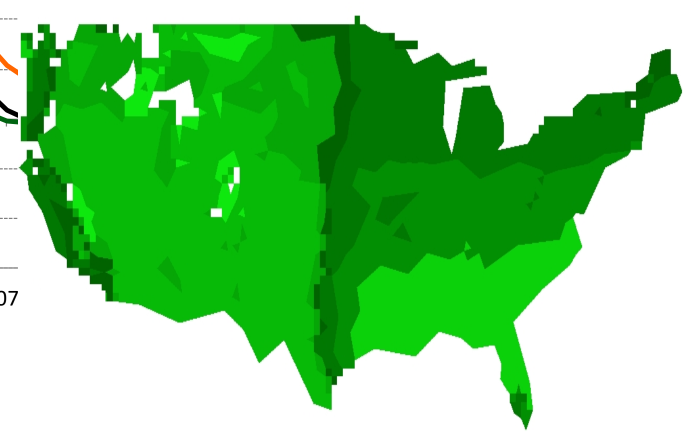
2000's

Mitigation and land use

Land Use Change Emissions



Crop production and land use changes



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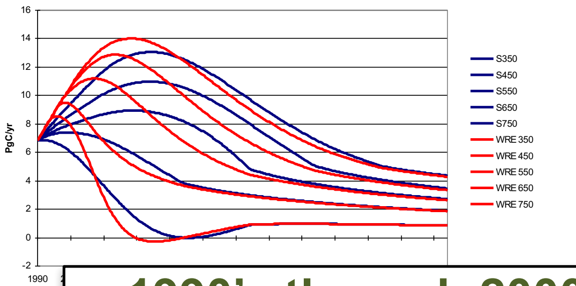
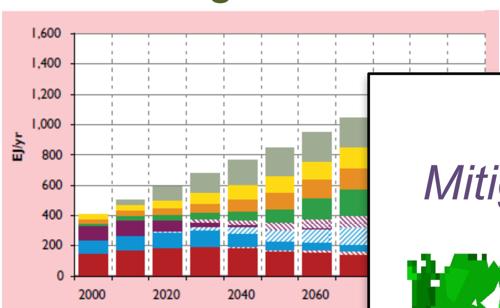


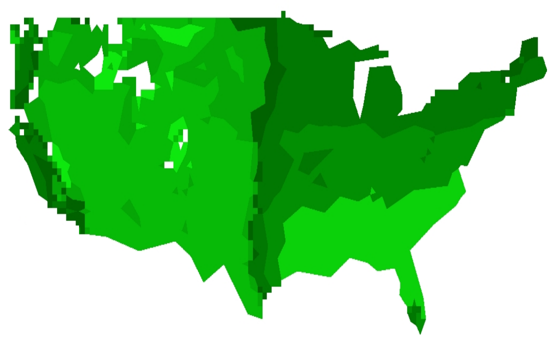
1990's through 2000's

Energy, Technology, and Mitigation



2000's

Mitigation and land use



TODAY

????

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What are some key questions motivating today’s science?

- How will infrastructure investments interact with both human system (e.g., technology, population, economic growth) and natural system (e.g., extreme events, long-term climate) stressors and dynamics?
- Where are the biggest future national and international security risks that emerge from the interactions between human and natural systems?
- What will be the effect of international policies and pledges (e.g., climate pledges, energy policies) on the broad set of human and natural system dynamics?
- Can you help us interpret and understand this stuff given all the uncertainty about the future? What’s the confidence in any of this?

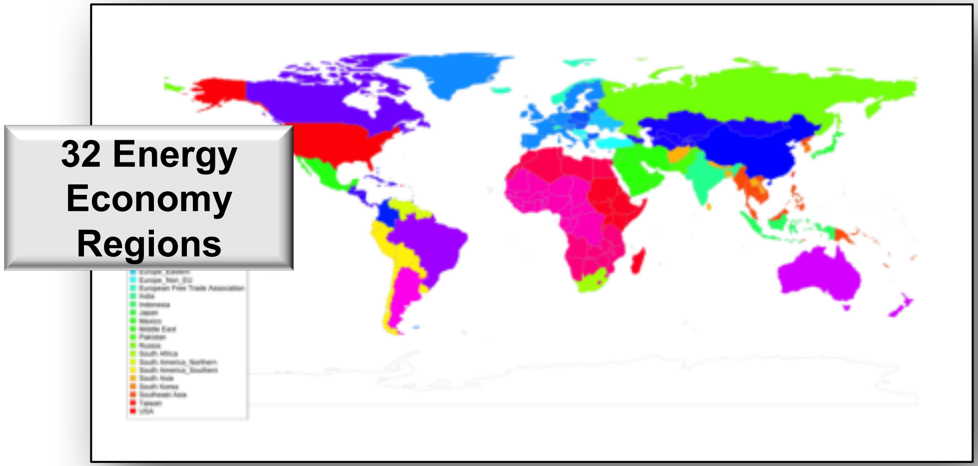
Incorporating natural system feedbacks on human systems

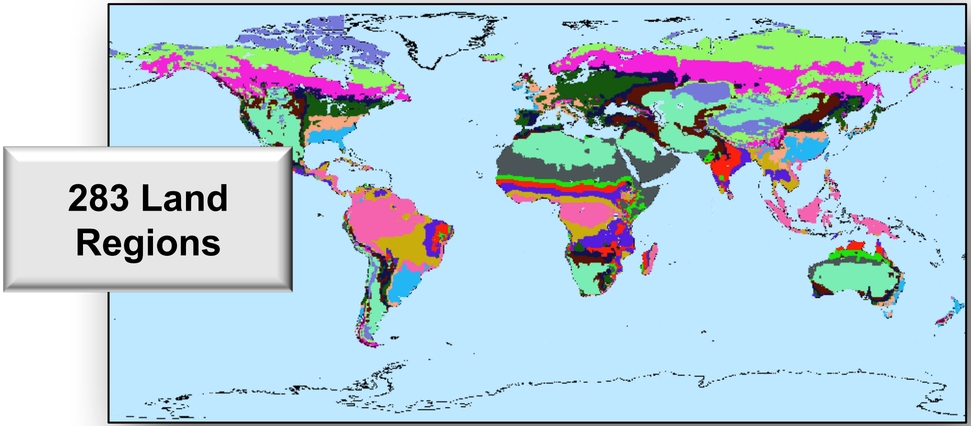
Increased “realism”, particularly with regards to nearer-term and regional dynamics

Multi-model analysis to bridge across scales

What is GCAM?

Quick Overview of GCAM



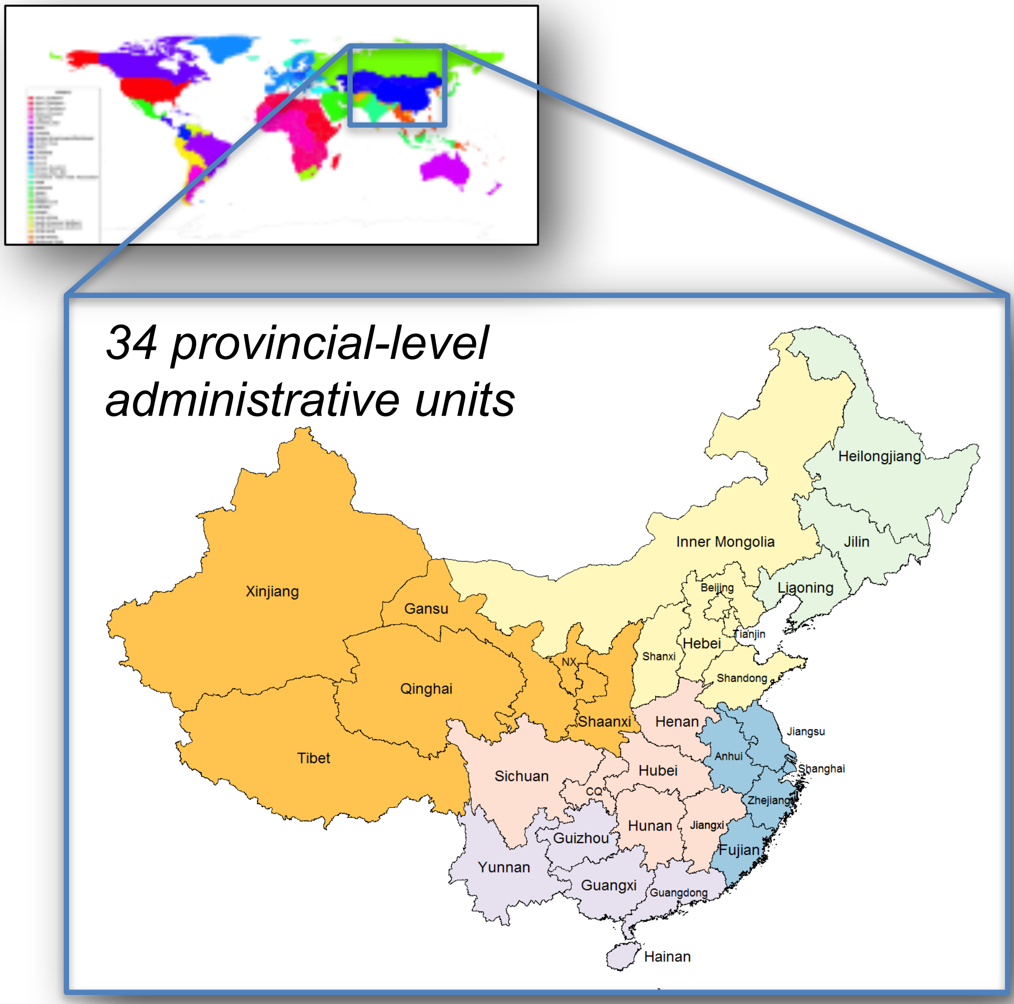


- GCAM is a global integrated assessment model
- GCAM links **Economic**, **Energy**, **Land-use**, and **Earth** systems
- GCAM is a market-equilibrium model; it is not an optimization model.
- GCAM runs in 5-year time-steps through the end of the century
- GCAM is a community model
- Documentation available at: **http://jgcri.github.io/gcam-doc/toc.html**

GCAM is structured for detailed regional and sectoral disaggregation

Example: GCAM research branches with disaggregated regions

- GCAM-USA
- **GCAM-China**
- India Buildings
- U.S. Midwest agriculture



The GCAM Framework has Three Components

Data Development System → **GCAM Core: Dynamic Integration** → **Disaggregation Models (*Research*)**

Data Development System

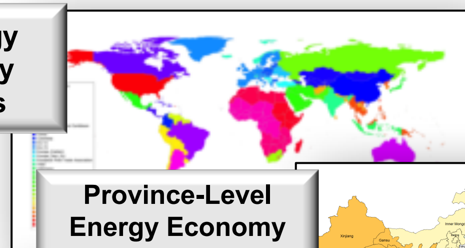
EIA	IEA
GTAP	HYDE
SAGE	OECD
FAO	IMAGE
MIRCA	Aquastat
USDA	USGS
CDIAC	IIASA

Others….

Papers: Houghton, Rogner, others

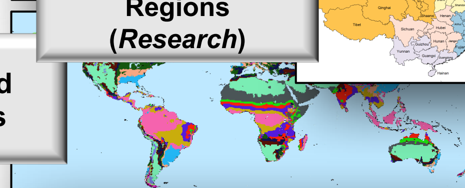
GCAM Core: Dynamic Integration

32 Energy Economy Regions



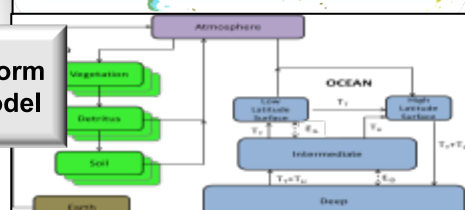
Province-Level Energy Economy Regions (*Research*)

283 Land Regions

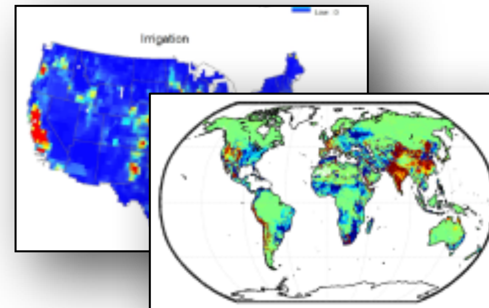


233 Water Basins (*Research*)

Reduced-Form Climate Model



Disaggregation Models (*Research*)

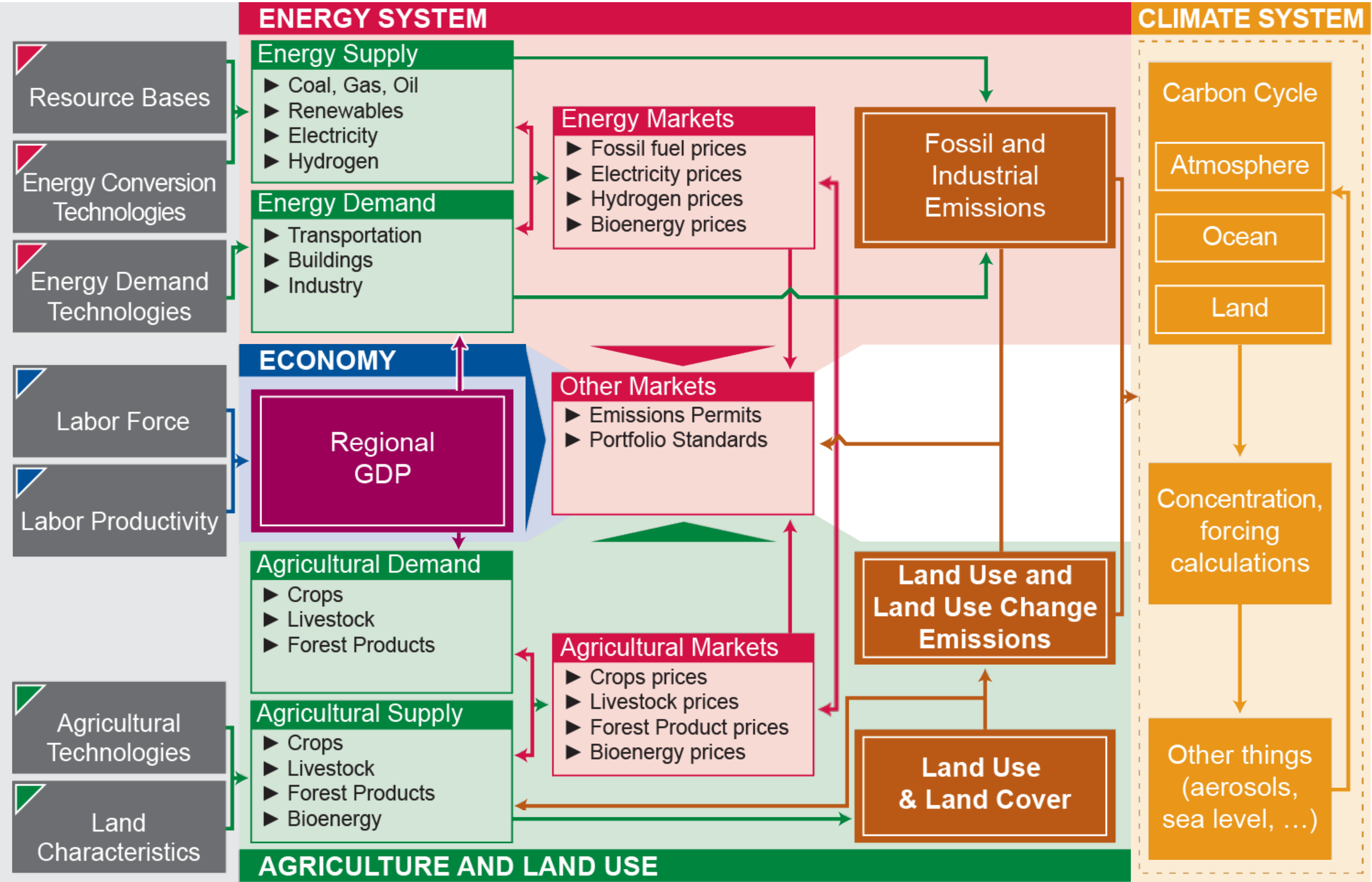


Digital Map of Irrigated Areas	MODIS
Union of Concerned Scientists	Gridded Livestock of the World

Others….

Papers: Friedl, Portmann, Sleeter, Radeloff, others

What's inside the GCAM Core?

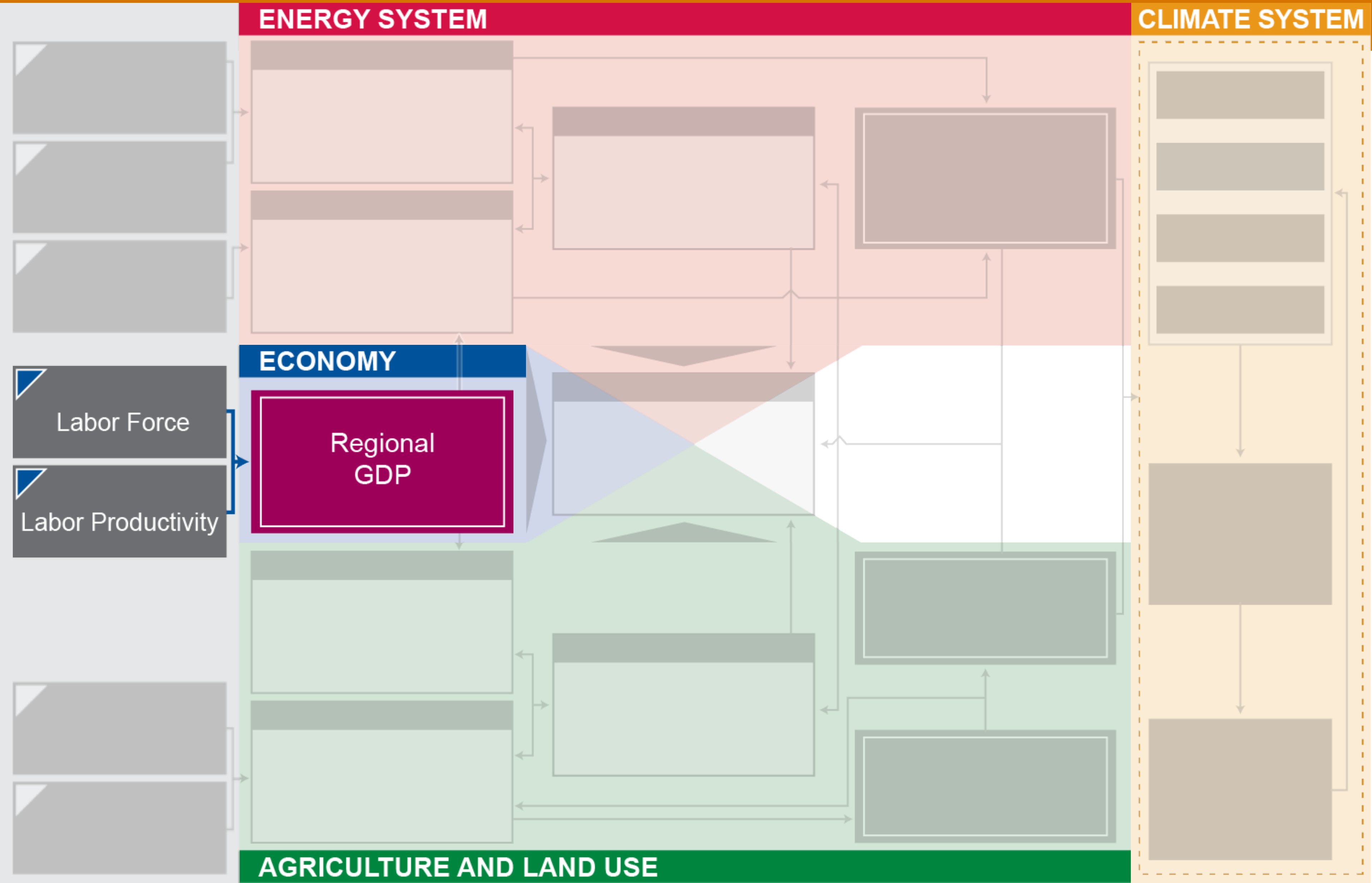


The Macro-economy in GCAM

Stephanie Waldhoff

2017

What's inside GCAM?



The GCAM 4.4 macro-economy

$$GDP_{r,t+1} = POP_{r,t+1} * (GDP/cap_{r,t}) * (1 + g_{r,t})^{t\_step}$$

Where:

r = region, t = model period, t_step = years in model period

POP = population

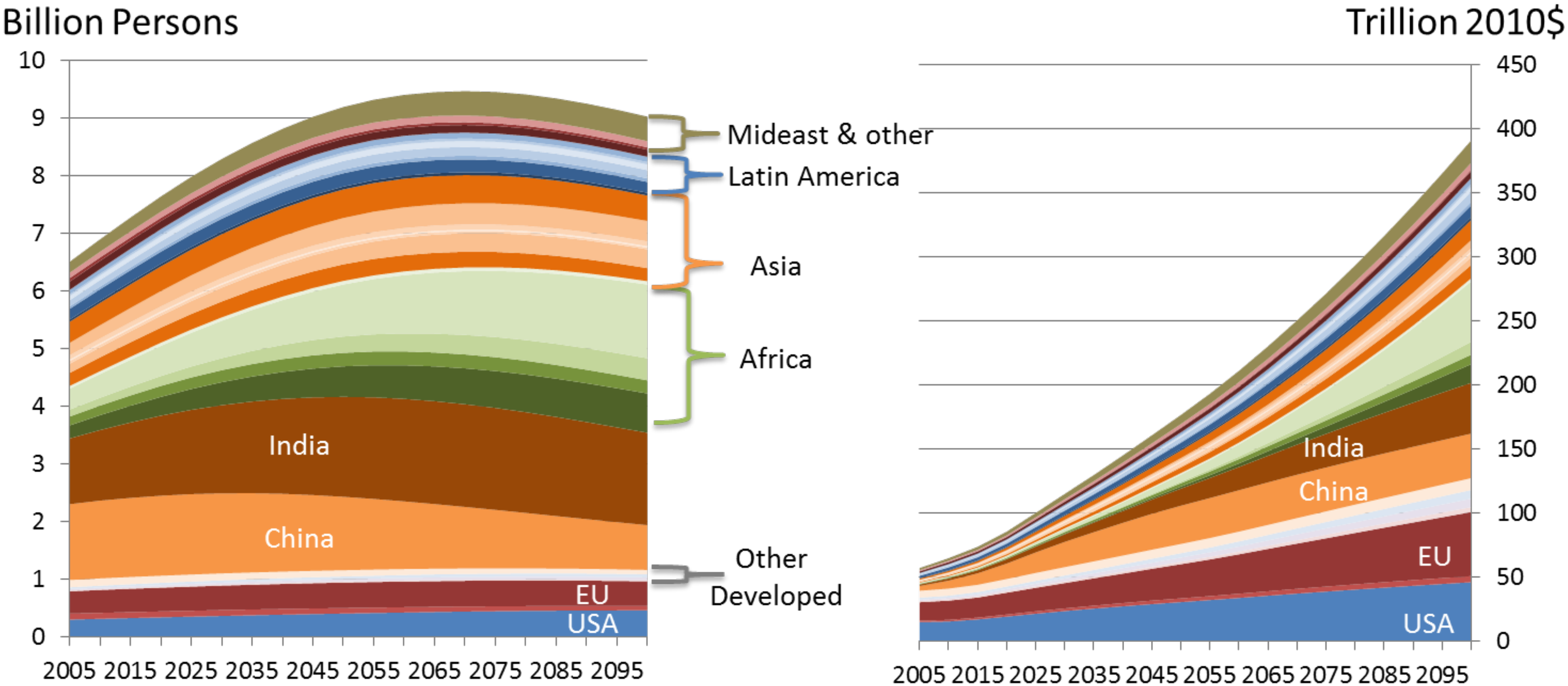
g = annual rate of growth of per capita income

- GDP increases with population and annual growth rate

Socioeconomic projections: SSP2 population and GDP

- Middle of the Road scenario from Shared Socioeconomic Pathways, *O'Neill et al. Climatic Change (2014) 122: 387*
- Near-term GDP growth reflects observed economic stagnation in several regions
- Current release does not include other SSP assumptions beyond population and GDP

Population and GDP



USA	EU-12	EU-15	European Free Trade Association	Australia_NZ
Canada	Japan	China	India	Africa_Eastern
Africa_Northern	Africa_Southern	Africa_Western	South Africa	Indonesia
Pakistan	South Korea	Taiwan	Central Asia	South Asia
Southeast Asia	Argentina	Brazil	Colombia	Mexico
Central America and Caribbean	South America_Northern	South America_Southern	Russia	Europe_Eastern
Europe_Non_EU	Middle East			

Energy

2017

Page Kyle

Marshall Wise

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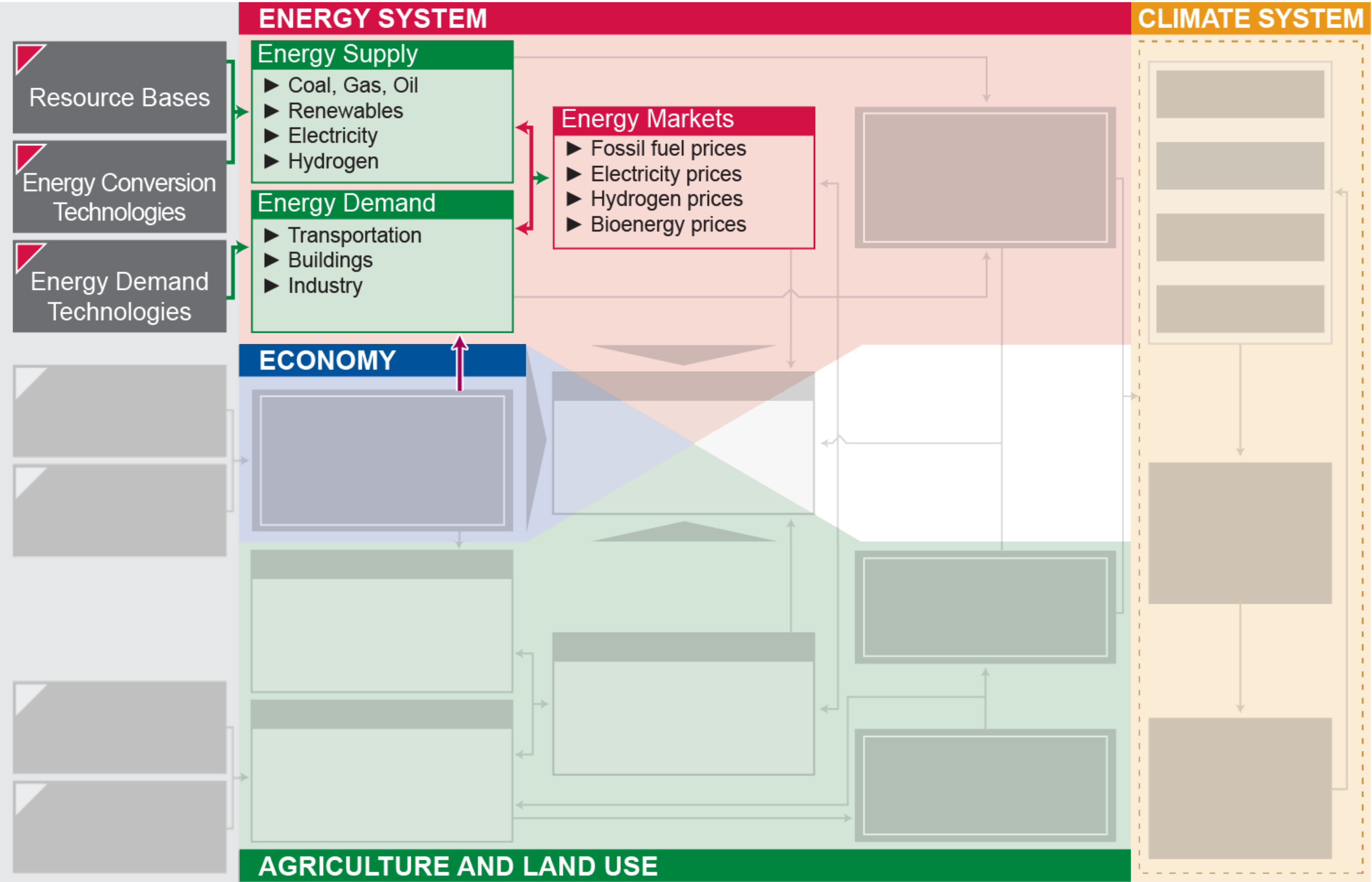
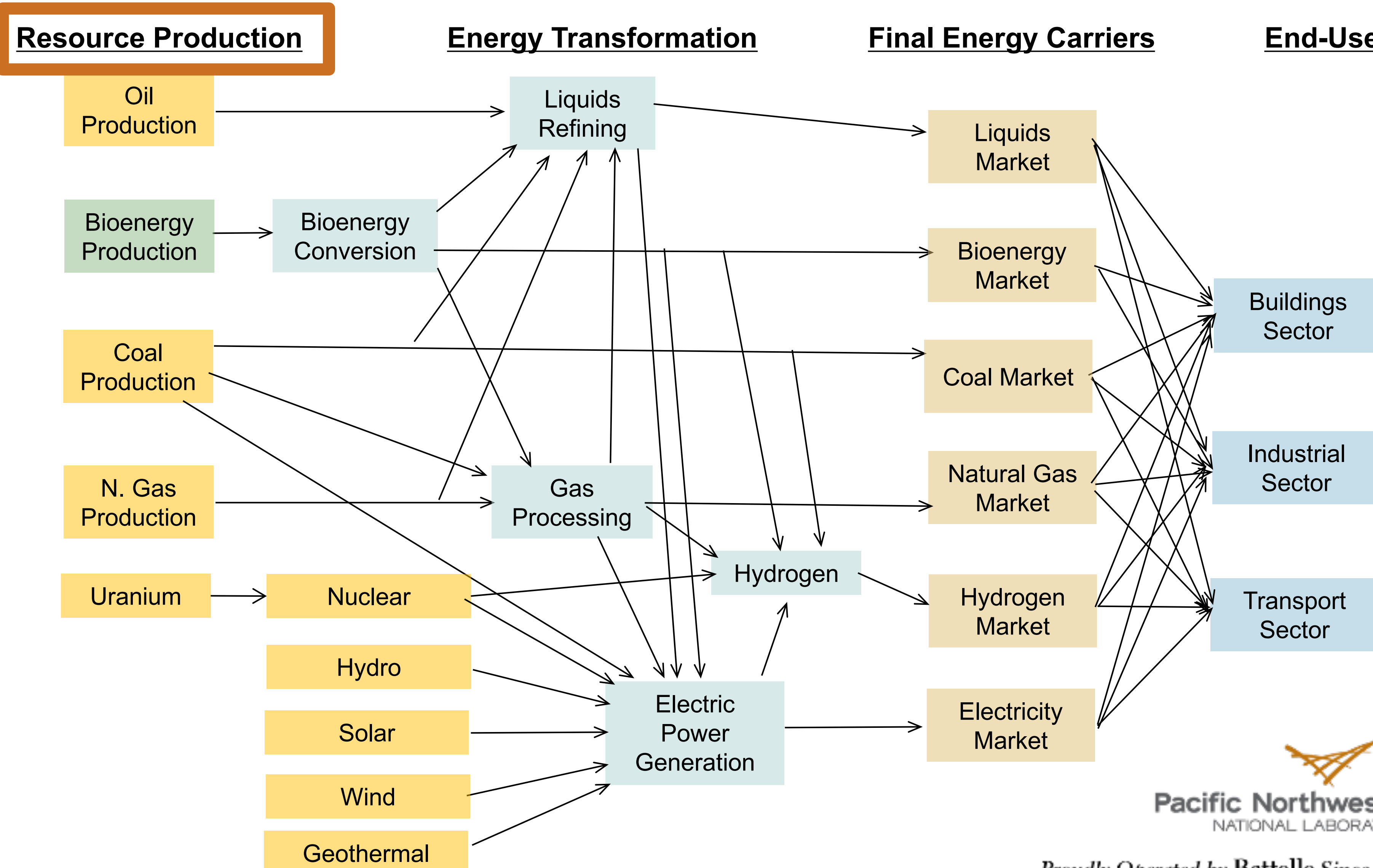
The Global Change Assessment Model



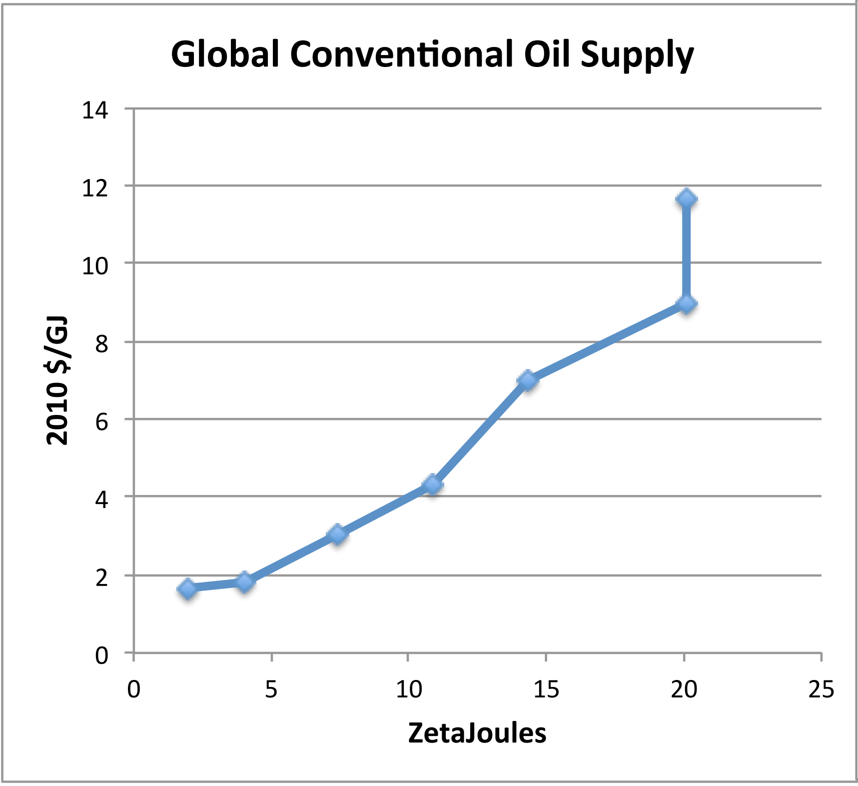
The Energy System: Structure

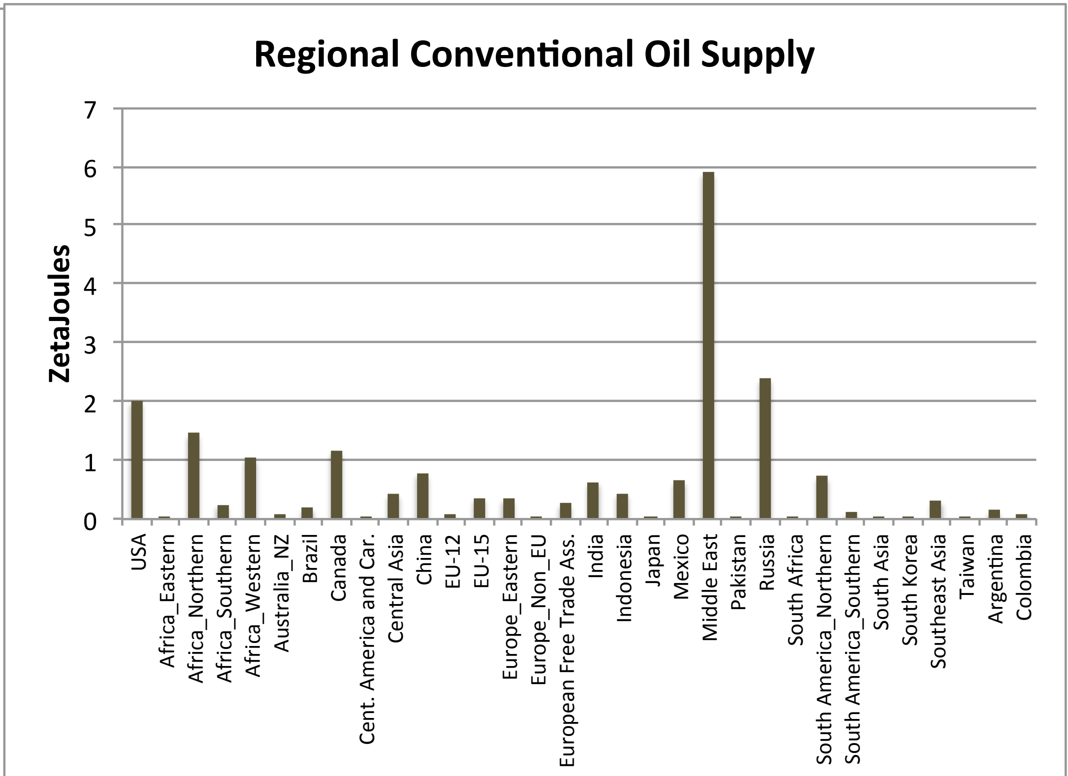


The Energy System: Resources

- Resources serve as inputs to conversion technologies to produce energy carriers such as electricity, liquid fuels, and hydrogen.
  - For example, several types of solar technologies – CSP, central PV, rooftop PV – draw from the solar resource to produce electricity.
- Exhaustible Resources in GCAM
  - Coal
  - Natural Gas
  - Oil (conventional and unconventional)
  - Uranium
- Renewable Resources in GCAM
  - Solar
  - Wind (onshore and offshore combined into one)
  - Geothermal
  - Bioenergy (several forms)

The Energy System: Resources: Conventional Oil





- Oil, Gas, and Coal Resources derived from Rogner 1997 (per the GCAM wiki), but please refer to that source for original data.
- Note: there is an additional 90 ZJ of unconventional oil in GCAM 4

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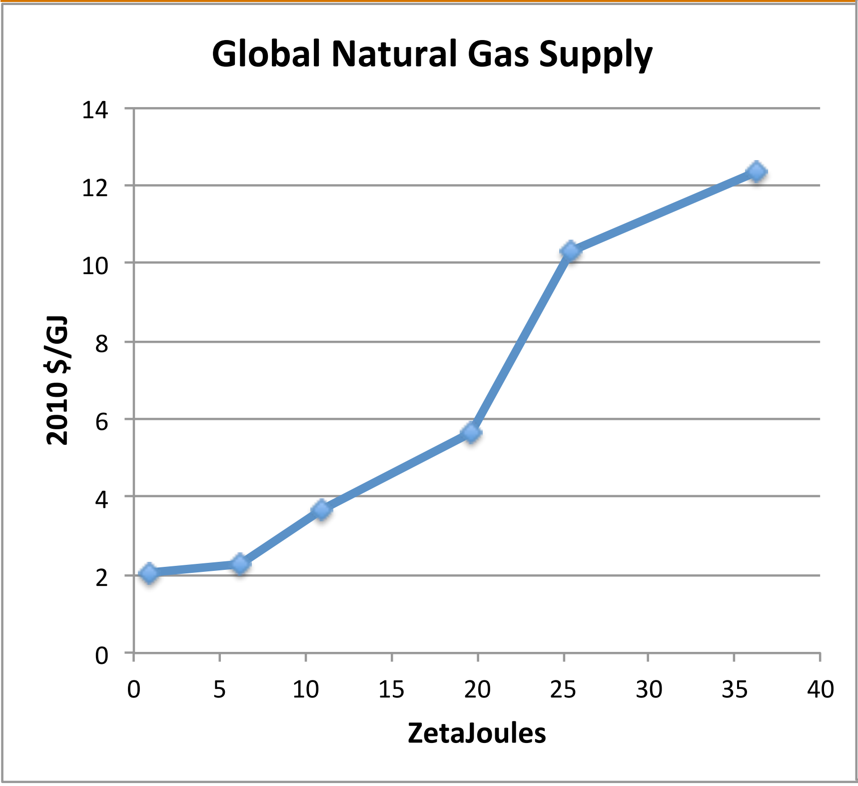
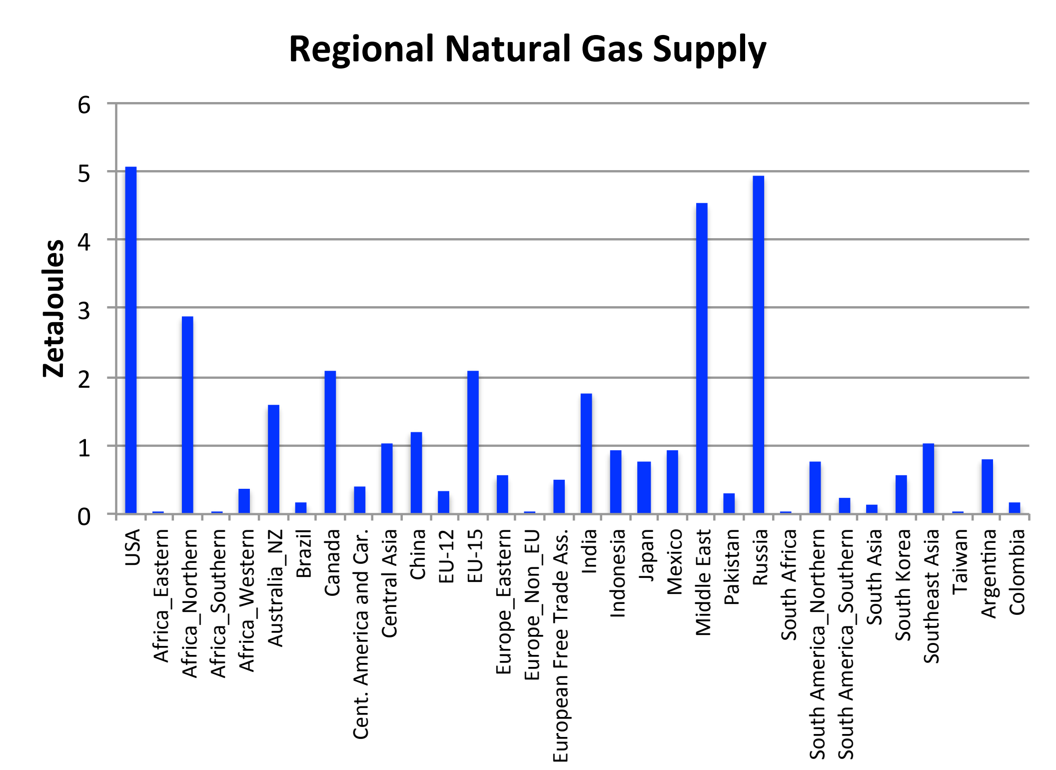
The Energy System: Resources: Natural Gas





- Oil, Gas, and Coal Resources derived from Rogner 1997; please refer to that source for original data.
- Note: The highest cost grade of natural gas is not shown here. We have ~200 ZJ more natural gas available in the model (hydrates).

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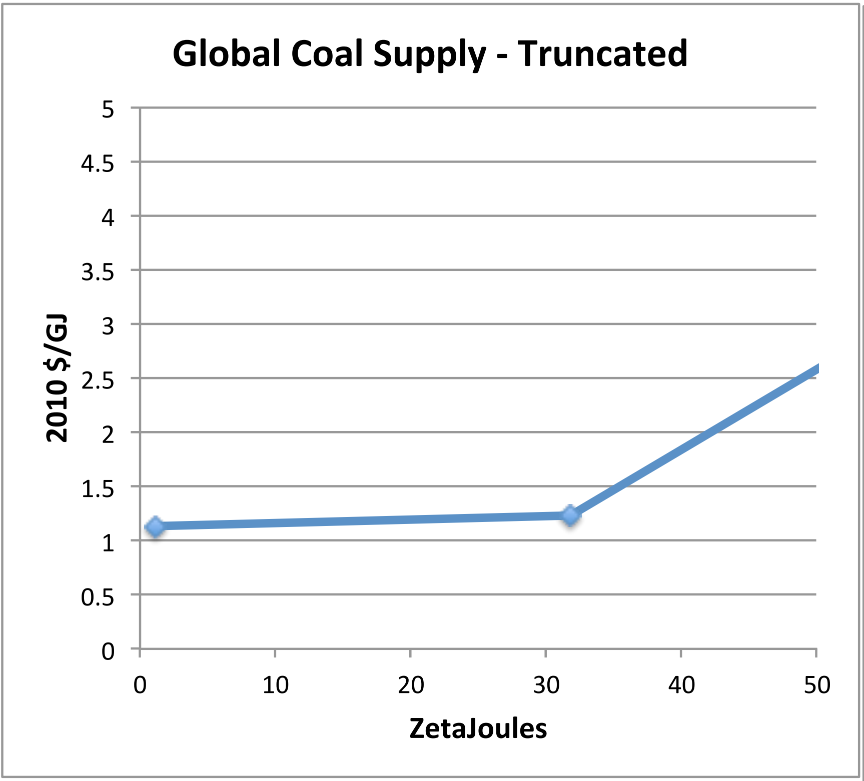
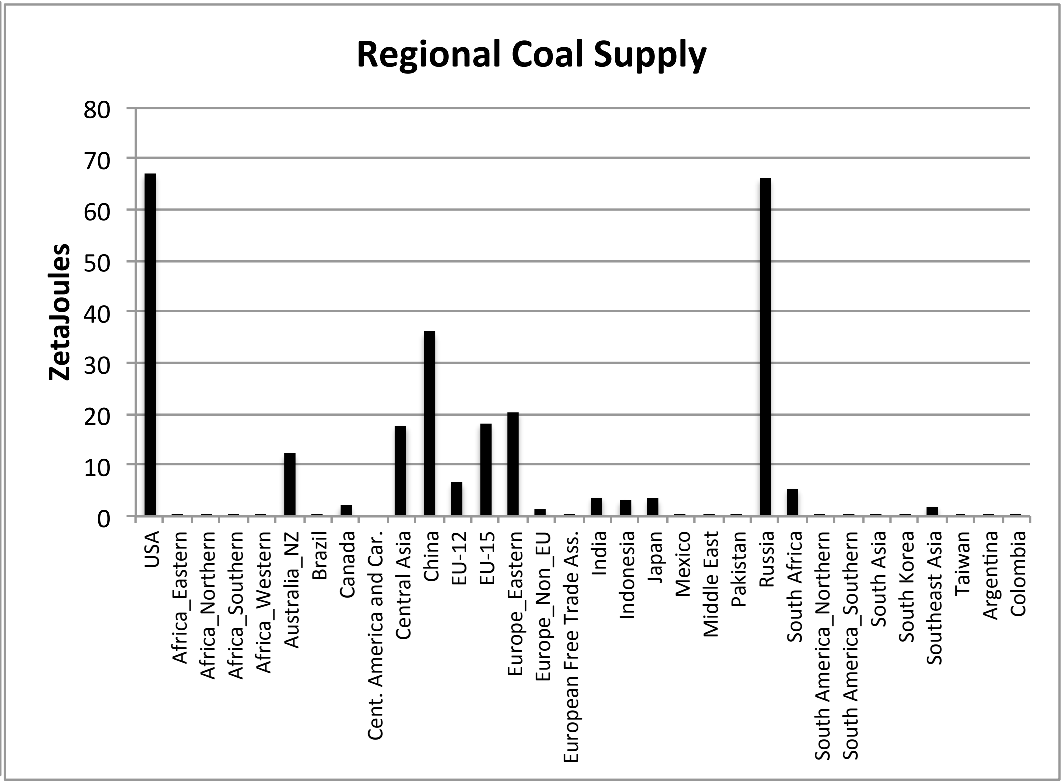
The Energy System: Resources: Coal





- Typically use around 30 ZJ to 2100 – so very flat part of curve
- Total Resources in GCAM extend to over 250 ZJ at higher costs

The Energy System: Renewable Resources

- In GCAM the capacity factors of wind turbines are based on detailed global supply curves [1, 2]. Similarly, the capacity factors of photovoltaic panels in GCAM are based on rooftop PV supply curves developed for the United States [3].

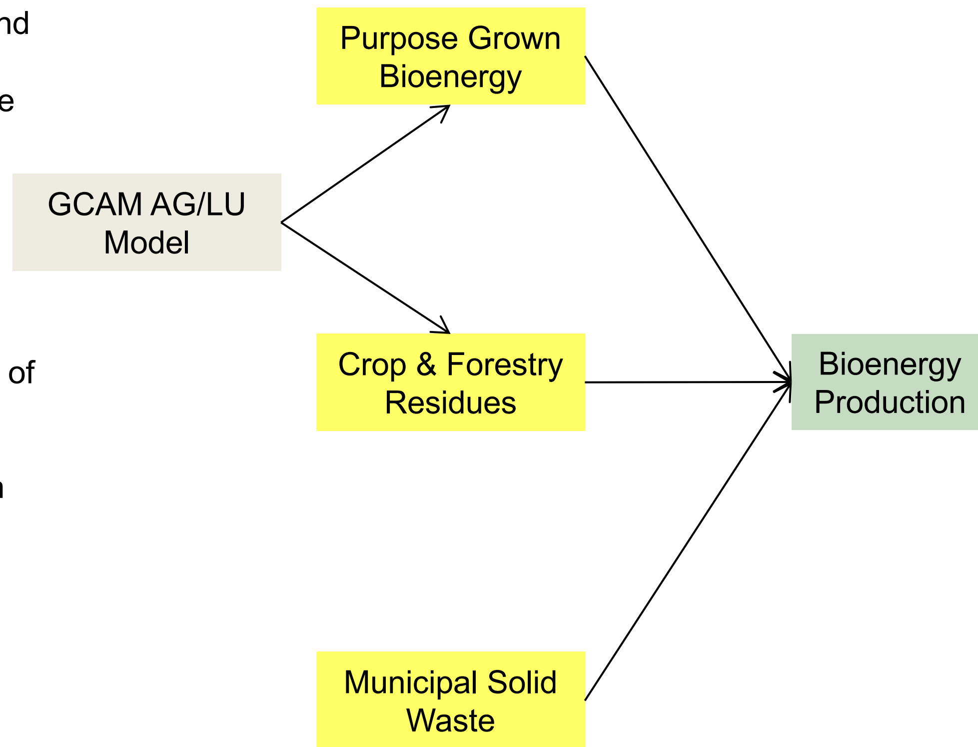
- [1] Y. Zhou and S. J. Smith, "Spatial and temporal patterns of global onshore wind speed distribution," Environmental Research Letters, vol. 8, no. 3, p. 034029, 2013.
- [2] Y. Zhou, P. Luckow, S. J. Smith, and L. Clarke, "Evaluation of global onshore wind energy potential and generation costs," Environmental science & technology, vol. 46, no. 14, pp. 7857–7864, 2012.
- [3] P. Denholm and R. Margolis, "Supply curves for rooftop solar pv-generated electricity for the united states," 2008.

Bioenergy Production

Purpose Grown Bioenergy:
• Production depends on land allocation and regional yield from Ag model
• Land allocation depends on the profit rate of biomass AND all competing land uses
• Includes 1st and 2nd generation crops

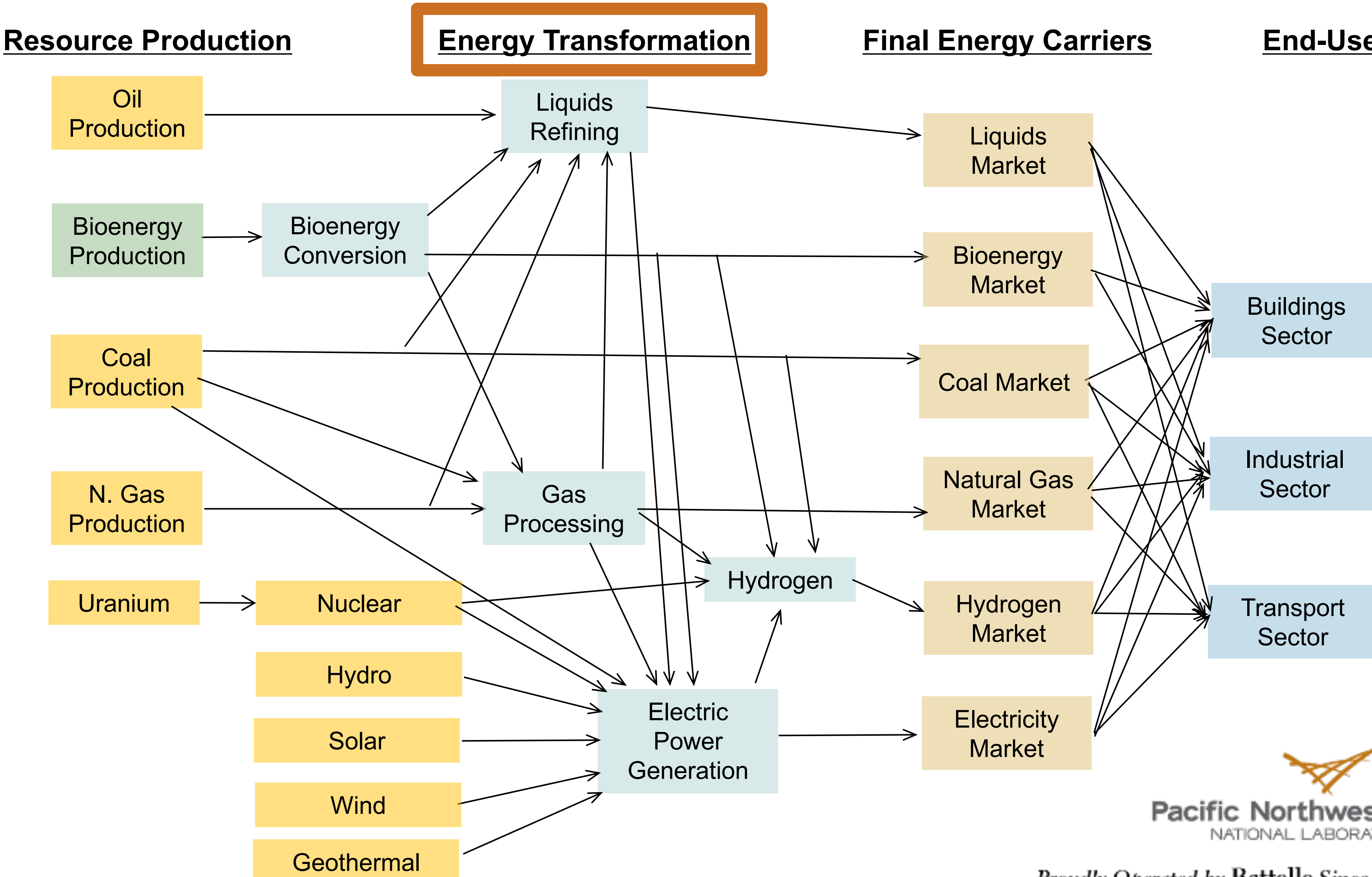
Crop & Forestry Residues:
• Potential production depends on crop production in ag model
• Fraction harvested depends on the price of bioenergy; higher prices lead to more production
• Some amount of residue must remain on the field for erosion control

Municipal Solid Waste:
• Potential production depends population and income
• Fraction used for bioenergy depends on the price of bioenergy; higher prices lead to more production



Note: We also model traditional bioenergy. However, it is not added to the bioenergy resource pool and is instead consumed directly by the buildings sector. Similarly, we model 1st generation bioenergy (corn, sugar, oil crops), but it is converted directly to ethanol or diesel and not added to the bioenergy resource pool.

The Energy System: Structure



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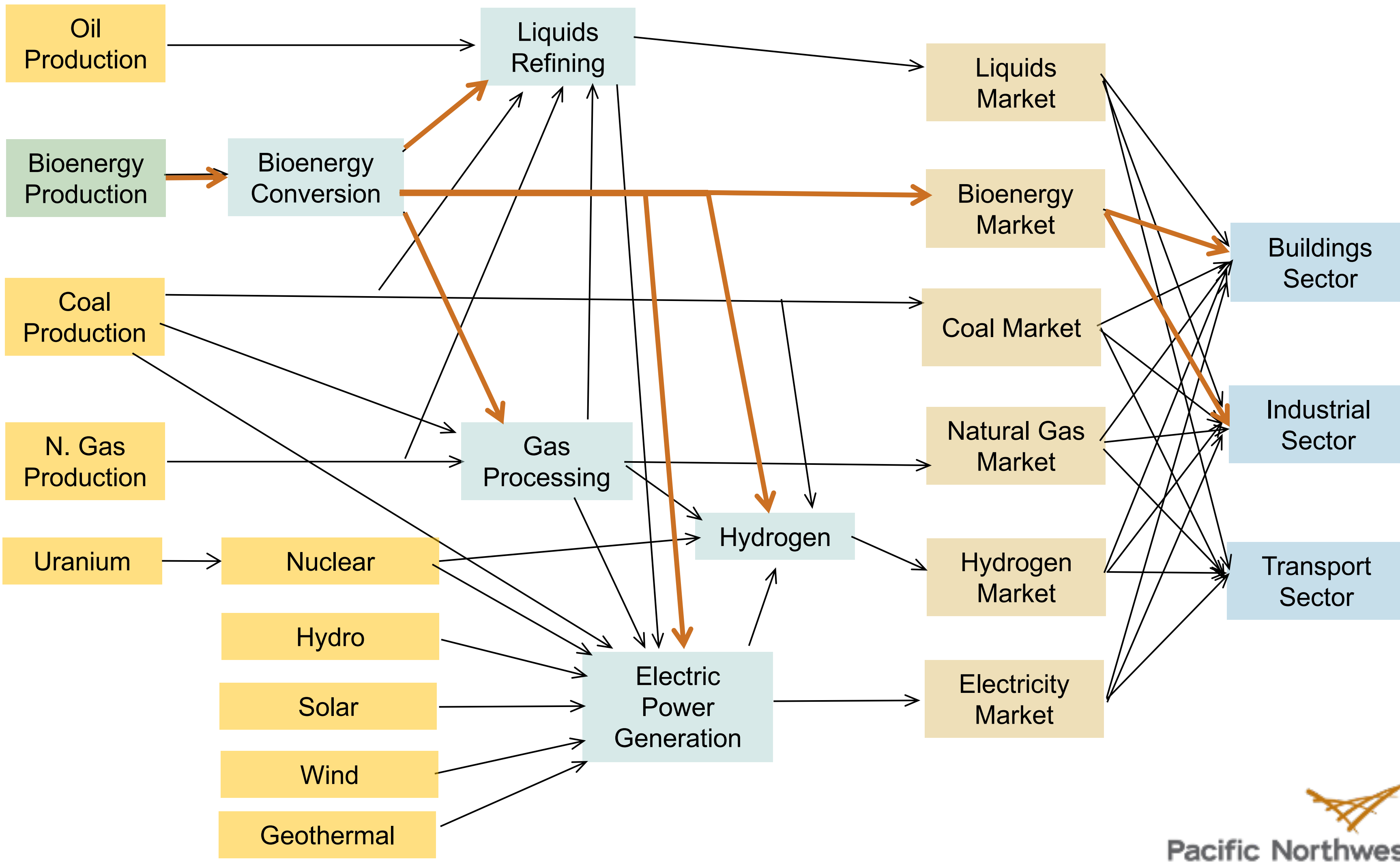
The Energy System: Energy Transformation and Conversion

- Final energy sectors in GCAM consume several fuels:
  - Electricity
  - Liquid Fuels
  - Coal
  - Bioenergy
  - Gas
  - Hydrogen
- Corresponding to each of these is a conversion sector that takes as inputs various resources.
  - For example, liquid fuels are produced from bioenergy, conventional and unconventional oil, coal, and natural gas.
- Conversion sectors can utilize a number of technologies, even for a single input fuel.
  - Bioenergy-to-liquids, for example, can be produced

  through several different technologies, some with CCS options.

The Energy System: Bioenergy Pathways



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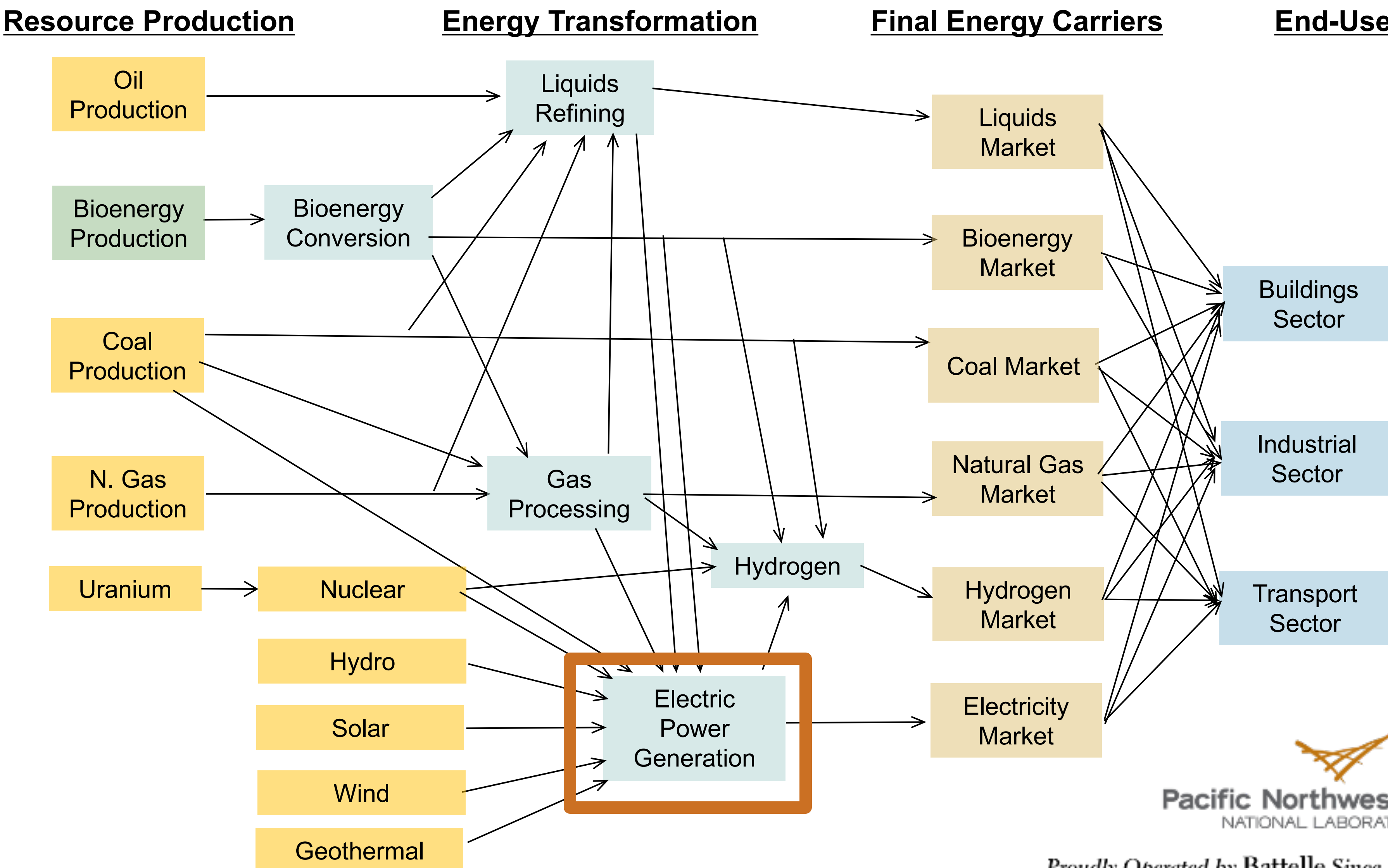
The Energy System: Electric Generation



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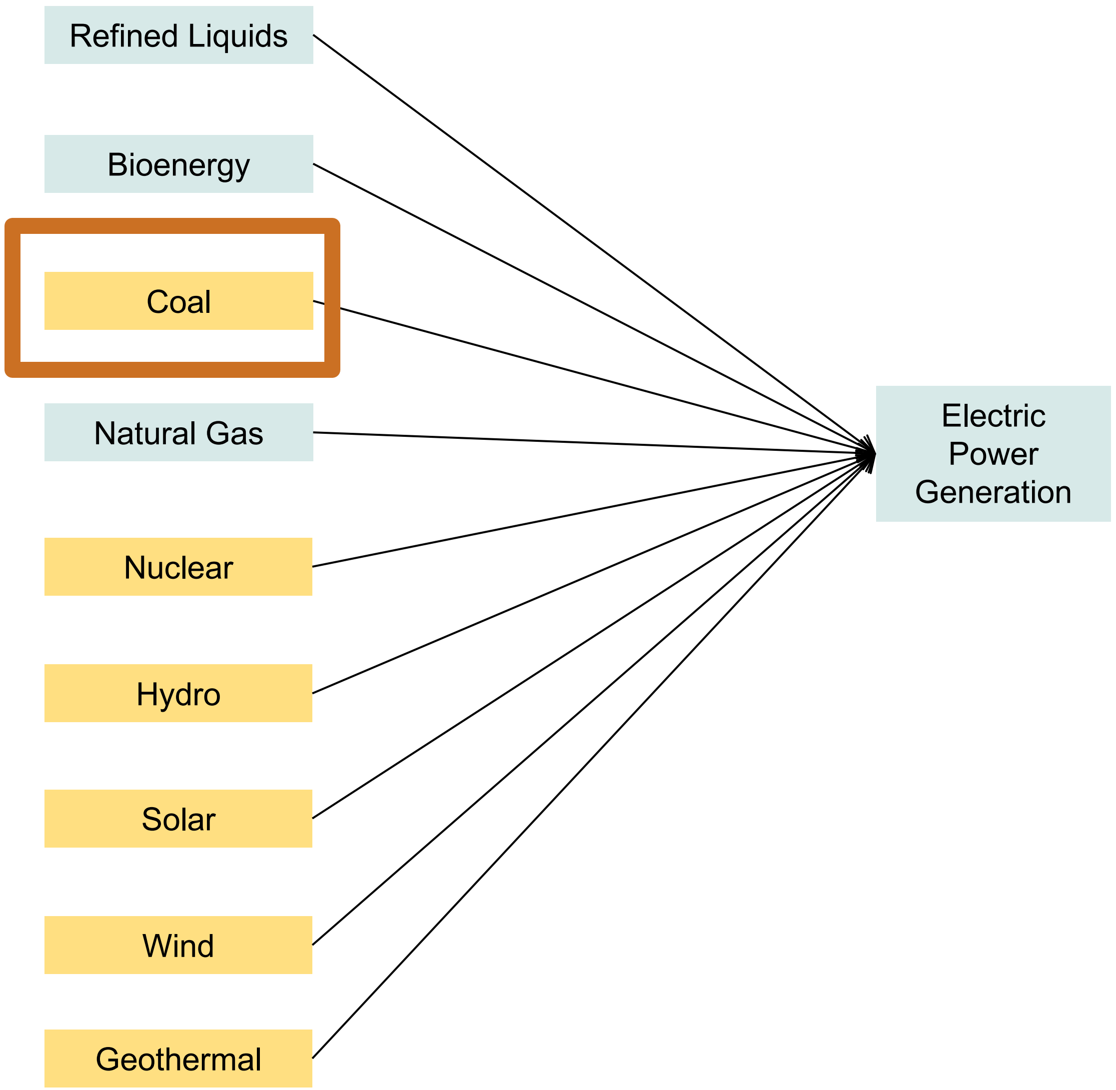
The Energy System: Electricity Generation



The Energy System: Electric Power Plants

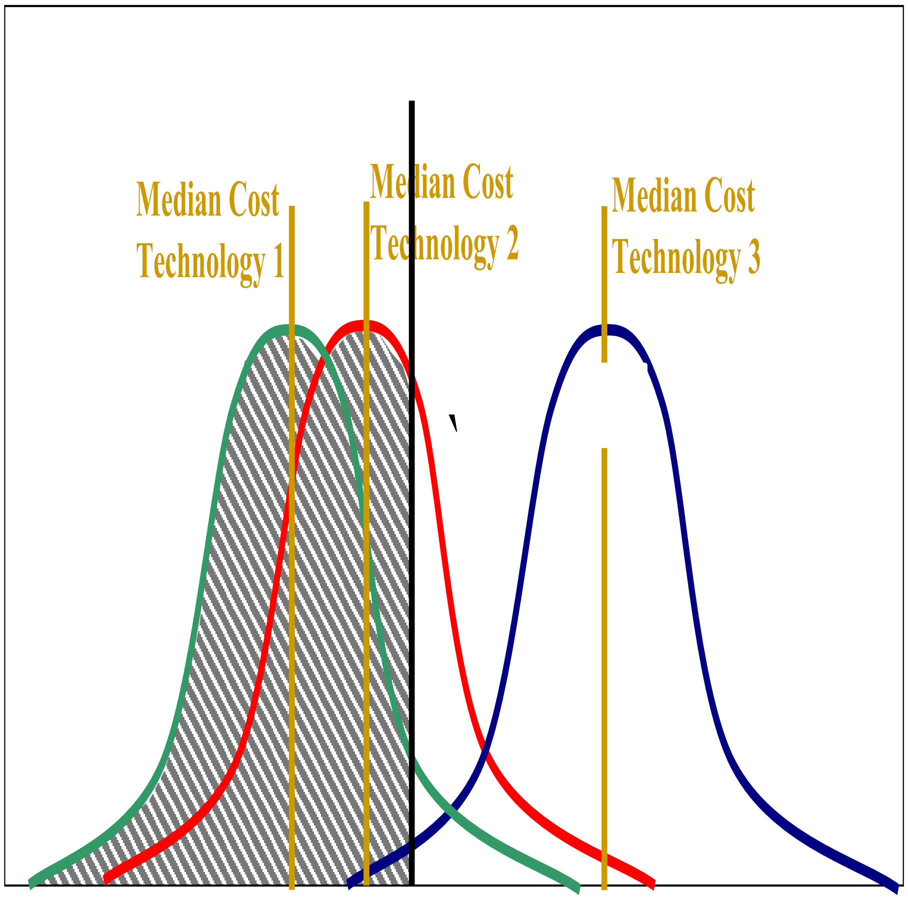
- We model several fuels and technologies for generating electric power.

- For example, the current GCAM core has 4 different technology options for coal power plants:
  - Pulverized coal steam plants
  - Pulverized coal steam plants with CO_2 Capture and Storage (CCS)
  - IGCC
  - IGCC with CO_2 Capture and Storage (CCS)

- Each power plant has a different efficiency, non-energy cost, and emissions factor.
  - Which technology is deployed depends on the trade-offs between emissions and other costs. For example, IGCC with CCS will only deploy with a higher value on CO2 – as in a climate policy scenario.

The Energy System: Technology Competition

A Probabilistic Approach

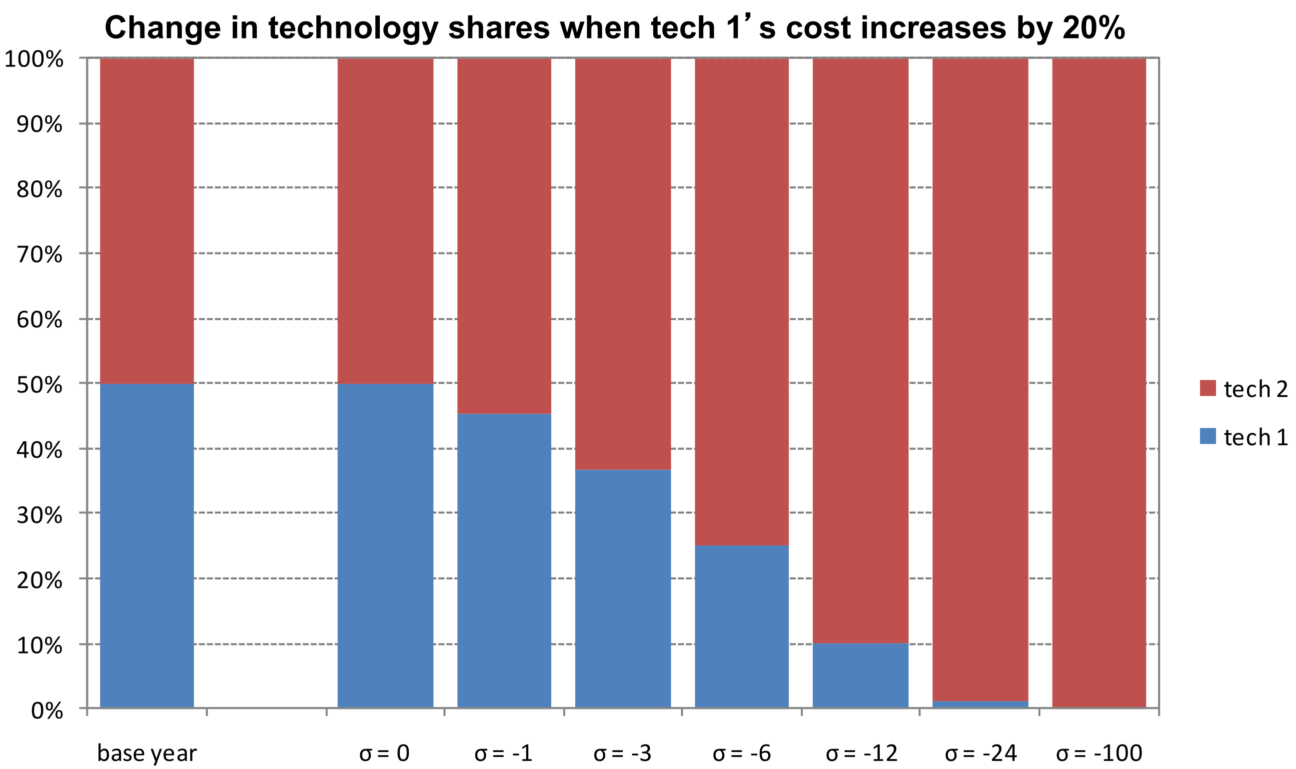


- Economic competition among technologies takes place at many sectors and levels.
- Assumes a distribution of realized costs due to heterogeneous conditions.
- Market share based on probability that a technology has the least cost for an application.
  - Avoids a "winner take all" result.
  - "Logit" specification.

The Energy System: Technology Competition

$$s_i = \frac{\alpha_i c_i^{\sigma}}{\sum_j \alpha_j c_j^{\sigma}}$$

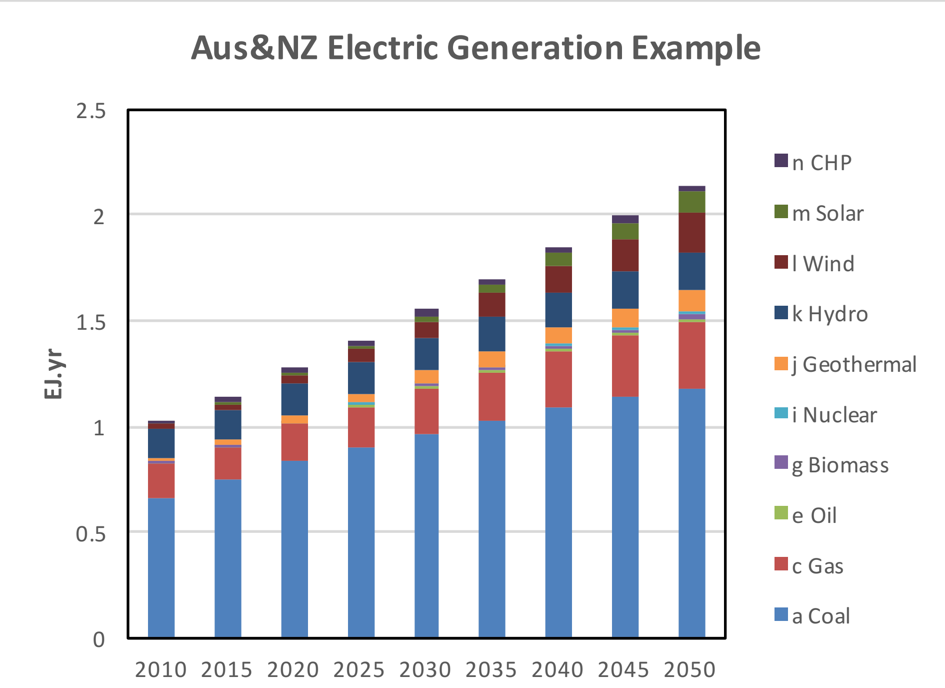
Source: Clarke and Edmonds (1993), McFadden (1974)

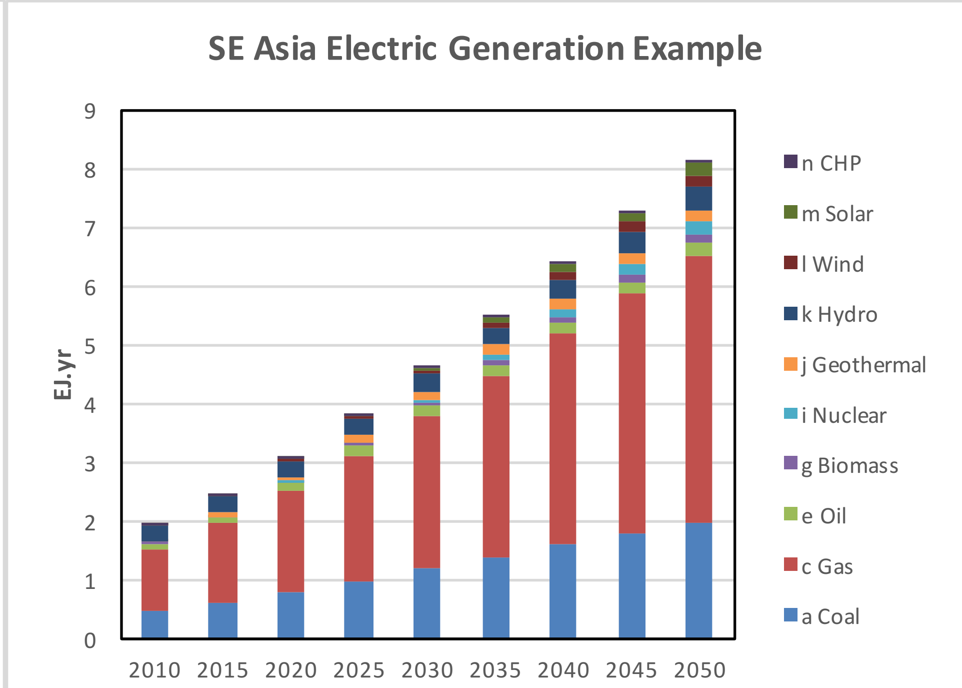


The Energy System: Vintaging of Capital

- We assume that capital stock in certain sectors (for example, electric power generation and oil refining sectors) is long-lived.
- This means that a power plant or refinery built in one model period *may* still be in operation many time periods later.
- However, we do not assume that existing capital is always in operation. Once the variable cost exceeds the market price, we begin to shut down existing units. This often occurs when a carbon price is applied.

Example Results: Electric Generation by Fuel





- Base Year 2010 calibrated to IEA data.
- Capital Stock vintaging and retirements
- Investments in new capital based on relative costs and calibrated preferences.

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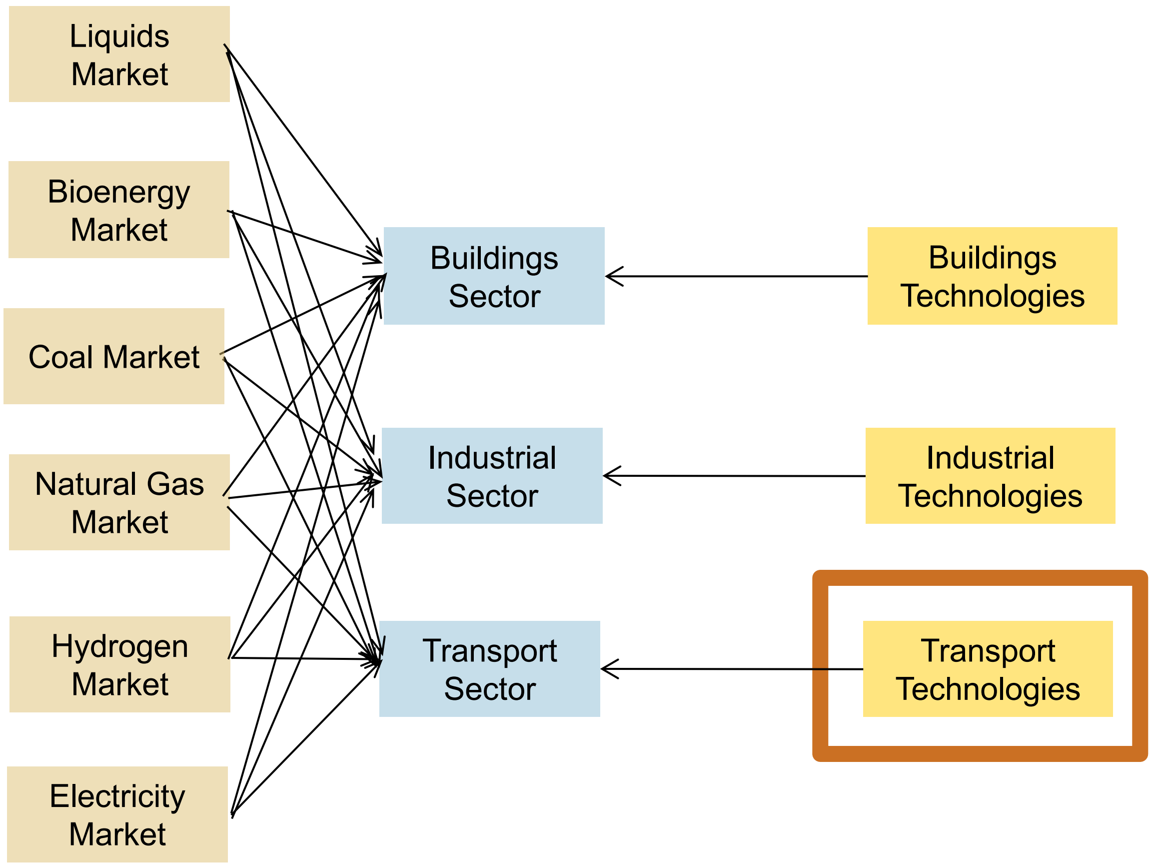
The Energy System: Energy Demand



We have detailed representations of transportation & buildings in all regions.

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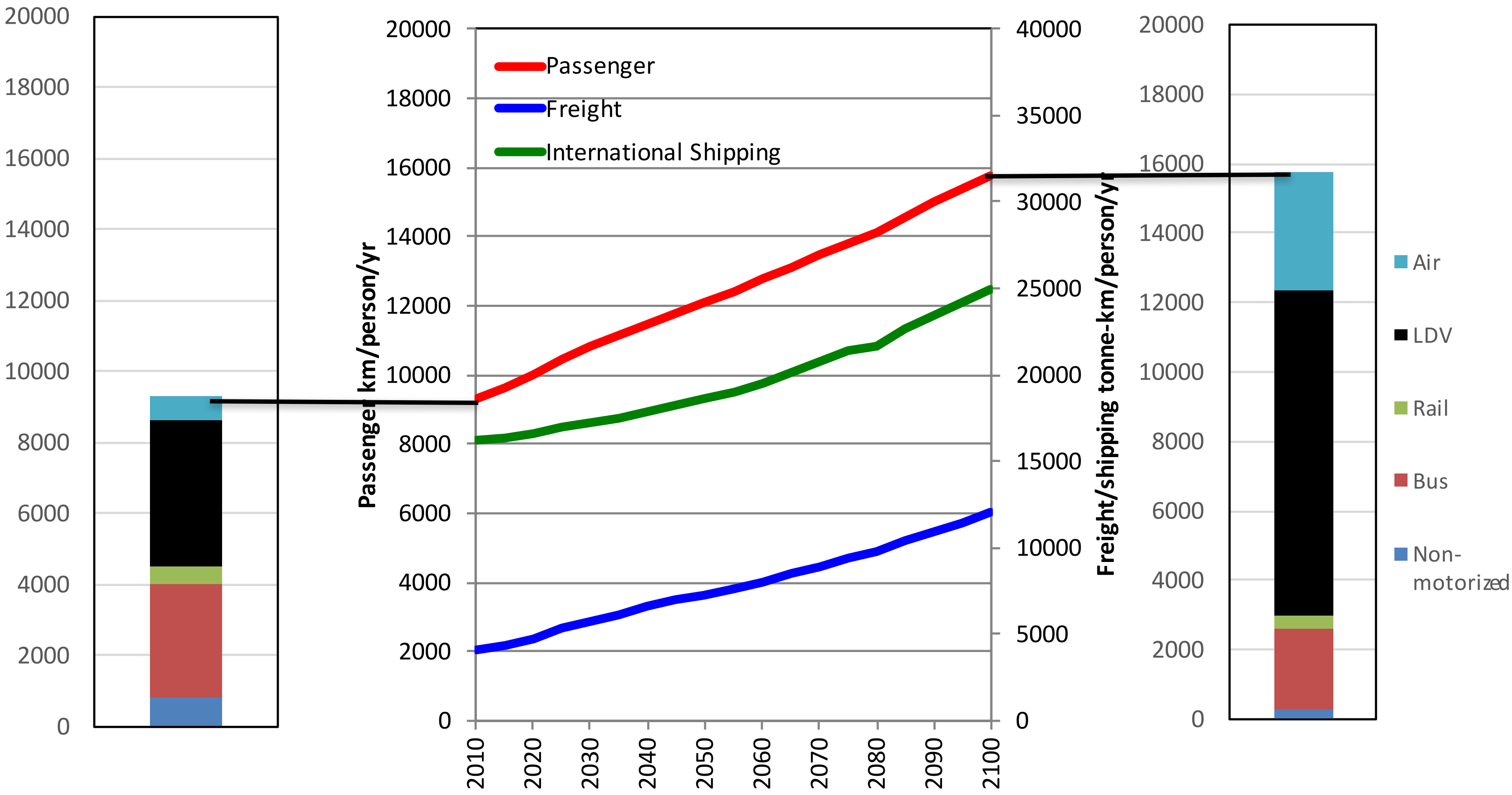
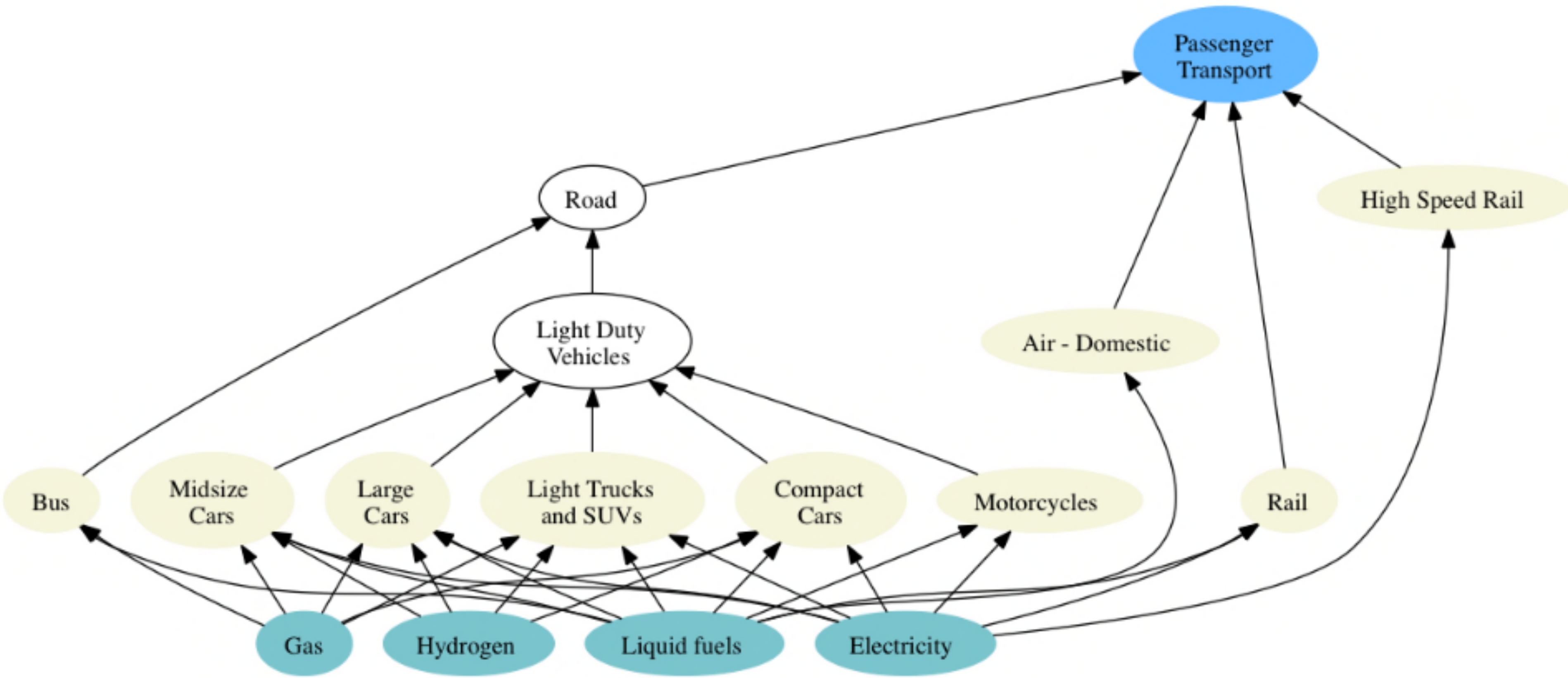
The Energy System: Transportation

- Per capita transportation service demands (measured in km/yr) are a function of income and the prices of services.



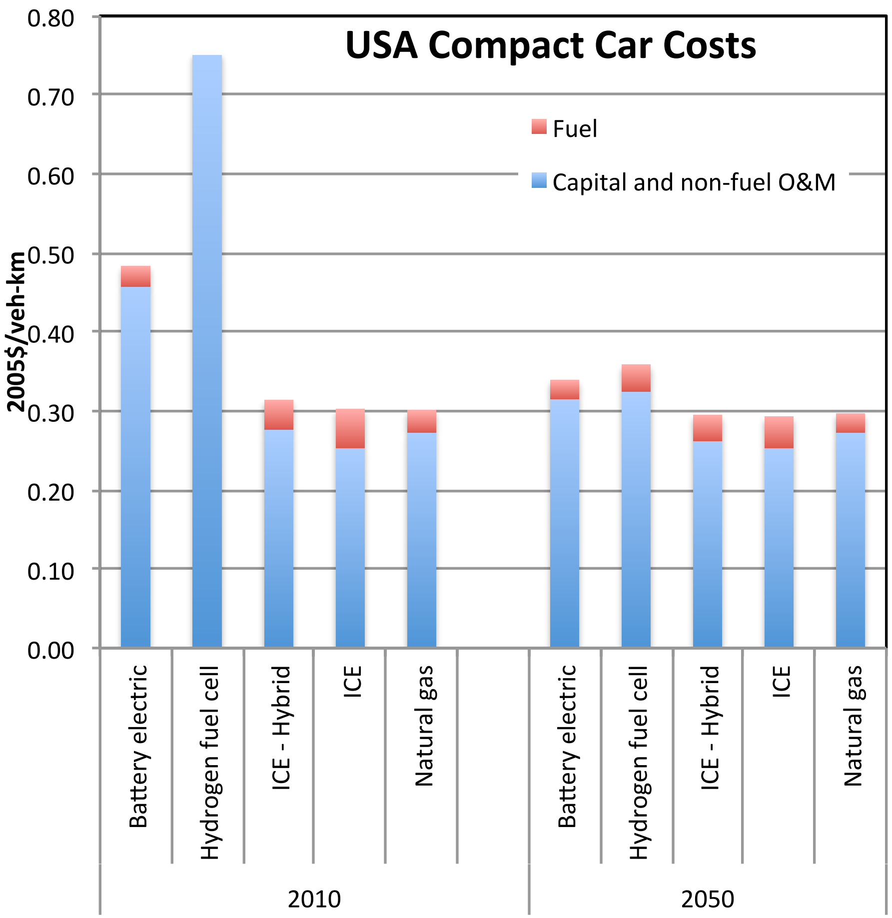
The Energy System: Transportation

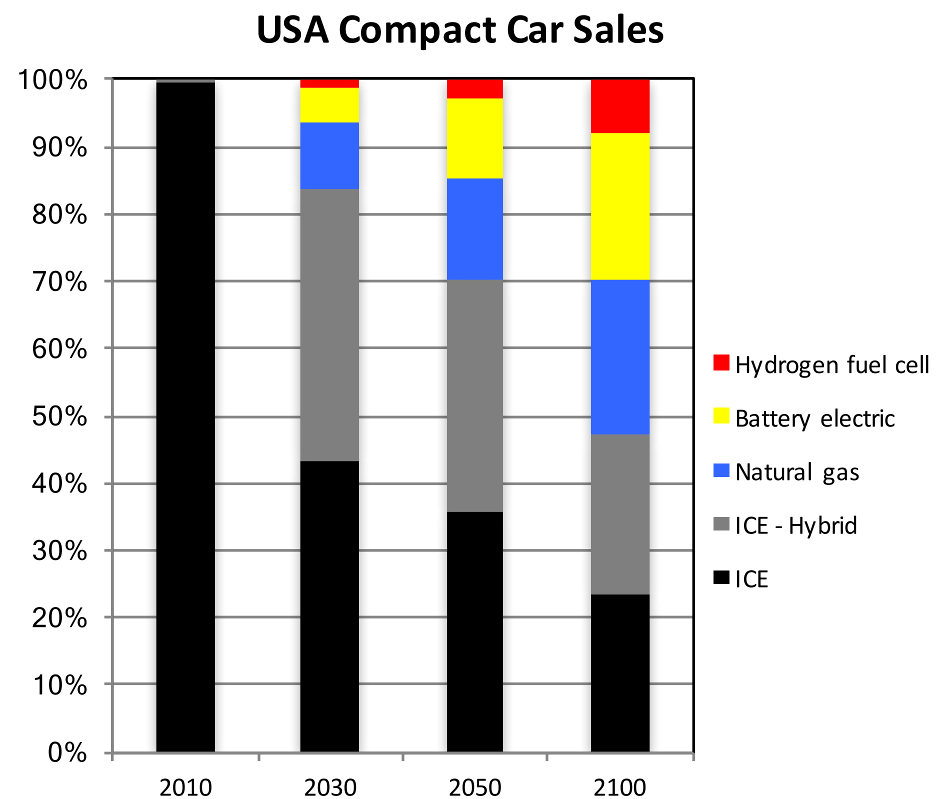
- The choice among modes of transportation in the passenger sector is a function of the cost of travel, the time it takes, and income.



The Energy System: Transportation

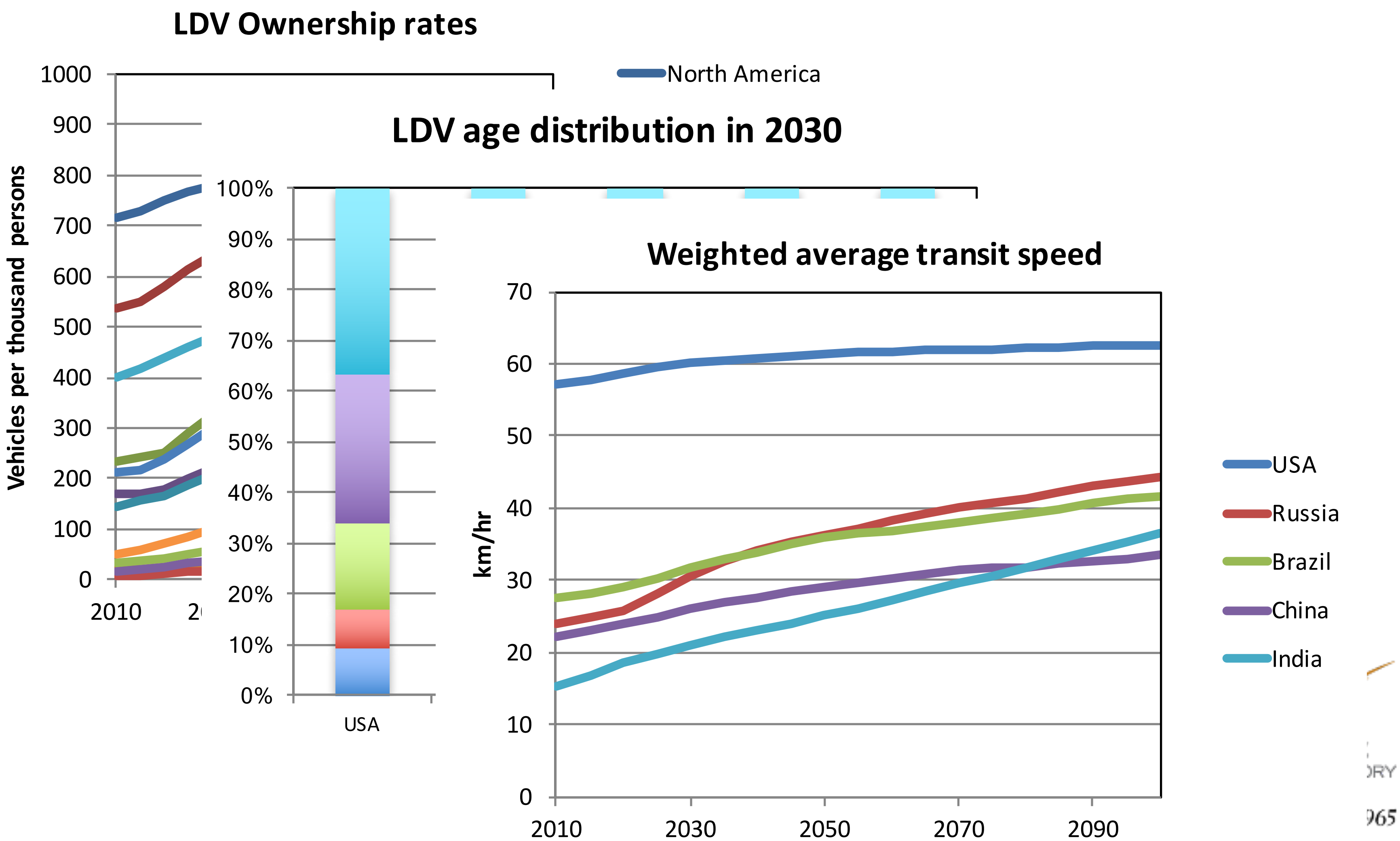
- The choice among fuels within a mode is a function of cost (including capital cost and the cost of fuel)



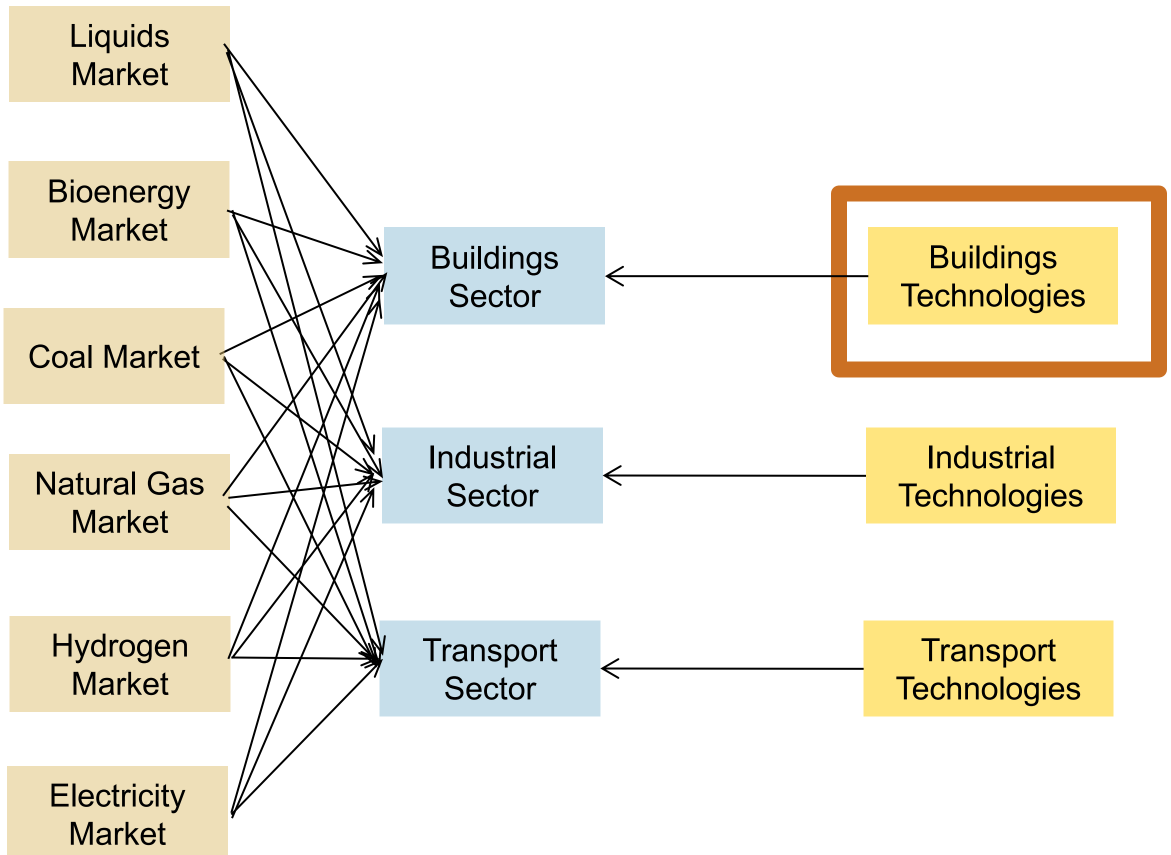


The Energy System: Transportation

- A wide variety of detailed output variables can be reported for the transportation sector



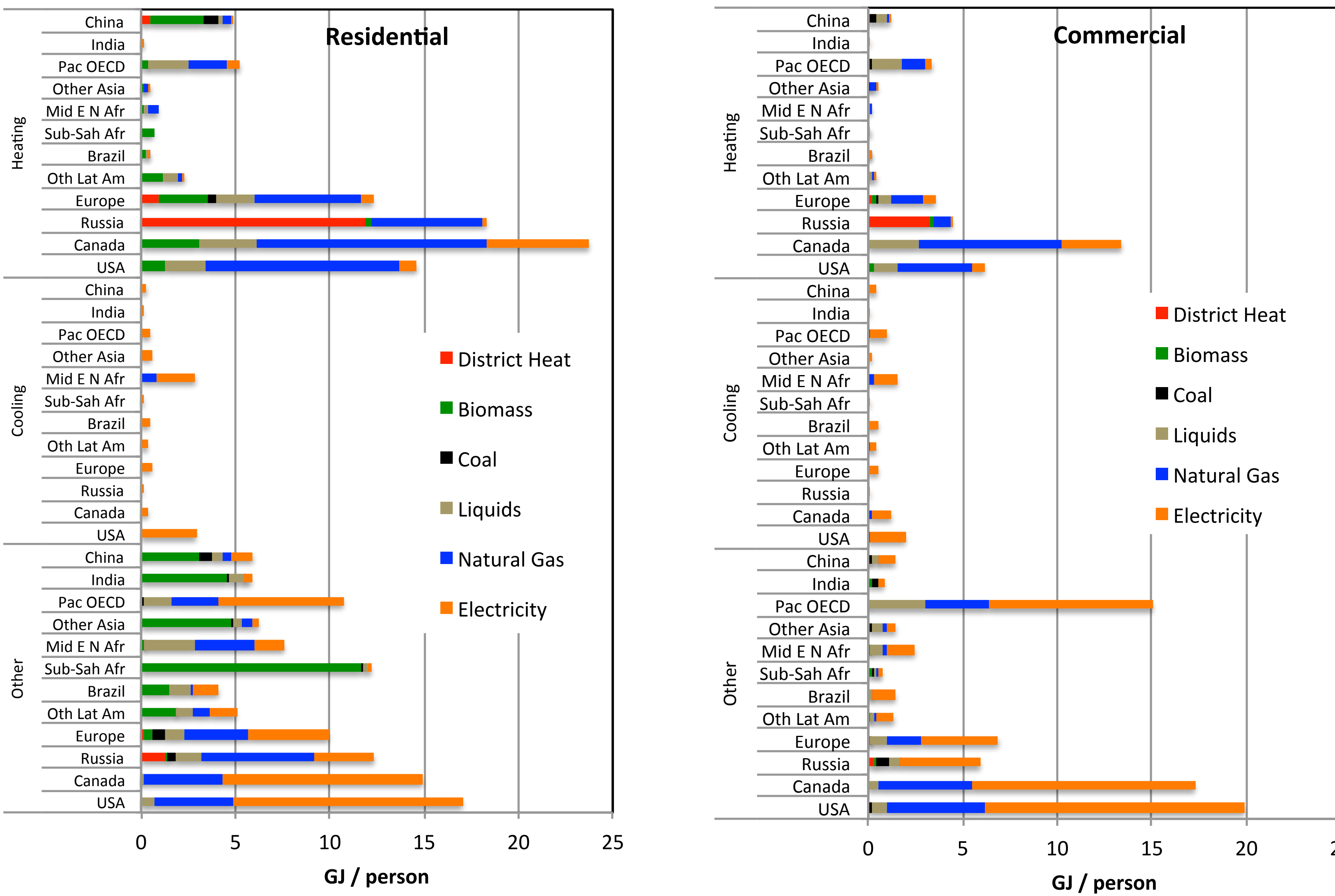
The Energy System: Energy Demand



We have detailed representations of transportation & buildings in all regions.

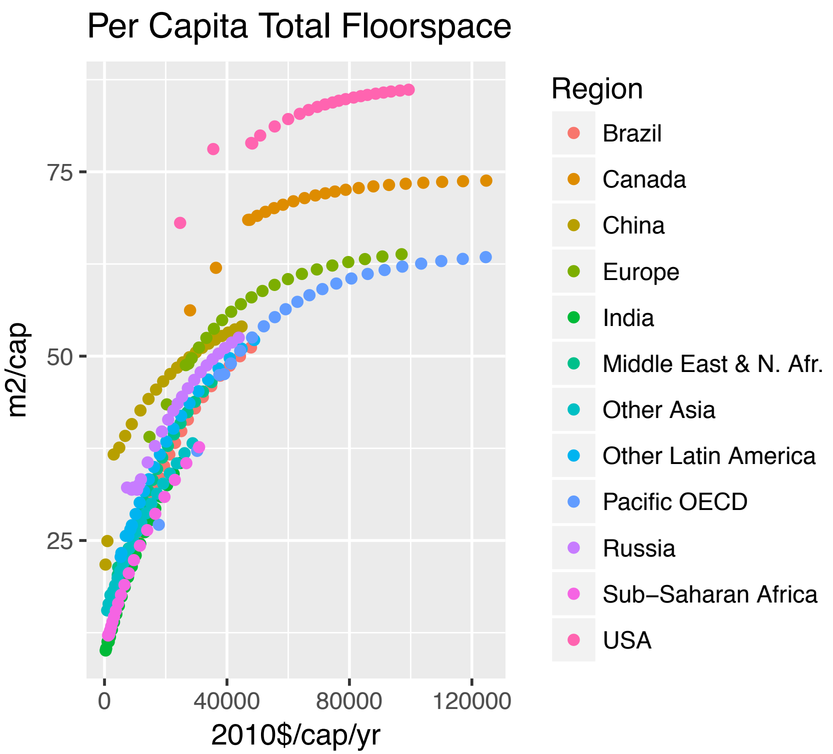
The Energy System: Buildings

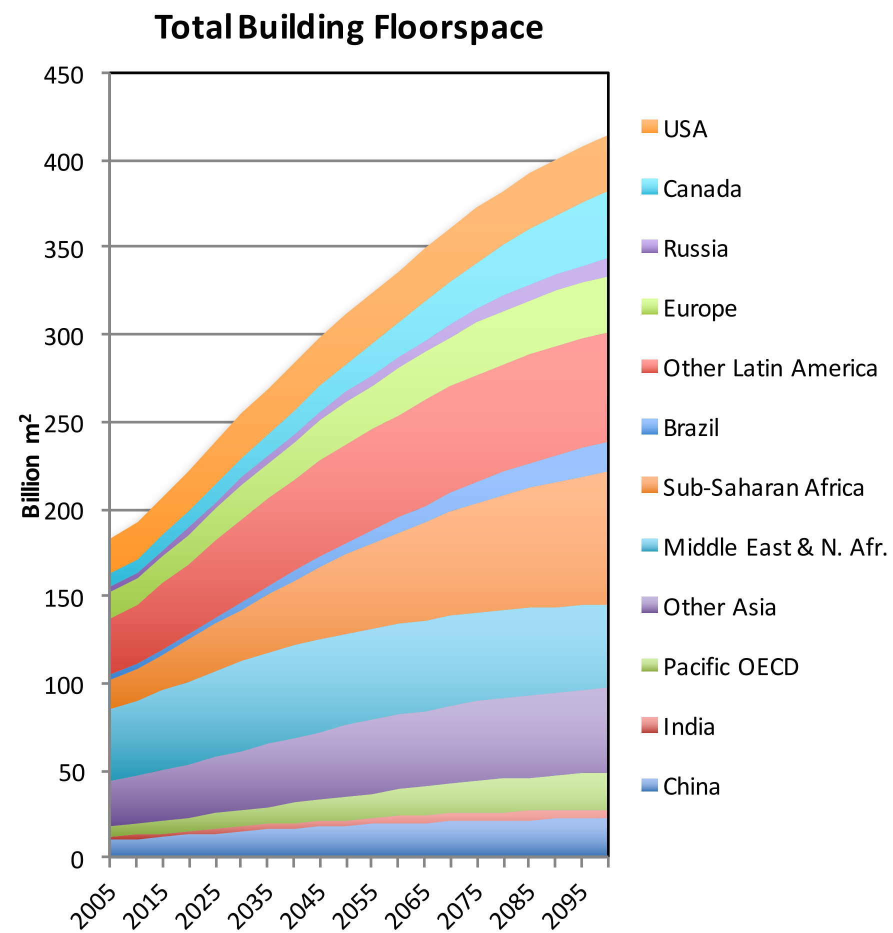
Per-capita Residential and Commercial Energy Use in 2010



The Energy System: Buildings

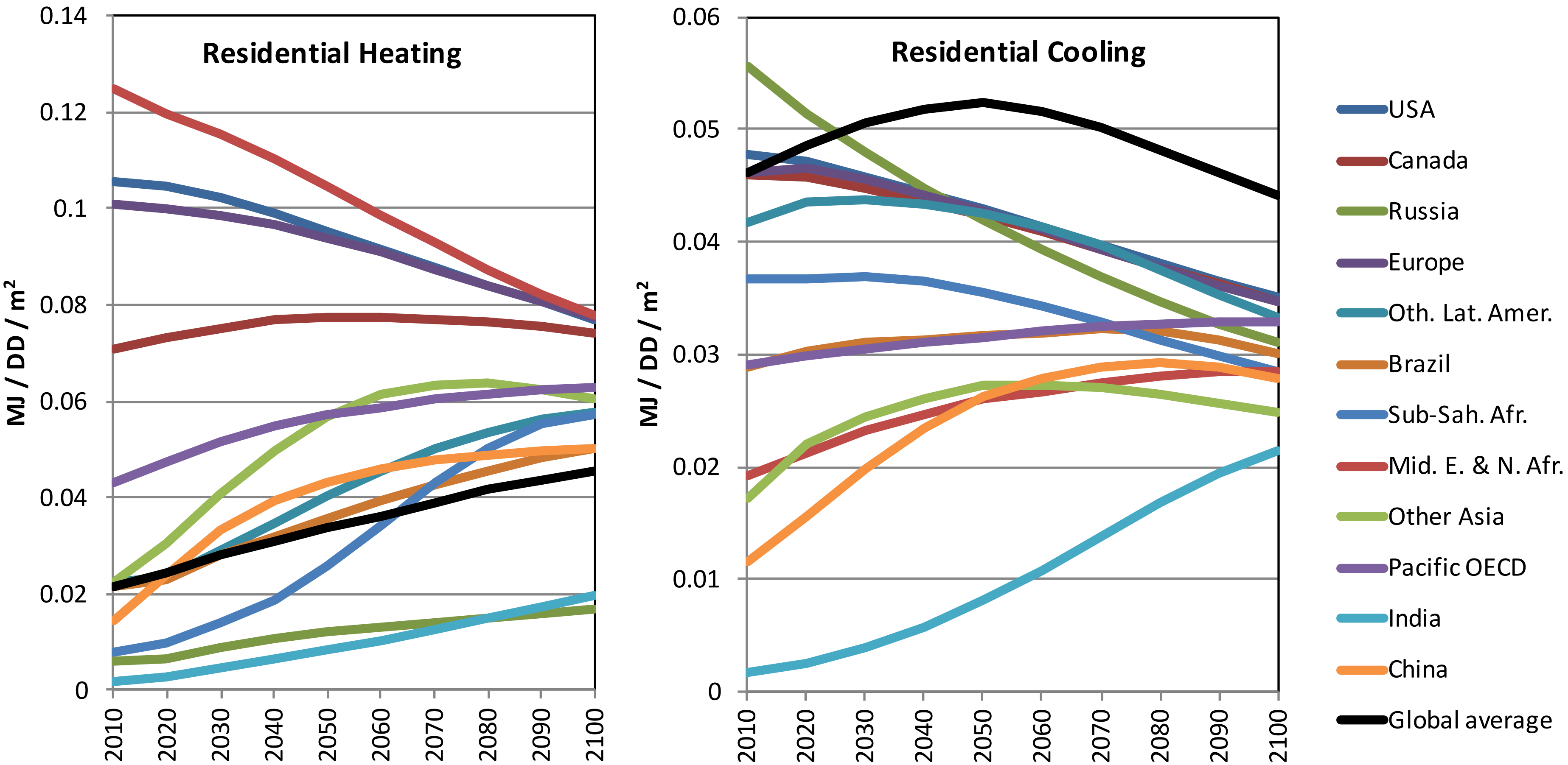
- Future evolution of building energy use is shaped by...
  - Residential and commercial floorspace
    - Population, GDP, and exogenous per-capita floorspace satiation levels





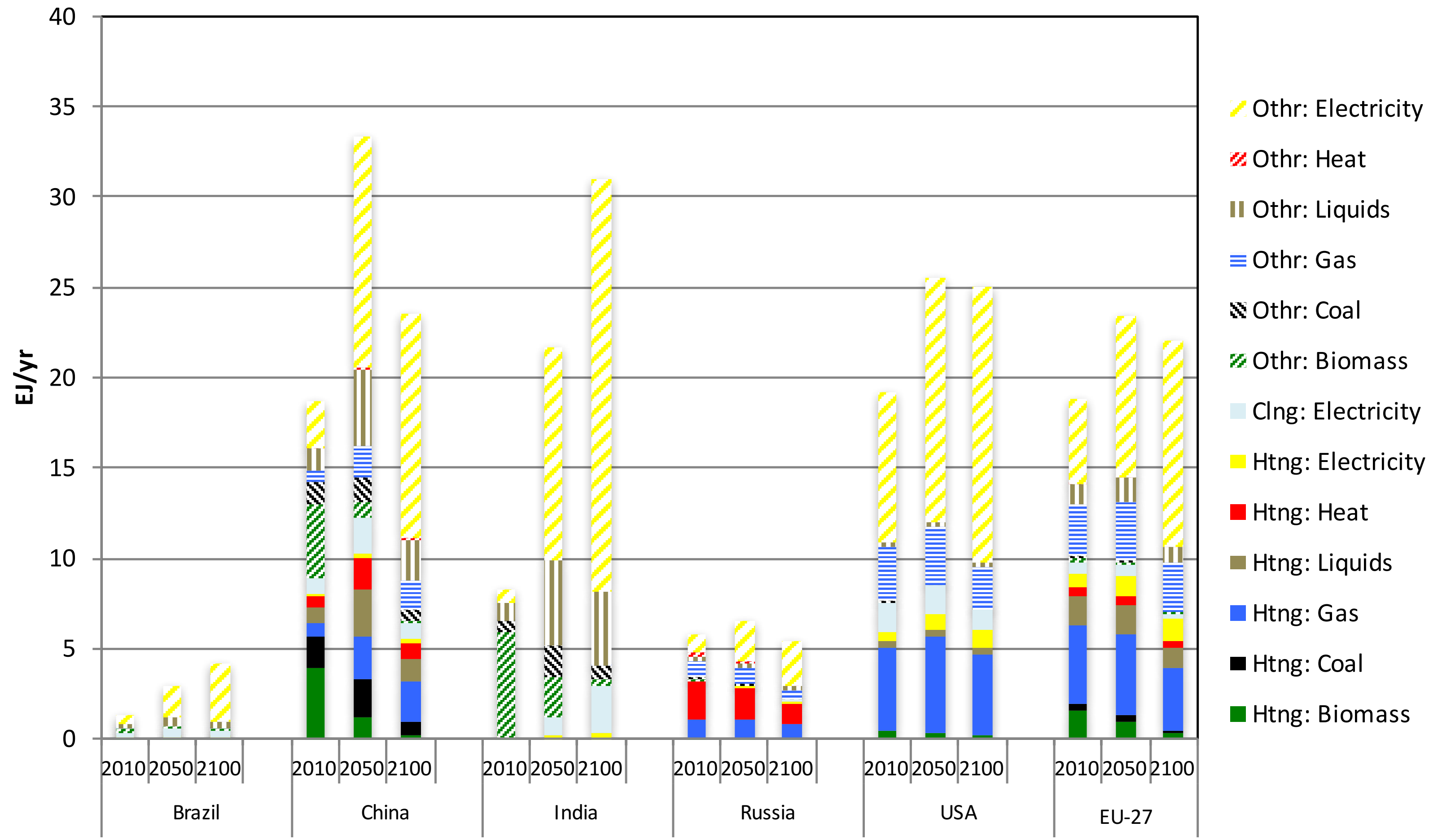
The Energy System: Buildings

- Future evolution of building energy use is shaped by...
  - Residential and commercial floorspace
  - Levels of building service demands per unit floorspace
    - Climate, building shell conductivity, GDP, and exogenous satiation levels



The Energy System: Buildings

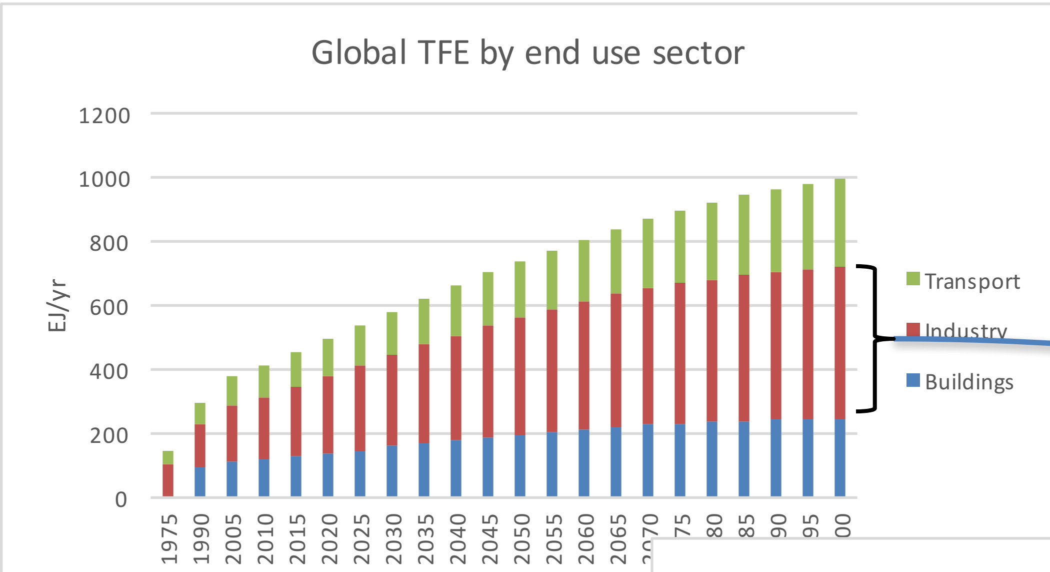
- Future evolution of building energy use is shaped by...
  - Residential and commercial floorspace
  - Levels of building service demands per unit floorspace
  - Fuel and technology choices by consumers

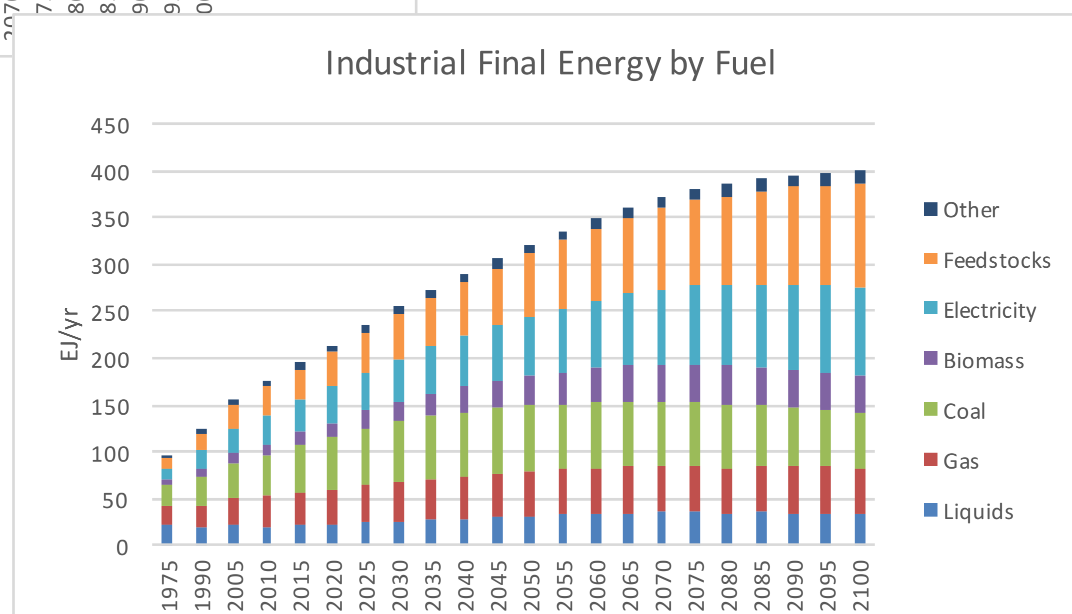


The Energy System: Calibration

- The current base year for the energy system is 2010.
- We use IEA energy balances as calibration data.
  - The calibration procedure calculates "share weights" such that the dataset derived from the IEA energy balances is reproduced.
  - These share weights reflect unmeasured and non-economic influences on decision-making.
    - If a technology has low costs but nevertheless has low market share (e.g. coal furnaces), then the model will compute a low share weight. If this base-year share weight is applied to future periods, then the market share of the technology will remain low even if it remains a relatively low-cost option.
  - In most cases, we retain these share weights in future years. In some cases (e.g. renewables in the electric sector, or alternative-fuel vehicles in the LDV sector), we have over-written them because the base-year shares do not reflect mature market equilibrium conditions.

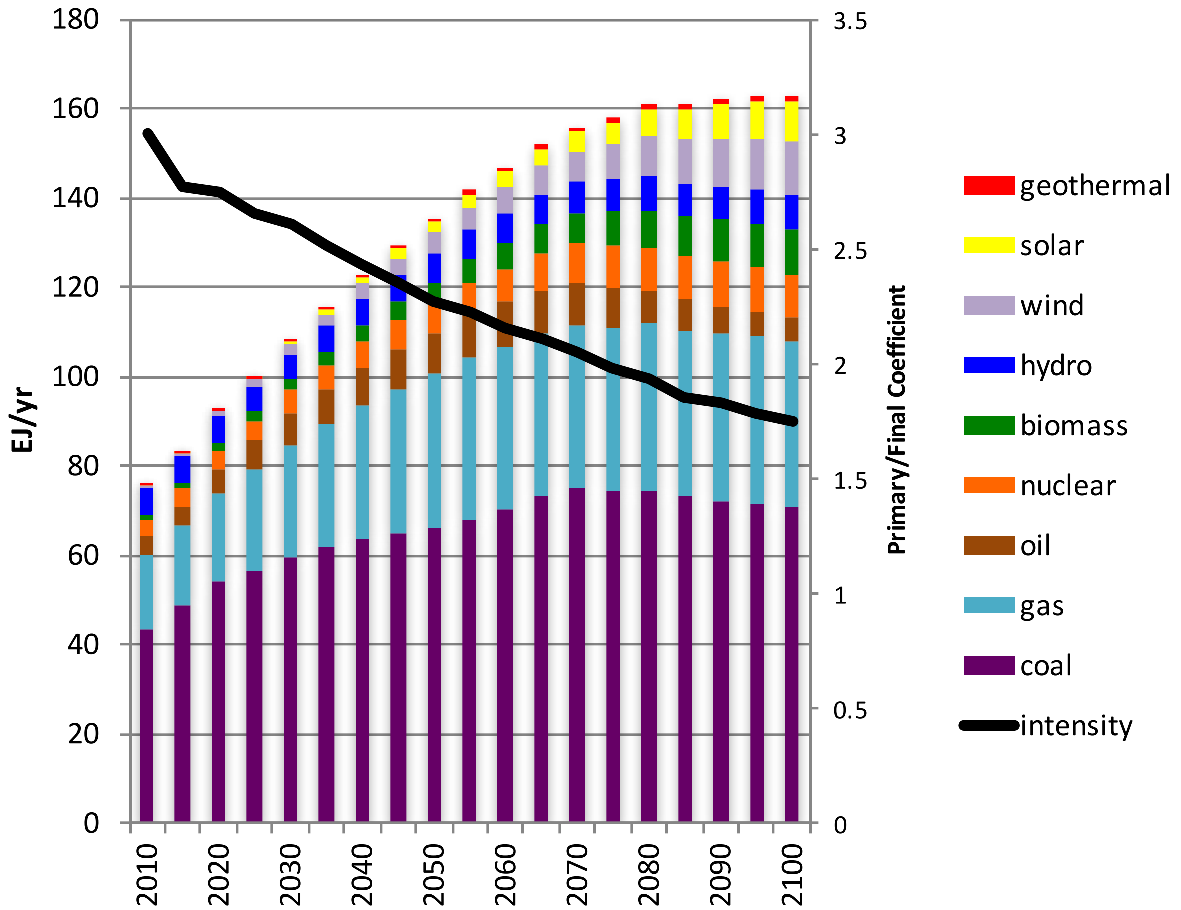
The Energy System: Results





The Energy System: Results

Primary Energy Inputs to Industrial Electricity



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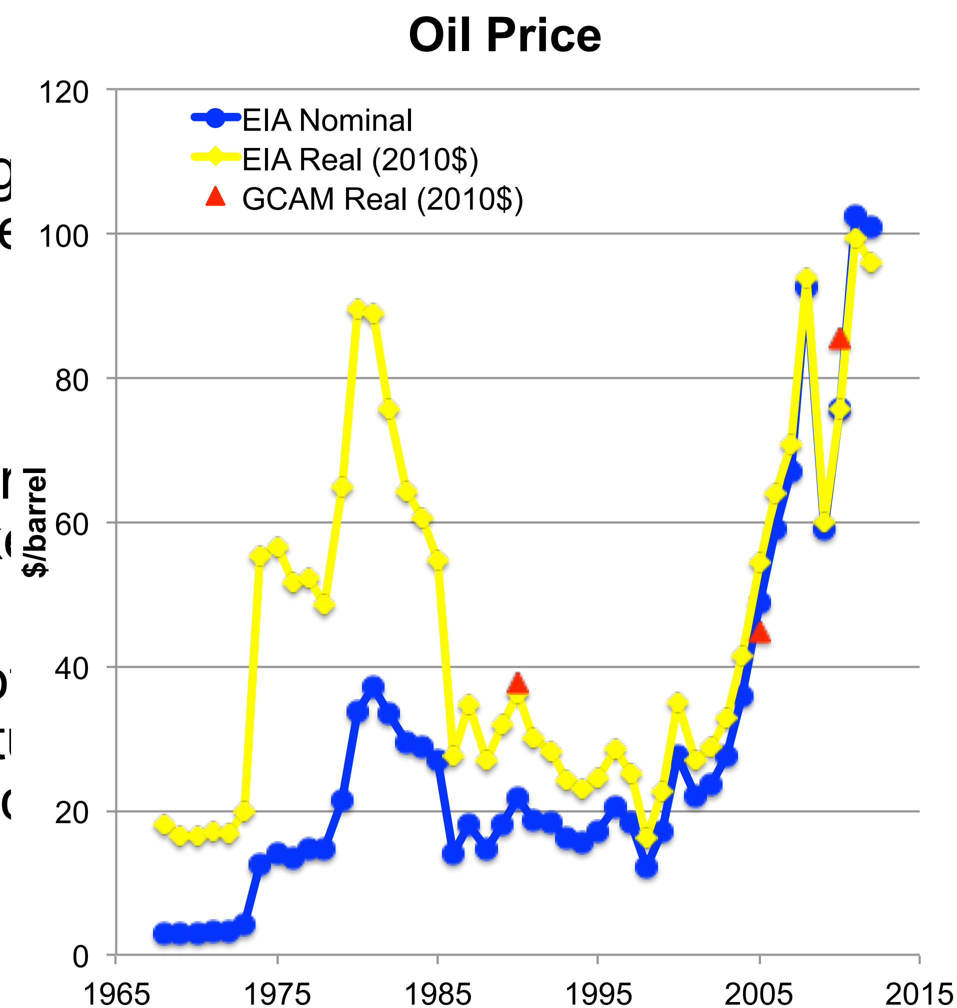
Frequently Asked Questions

- Common question:
  - Why are some of the energ
recent history or other proje
- Answer:
  - We are a long-term equilibr
to capture short-term mark
behavior.
  - In the case of oil, we do no
because the cost of substit
than the current market pri



Agriculture and Land use

2017

Kate Calvin

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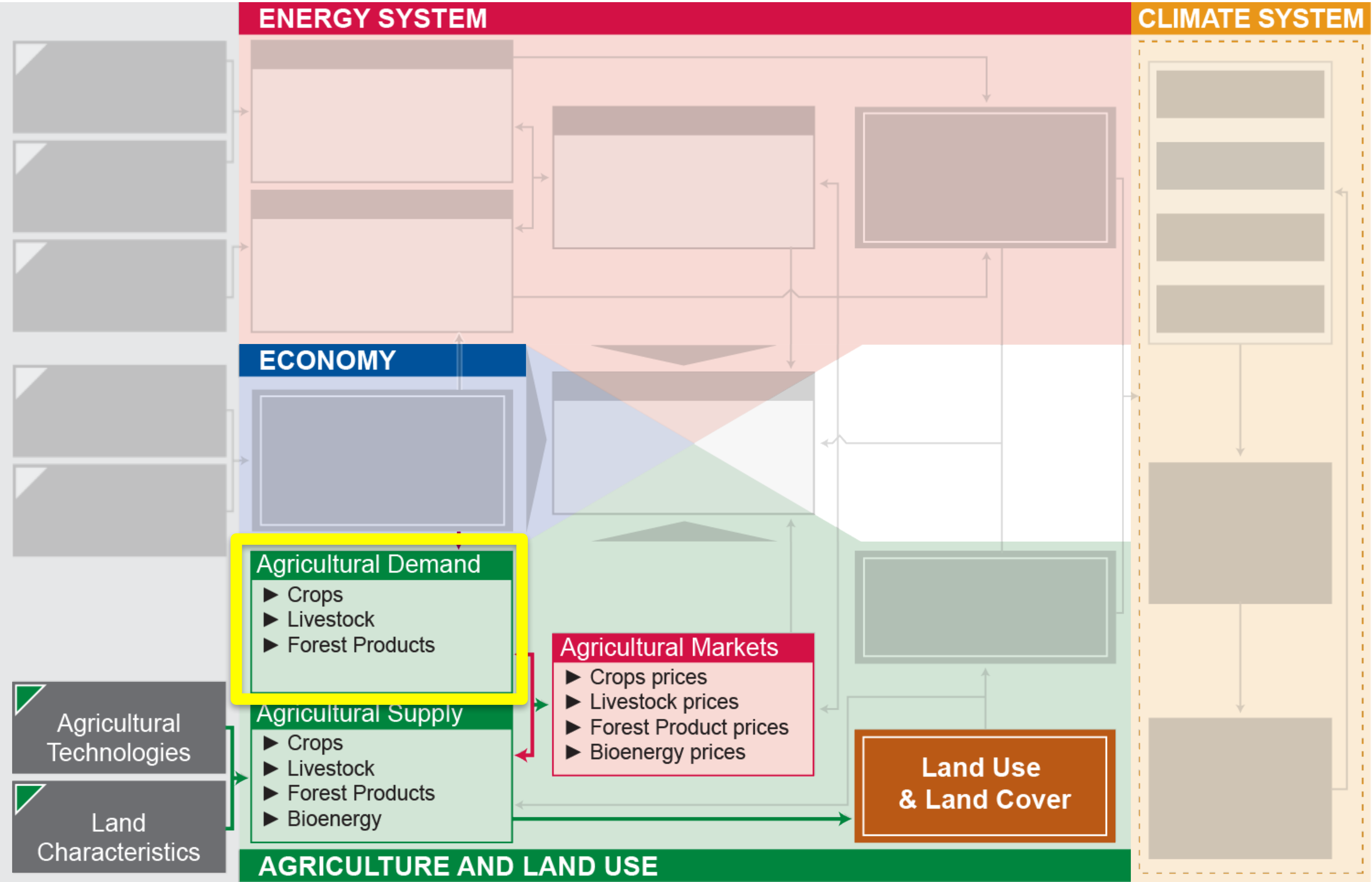
The Global Change Assessment Model



The Agricultural System: Demand

- GCAM currently models supply and demand for 13 crops, 6 animal categories, and bioenergy:
  - Crops: corn, rice, wheat, sugar, oil crops (e.g., soybeans), other grains (e.g., barley), fiber (e.g., cotton), fodder grass & herb (e.g., alfalfa), roots & tubers, fruits & vegetables, palm fruit
  - Animals: beef, dairy, pork, poultry, sheep/goat, other
  - Forest: roundwood
  - Bioenergy: switchgrass, miscanthus, willow, eucalyptus, corn ethanol, sugarcane ethanol, biodiesel (from soybeans and other oil crops)

- We account for both food and non-food demand, including animal feed.

- Demand is modeled at the 32 region level.

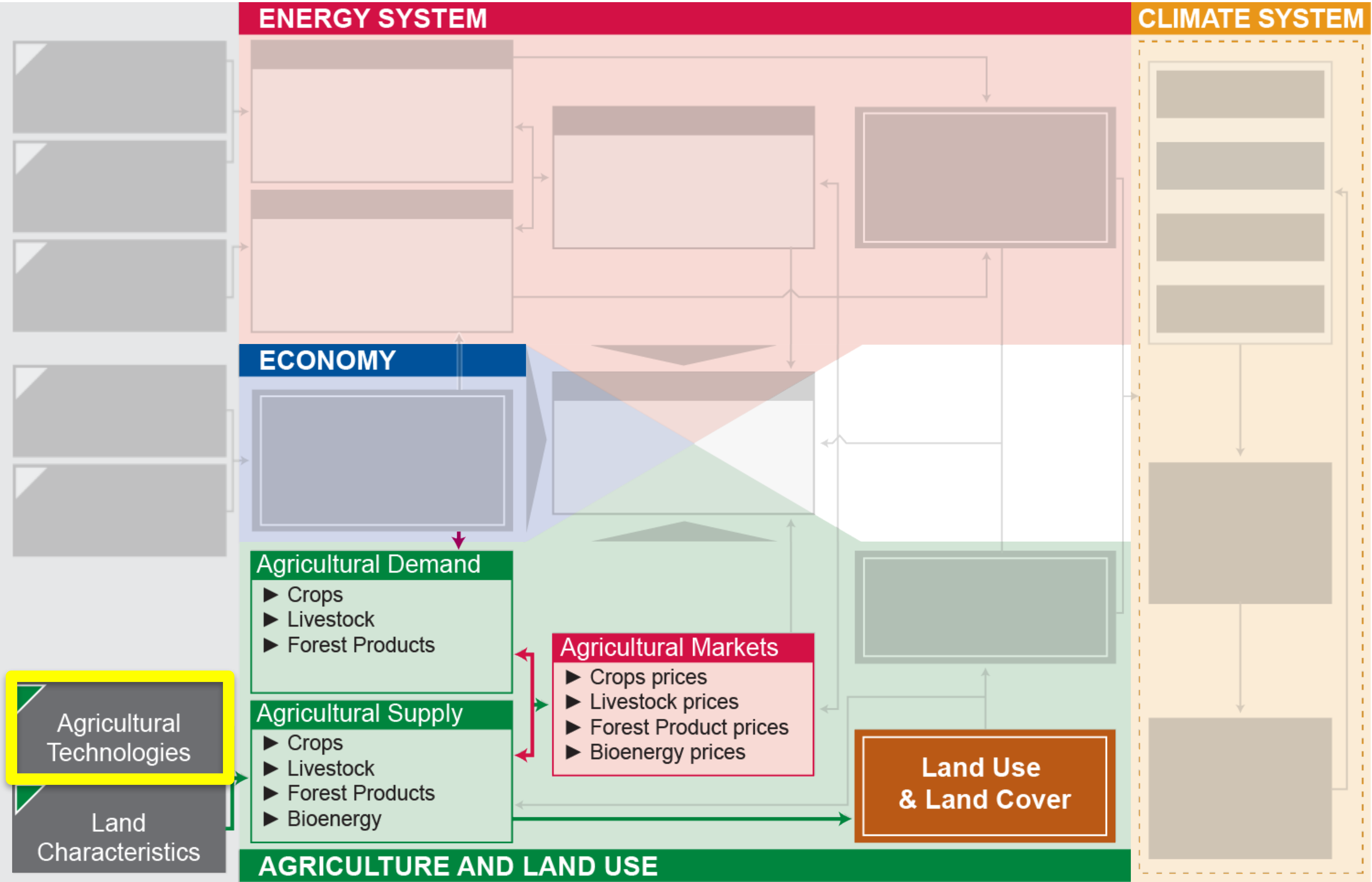
The Agricultural System: Demand

- Non-food, non-feed demand:
  - Base year demand for non-food, non-feed uses FAO statistics
  - Future demand:
    - Per capita demand for crops, animals, and forestry products is currently fixed.
    - Thus, demand grows proportional to population, regardless of income or price.
- Feed demand:
  - Base year demand for feed combines FAO statistics with data from the IMAGE model (PBL)
  - Future demand:
    - Depends on the growth in animal consumption, as well as the change in relative prices of feed options
    - Animal can either be grass-fed or grain-fed. The exact proportion of grass- vs. grain-fed depends on the price of pasture land as compared to the price of crops
    - Grain-fed animals can shift their diet as the relative prices of various crops change. However, the elasticity is relatively low to prevent dramatic shifts that may comprise an unsustainable diet.

The Agricultural System: Demand

- Food demand:
  - Base year demand for food uses FAO statistics
  - Future demand in the baseline is calibrated to match FAO projections of crop and meat demand through 2050. After 2050, we assume that per capita demand is constant.
  - Meat demand in GCAM is price responsive. As the price of meat increases, meat demand will decline.
    - The current price elasticity is very low (~0.25). This is consistent with USDA data for the USA and Australia. Developing countries typically have more elastic demand, but our default assumption is very conservative.
  - Crop demand is not price responsive.

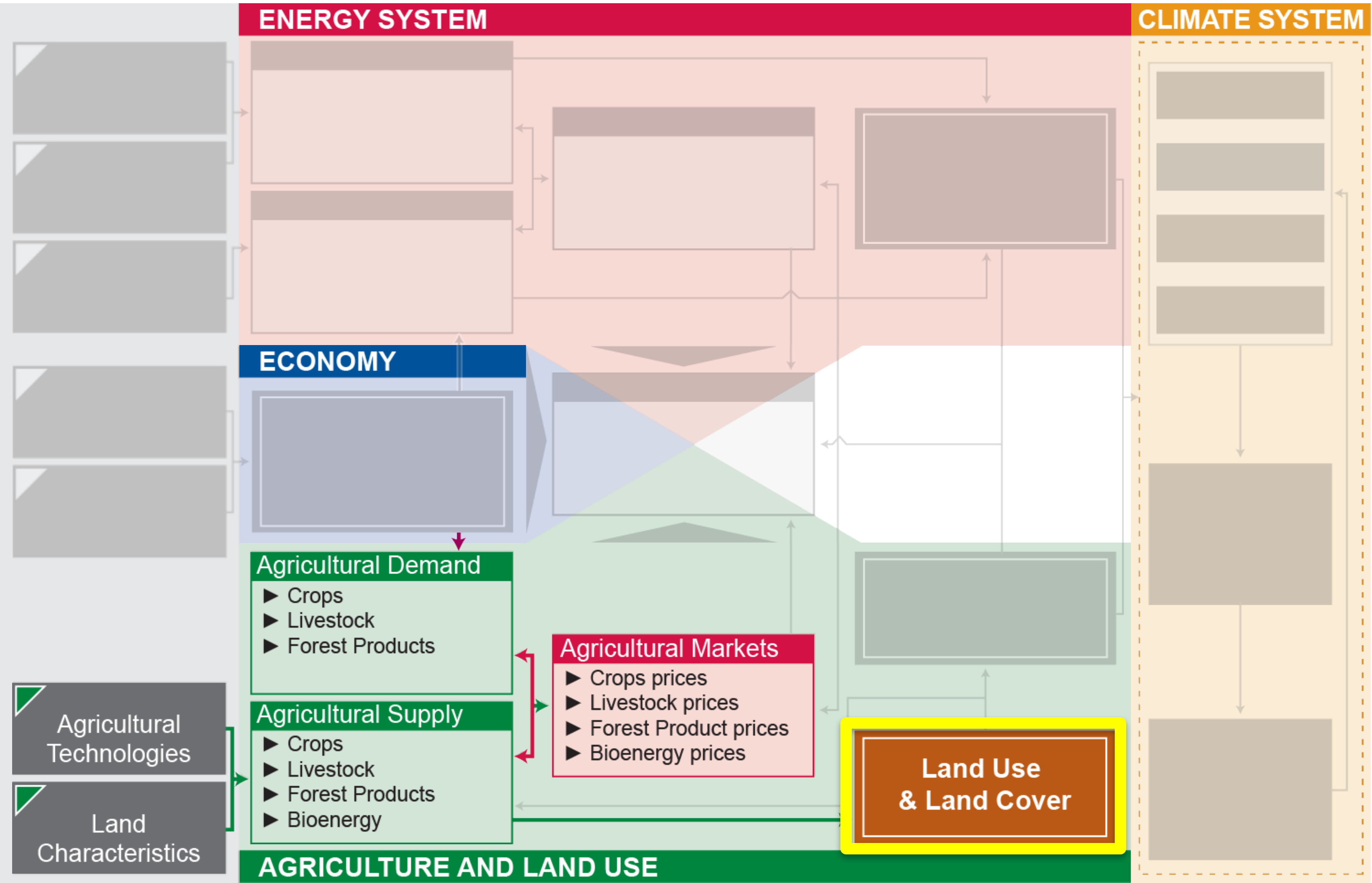
The Global Change Assessment Model



The Agricultural System: Technologies

- For each crop and region, we have a single production technology.
  - The yield for this technology is calculated from GTAP/FAO statistics, by dividing total production in a region by land area.
  - GCAM results are production per year, not per harvest. Thus, we use total physical crop land area to calculate yield and not harvested area. If a region actually harvests more than once a year, their "economic" yield (used by GCAM) will be larger than the actual physical yield.
- We exogenously specify technical change for agricultural technologies.
  - We use FAO projections through 2050.
  - After 2050, we assume that yields will improve by 0.25% per year for all crops and regions.

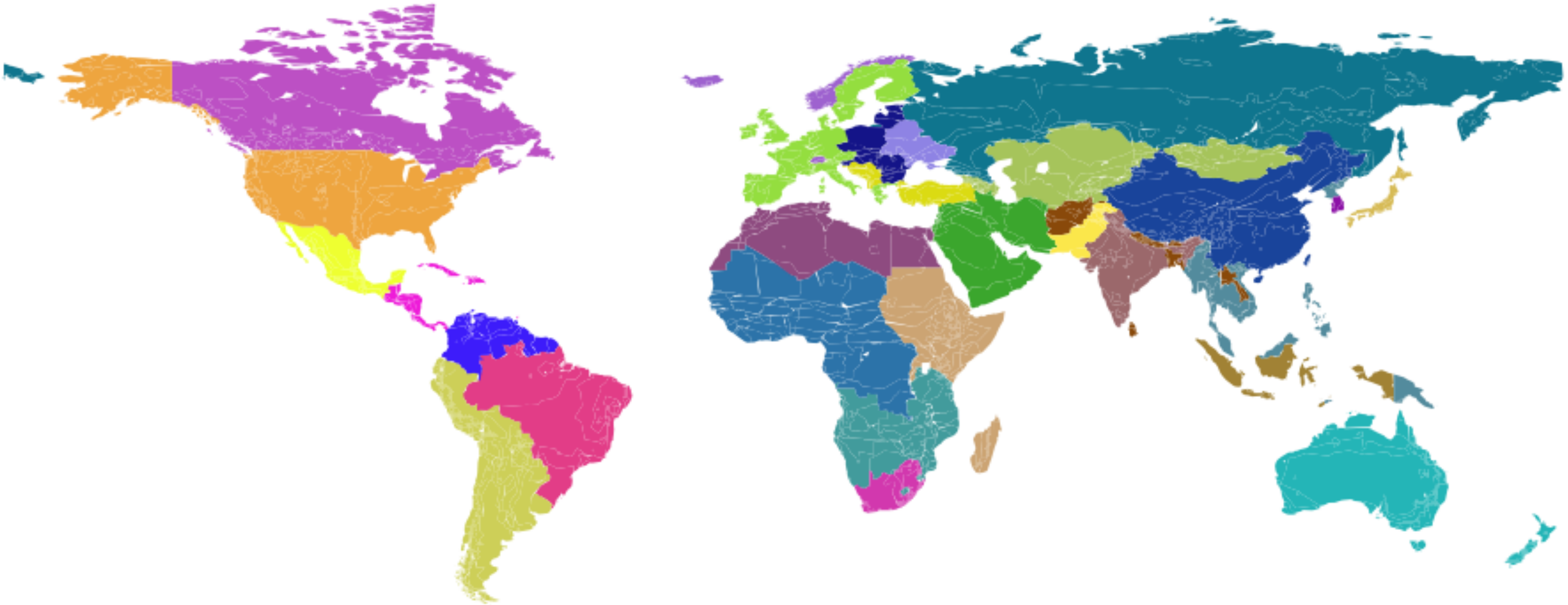
The Global Change Assessment Model



The Agricultural System: Basic Assumptions

- The world is divided into **283** regions

The Agricultural System: Regions



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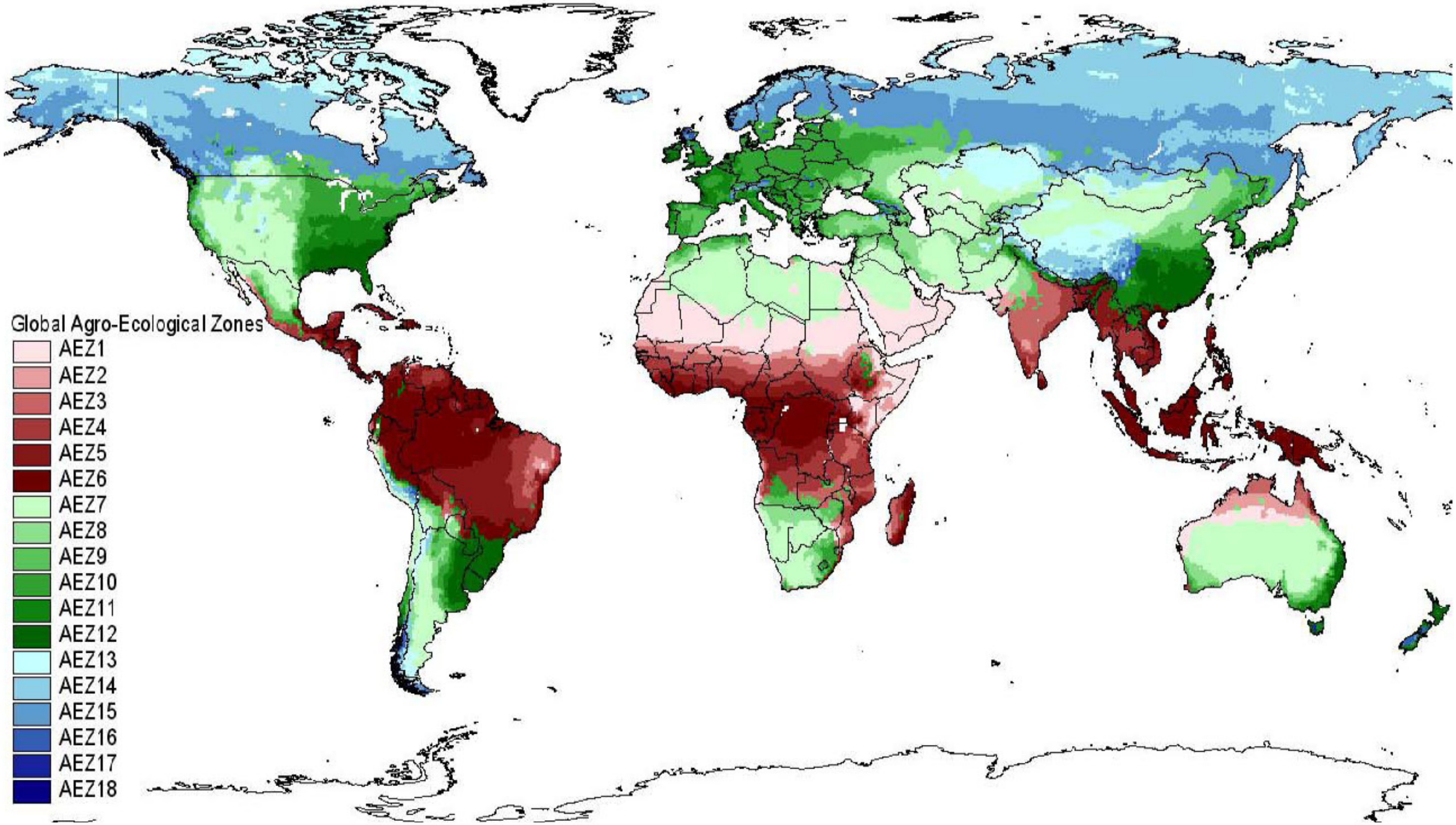
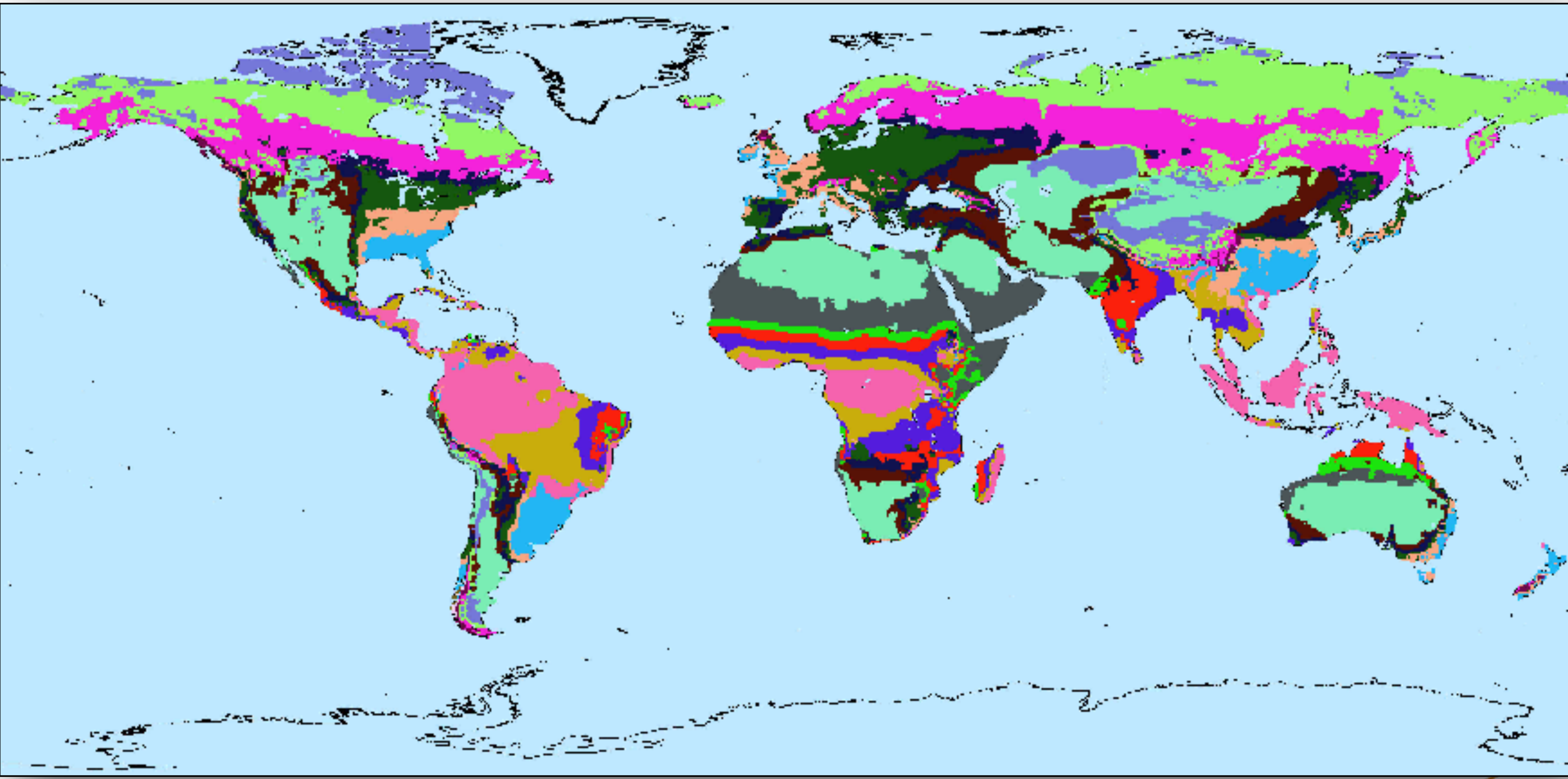
The Agricultural System: Regions



Monfreda et al. (2009)

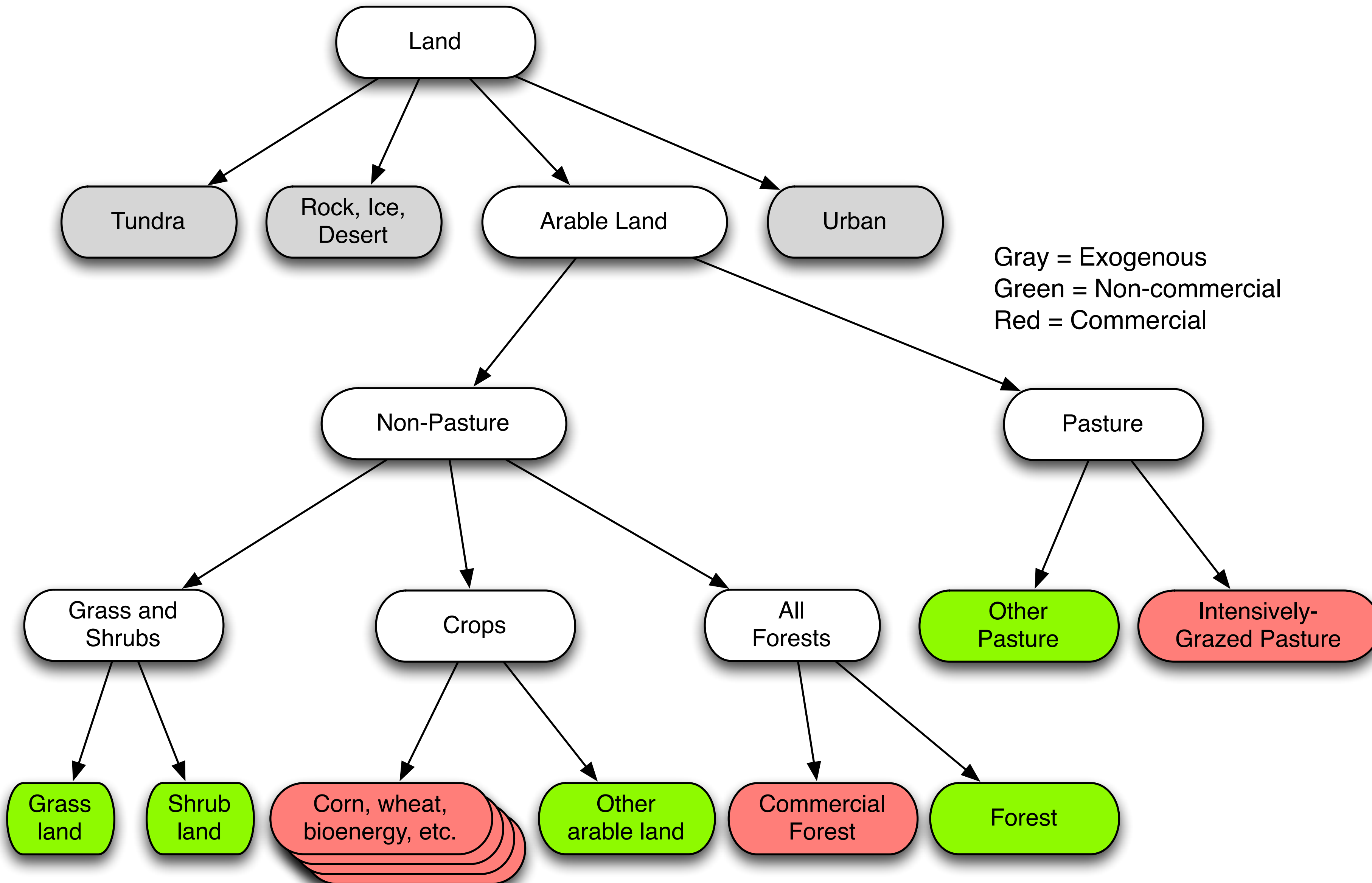


283 Different AgLU Supply Regions

The Agricultural System: Basic Assumptions

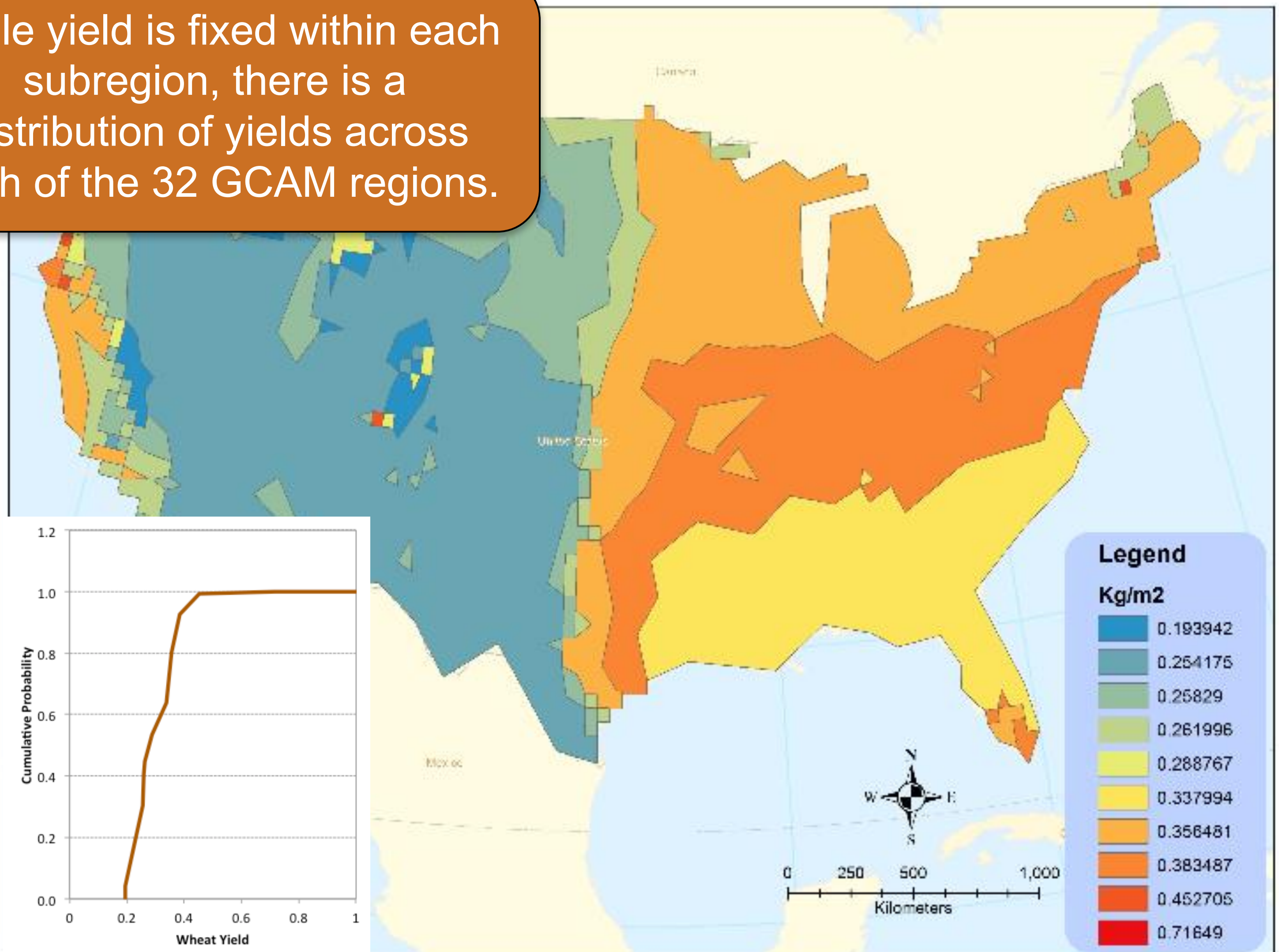
- The world is divided into **283** regions
- Farmers allocate land across a variety of uses in order to maximize profit
- There is a distribution of profits for each land type across each of the 283 regions
- The actual share of land allocated to a particular use is the probability in which that land type has the highest profit
- The variation in profit rates is due to variation in the cost of production
  - As the area devoted to a particular land use expands, cost increases
  - Yield is fixed within each region for each crop management practice

The Agricultural System: Nesting



The Agricultural System: USA Wheat Yield

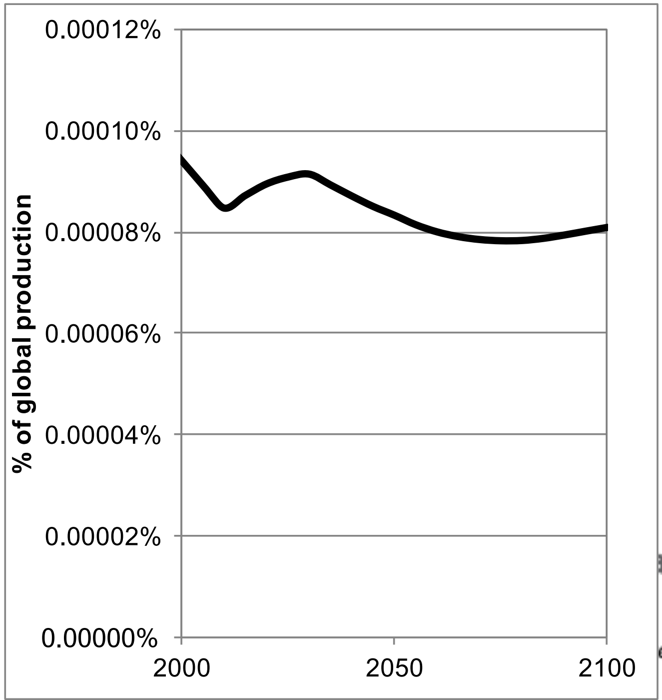
While yield is fixed within each subregion, there is a distribution of yields across each of the 32 GCAM regions.



The Agricultural System: Calibration

- Currently, we calibrate to an average of 2008-2010 data. This is to avoid using an anomalous weather year as a benchmark.
- During the AgLU calibration process, the model computes the average profit rate required to reproduce the base year land allocations. We assume that the difference between this profit and the observed profit (yield * (p – c)) is a cost to production that also applies in the future.
- Thus, if you have a region with a high crop yield, but low land allocation in the base year (e.g., Wheat in Alaska), the model assumes that there are some additional costs that must be considered when expanding its land area. As a result, that crop will continue to have a low share in the future in the absence of a technology or policy change.

Wheat production in USA AEZ16

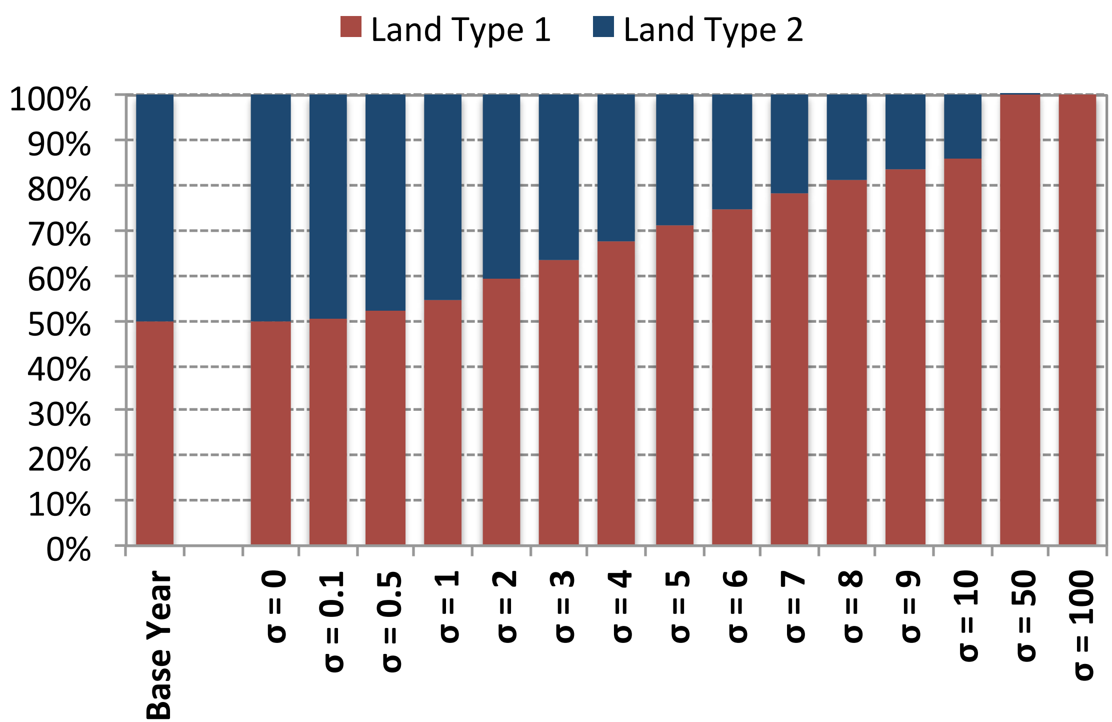


The Agricultural System: Land Competition

$$s_i = \frac{\left(\alpha_i \pi_i\right)^{\sigma}}{\sum_j \left(\alpha_j \pi_j\right)^{\sigma}}$$

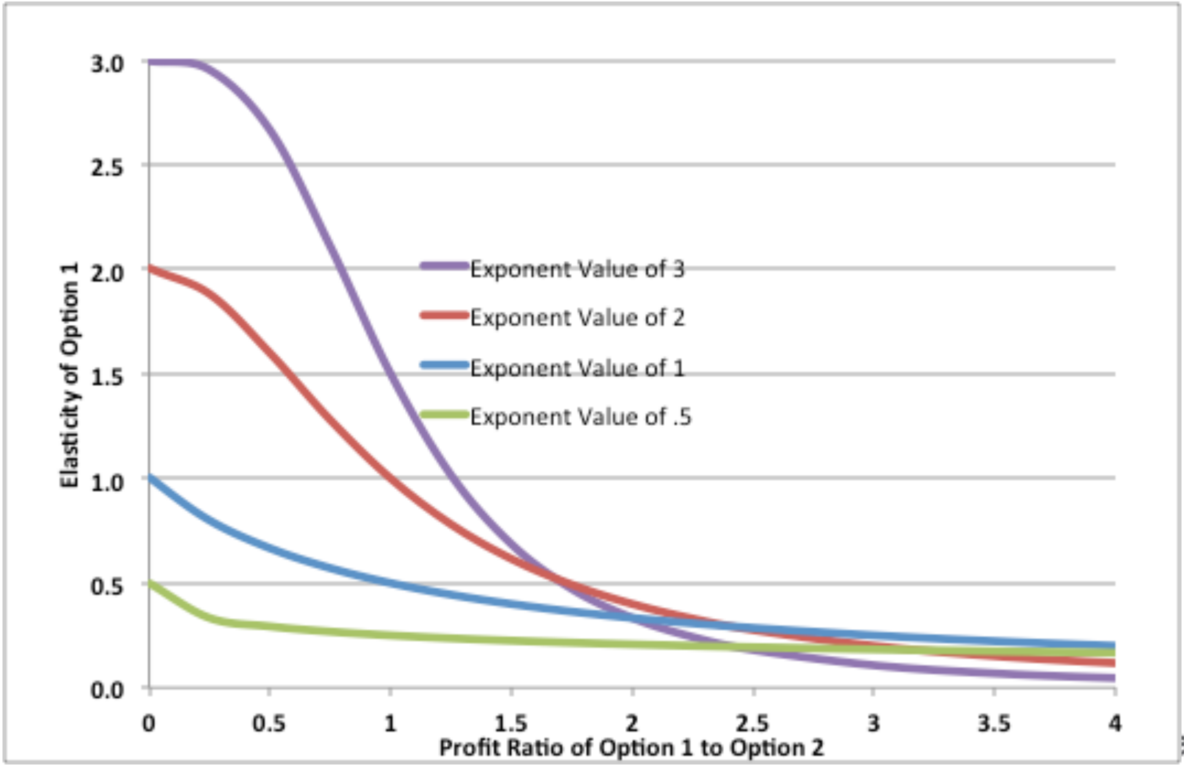
Source: Clarke and Edmonds (1993), McFadden (1974)

Change in land shares when land type 1's profit increases by 20%



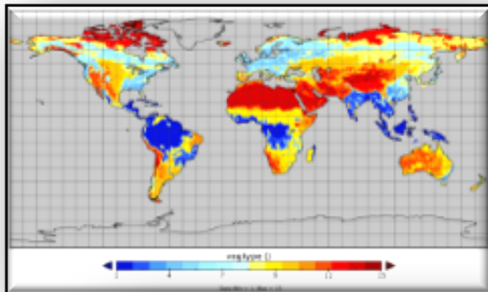
The Agricultural System: Land Competition

- Elasticities can be computed at each point, but
- By design, there is not a constant elasticity relationship with respect to changes in profit

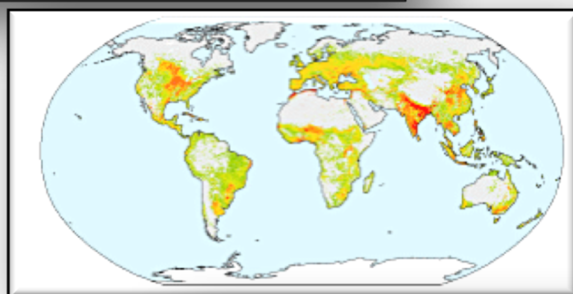


The Agricultural System: Land Cover Data

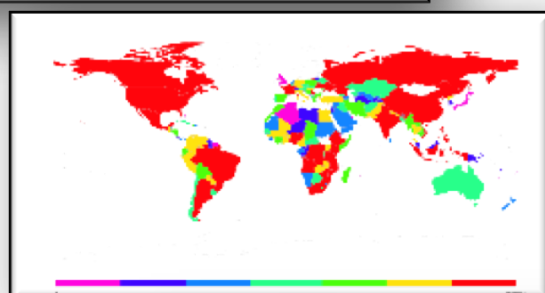
Potential Vegetation



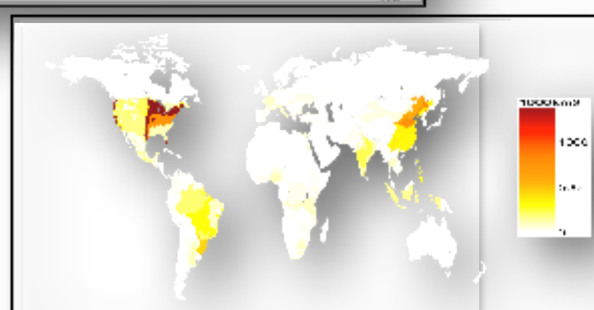
✚ Cropland area



✚ Crop-specific harvested areas

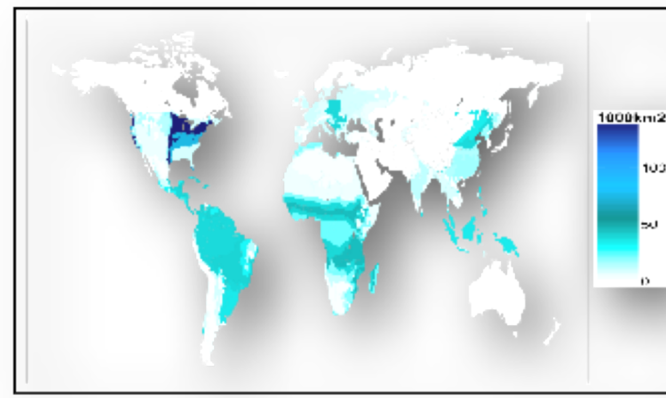


✚ Sub-national Harvested areas



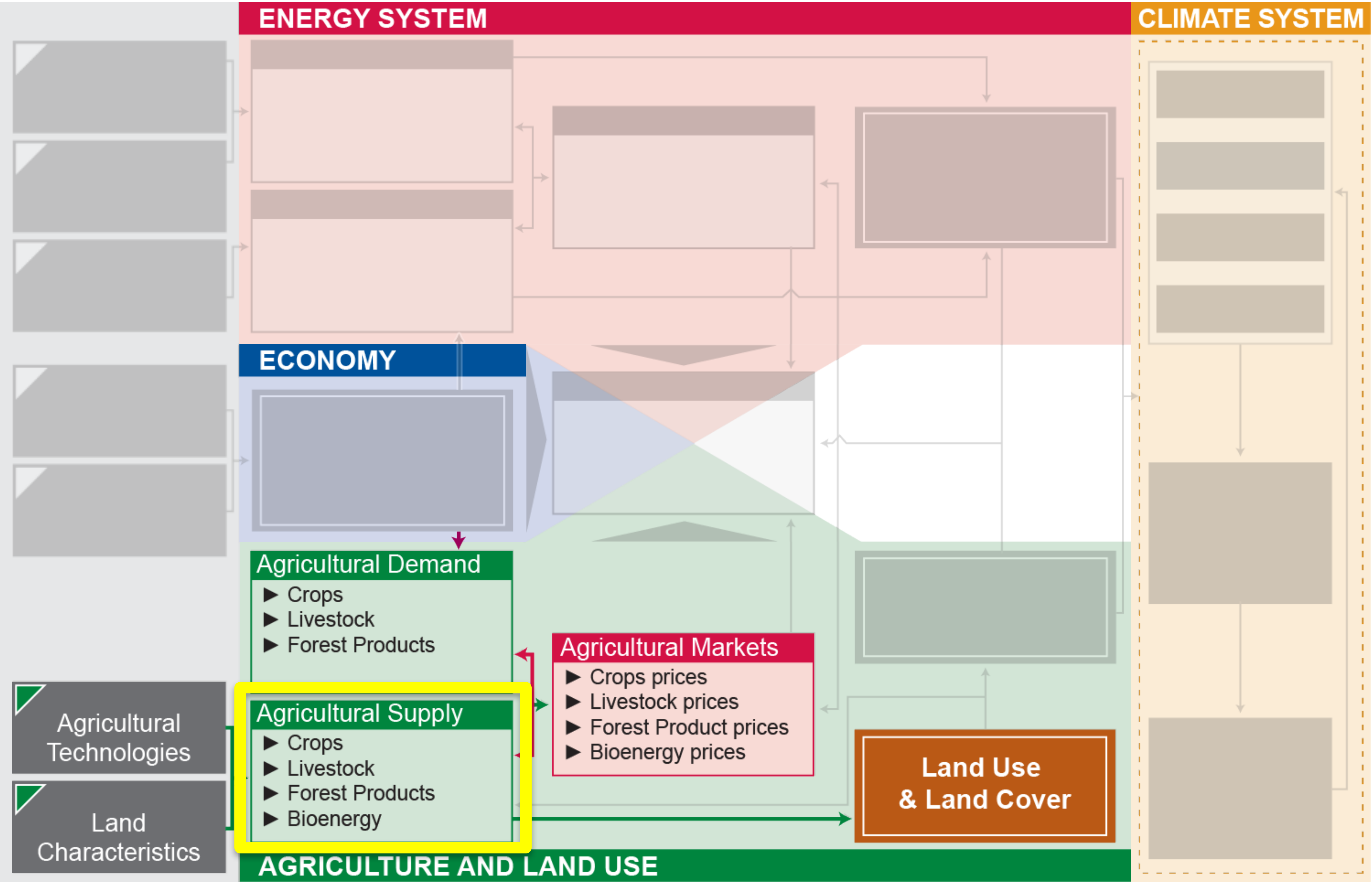
- **GCAM needs land cover by type (e.g., forest, grass, maize, wheat, etc.) for each region/AEZ combination in each historical year.**

Maize Area in 2010



- **We have similar methodologies in other sectors:**
  - **Population: IIASA, US Census**
  - **Energy: IEA, EIA, country studies**
  - **Agriculture: FAO, GTAP, MIRCA**
  - **Emissions: EDGAR, EPA, RCP**

The Global Change Assessment Model



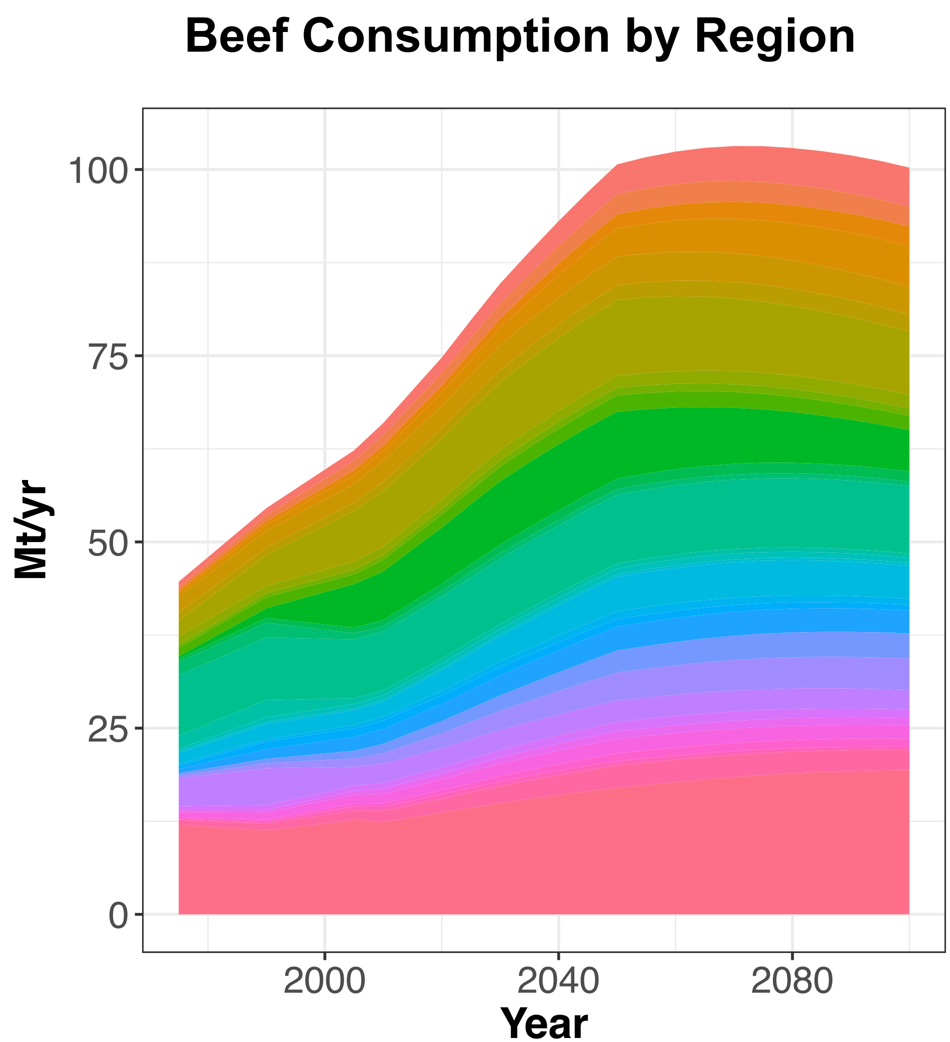
The Agricultural System: Supply

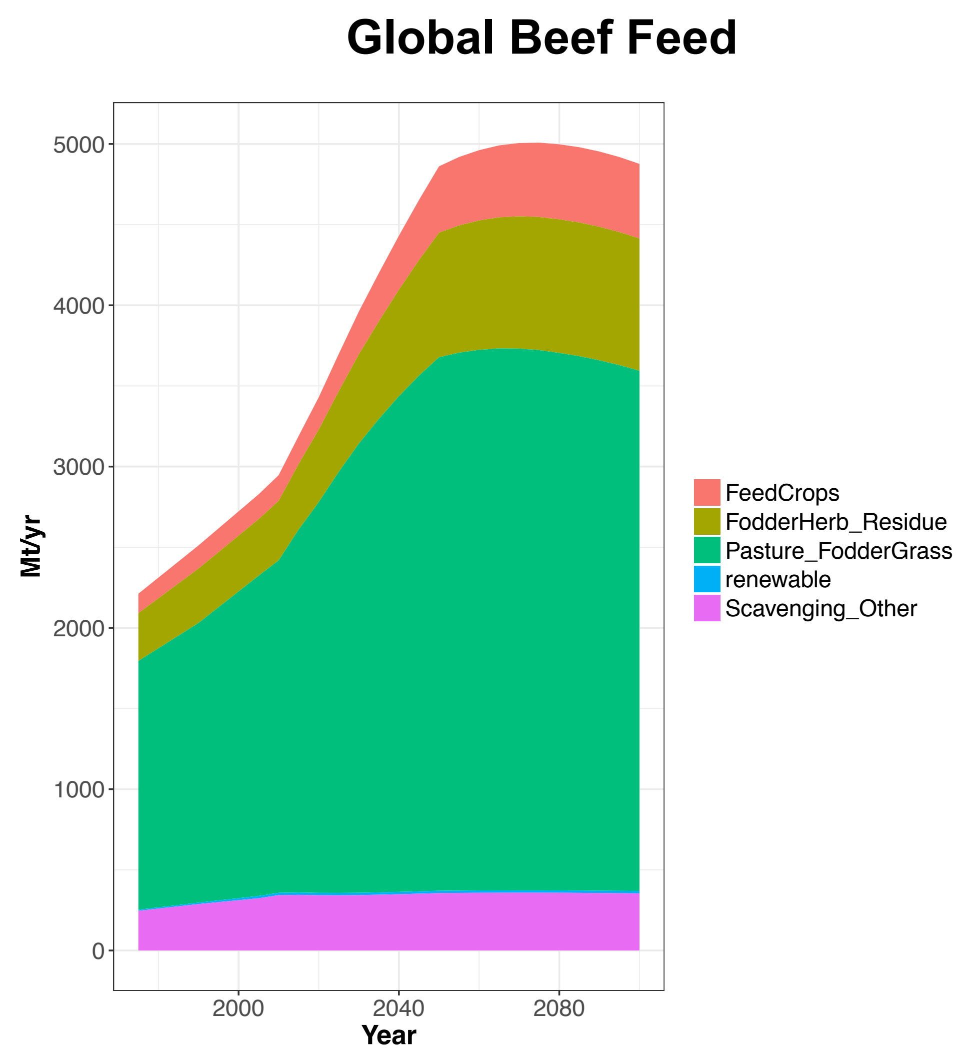
- Yield is exogenously calculated.
  - Base year derived from GTAP/FAO production and land area.
  - Yields increase over time based on exogenously specified technical change.

- Land area is endogenously calculated.
  - Each land types share of area in its region is the probability its profit is the highest in that region.

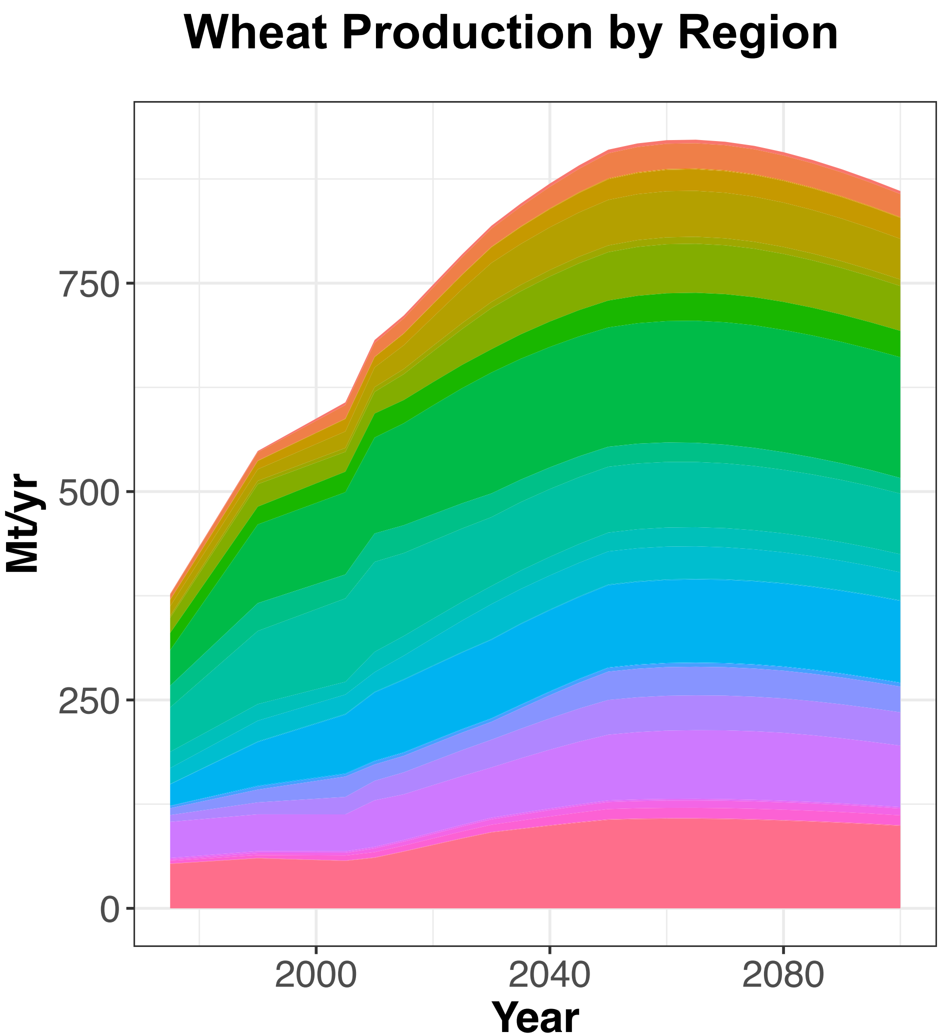
- Supply = land * yield

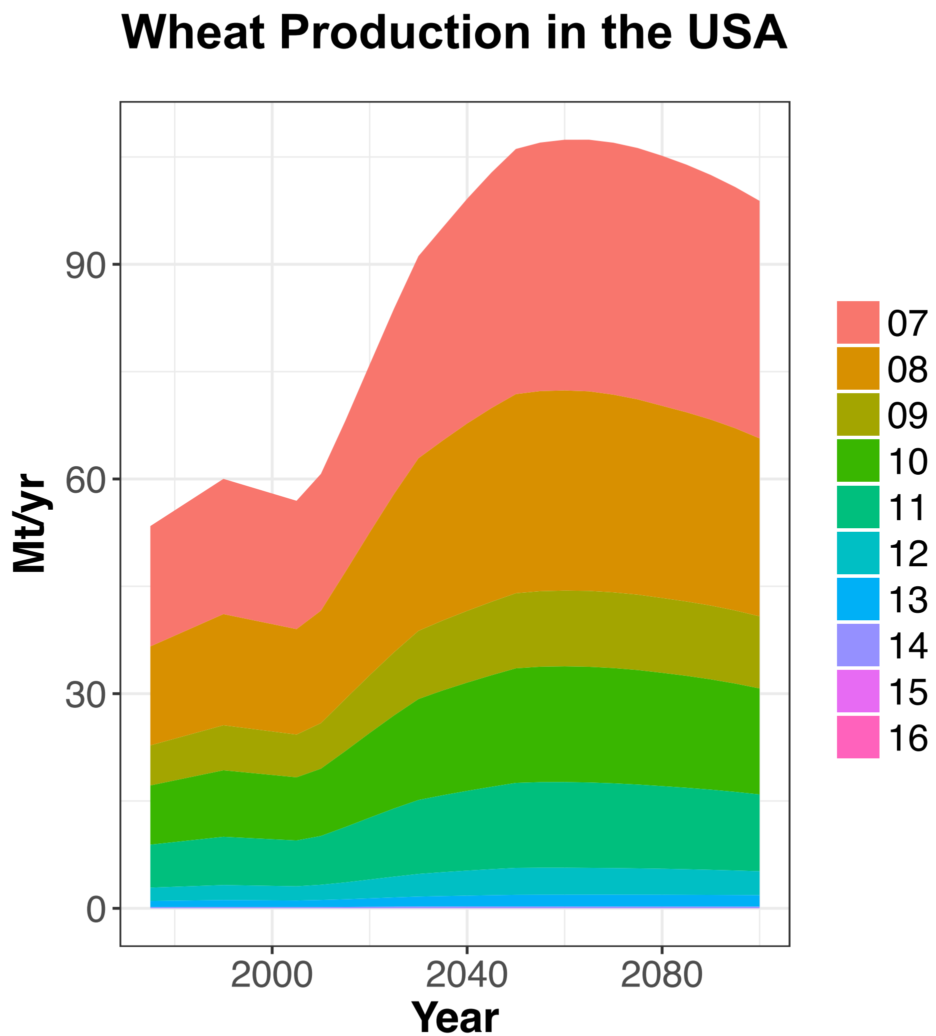
The Agricultural System: Results



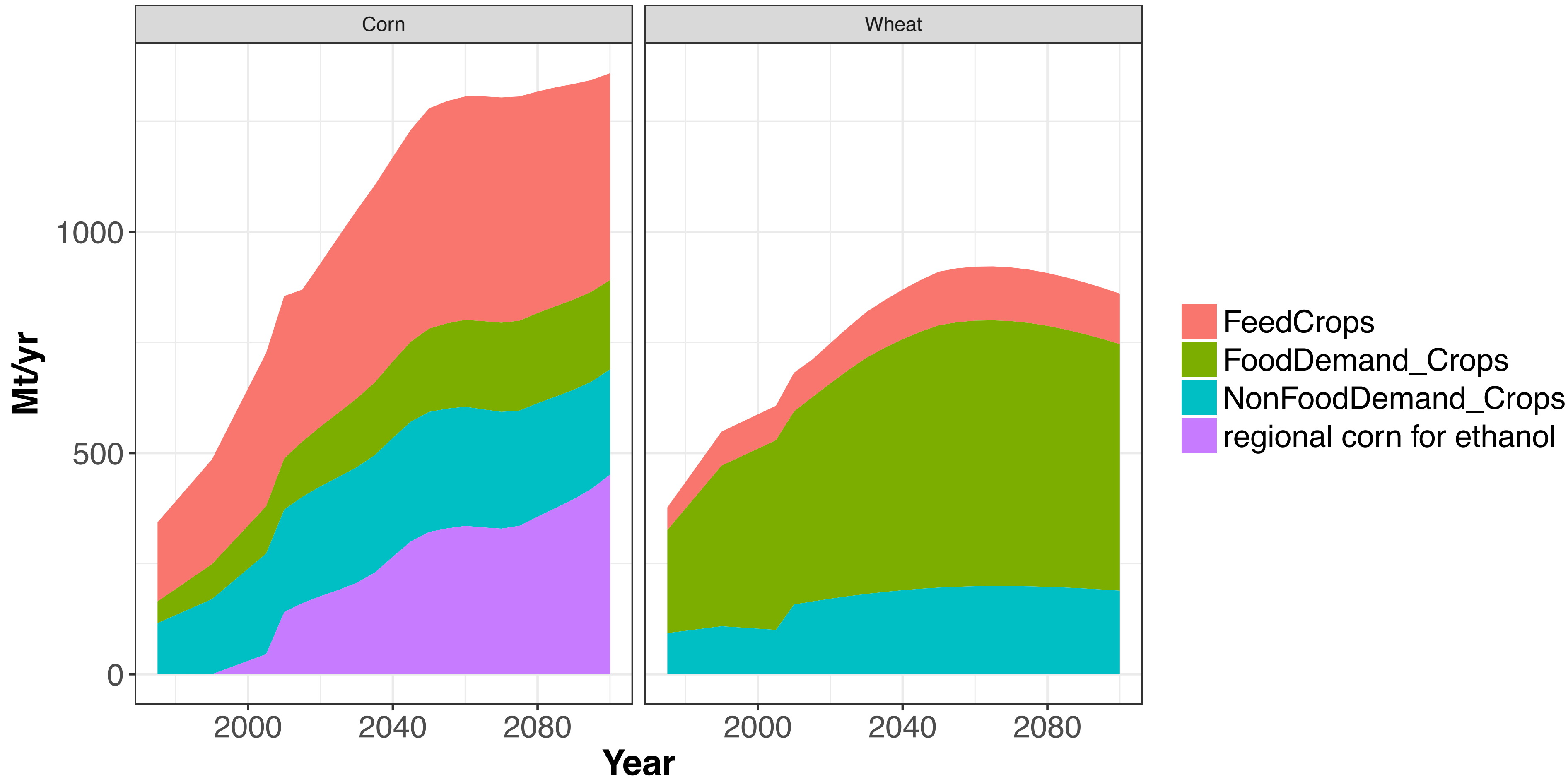


The Agricultural System: Results





The Agricultural System: Results



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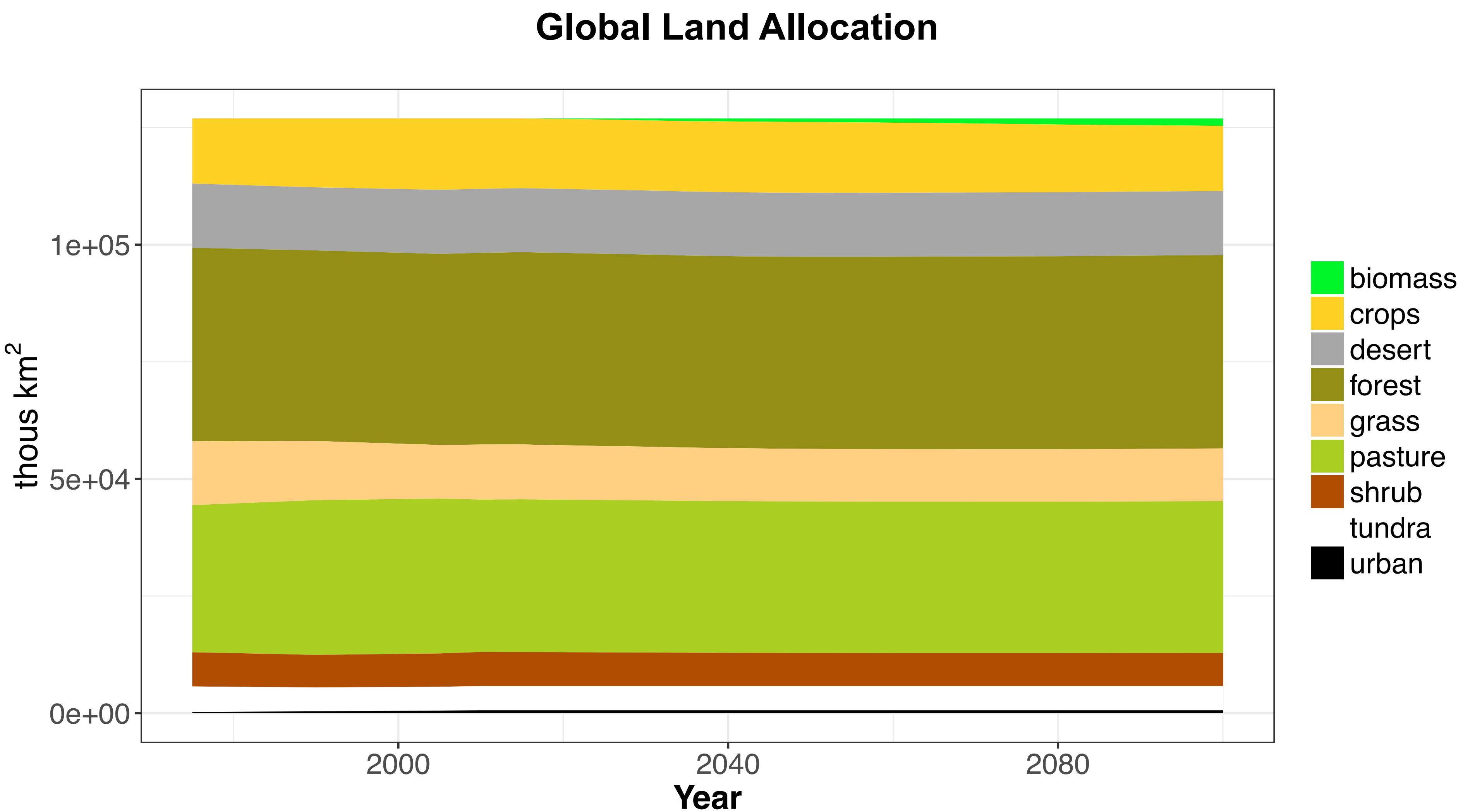
The Agricultural System: Results



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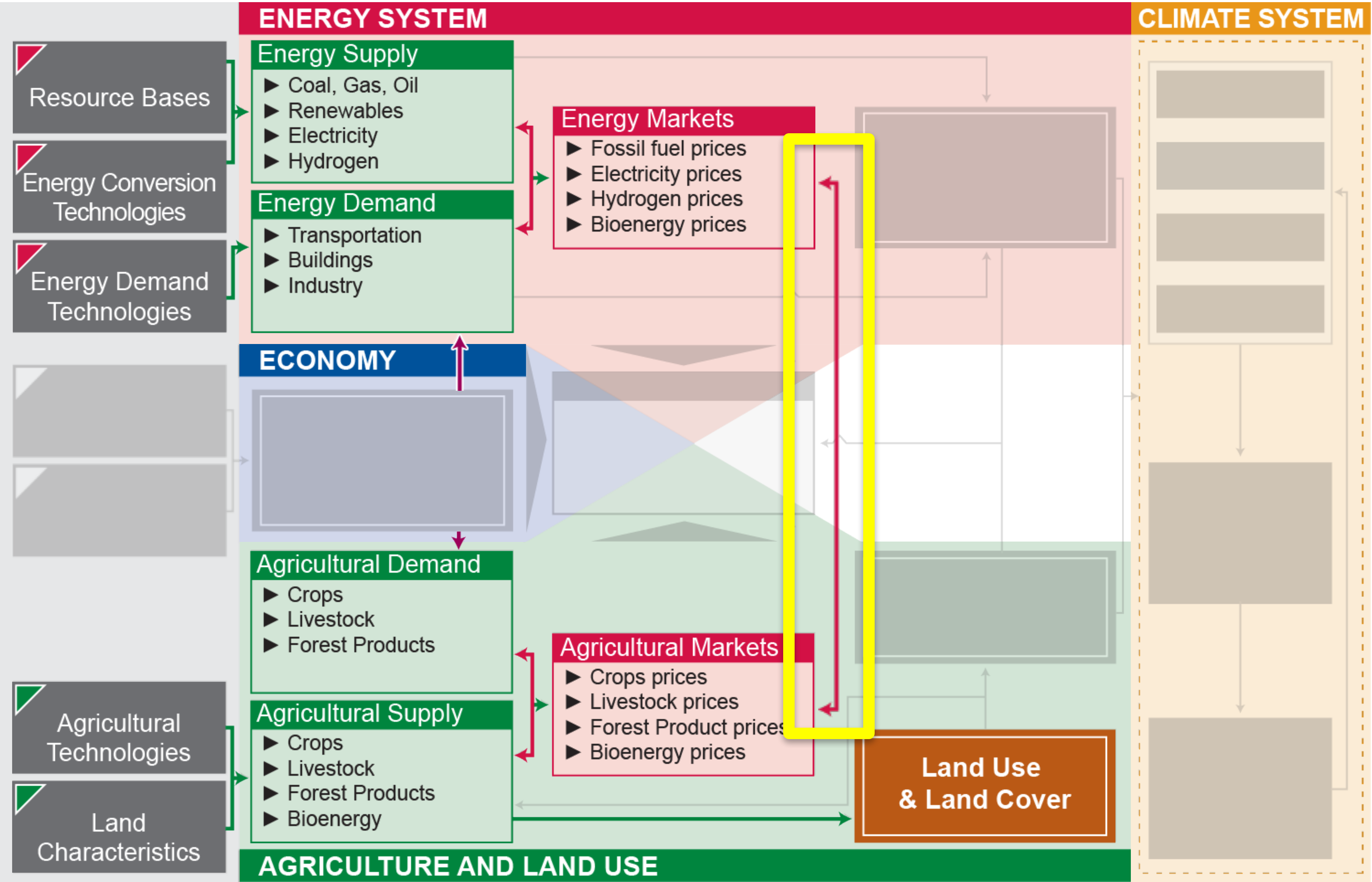


The Agricultural System: Linking the Energy & Agricultural Sectors

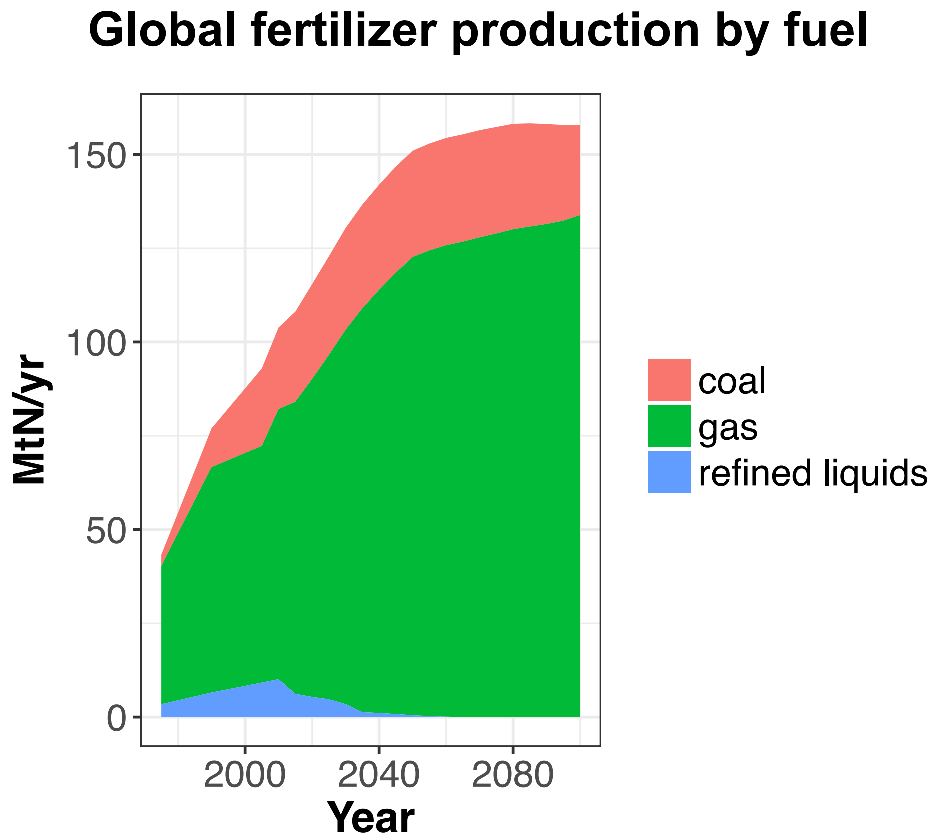
- While we can explain the energy and agricultural systems separately, these two systems cannot be separated in practice. Choices made in one sector affect outcomes in another sector.

- This is true both in the real world and in GCAM. You cannot run the different components of the model separately.

- GCAM currently has three means of linking the energy and agriculture systems:
  - Bioenergy: supplied by the agricultural system, demanded by the energy system
  - Fertilizer: supplied by the energy system, demanded by the agricultural system
  - DDGS: supplied by the energy system, demanded by the agricultural system

Fertilizer Supply

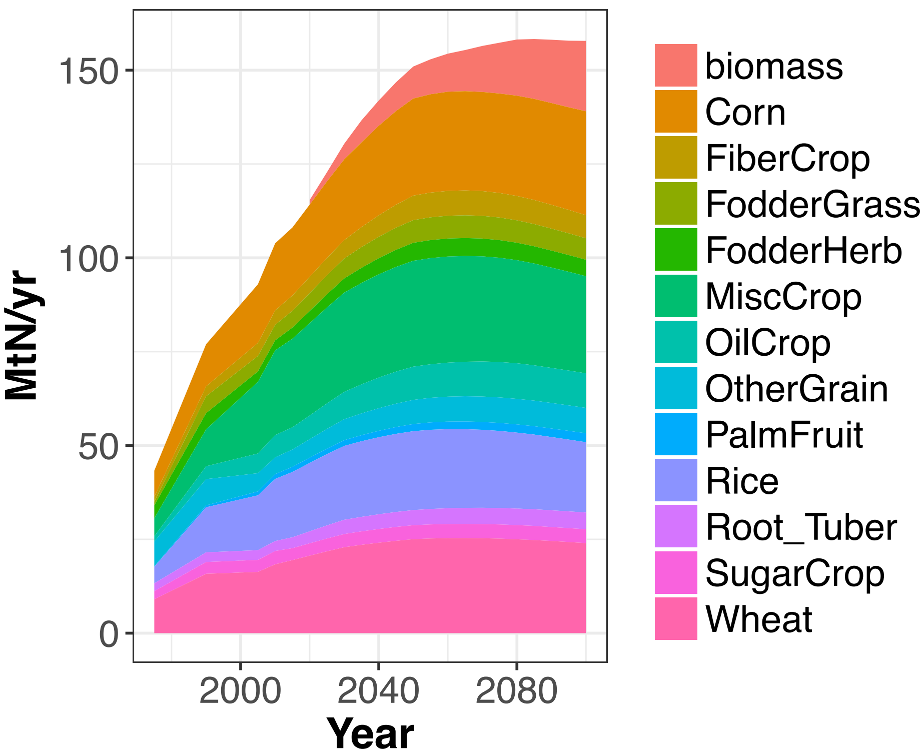
- We are modeling synthetic fertilizer production for use in the agricultural sector. We do not include non-agricultural uses of fertilizer or natural fertilizer.
- Production by technology is from IEA.



Fertilizer Demand

- Consumption by country (and therefore region) are from FAO ResourceSTAT.
- Consumption by region is first downscaled to crops according to a dataset put together by the International Fertilizer Industry Association working in collaboration with the FAO, and then downscaled to AEZ on the basis of crop production.

Global fertilizer consumption by crop



Modeling Policies

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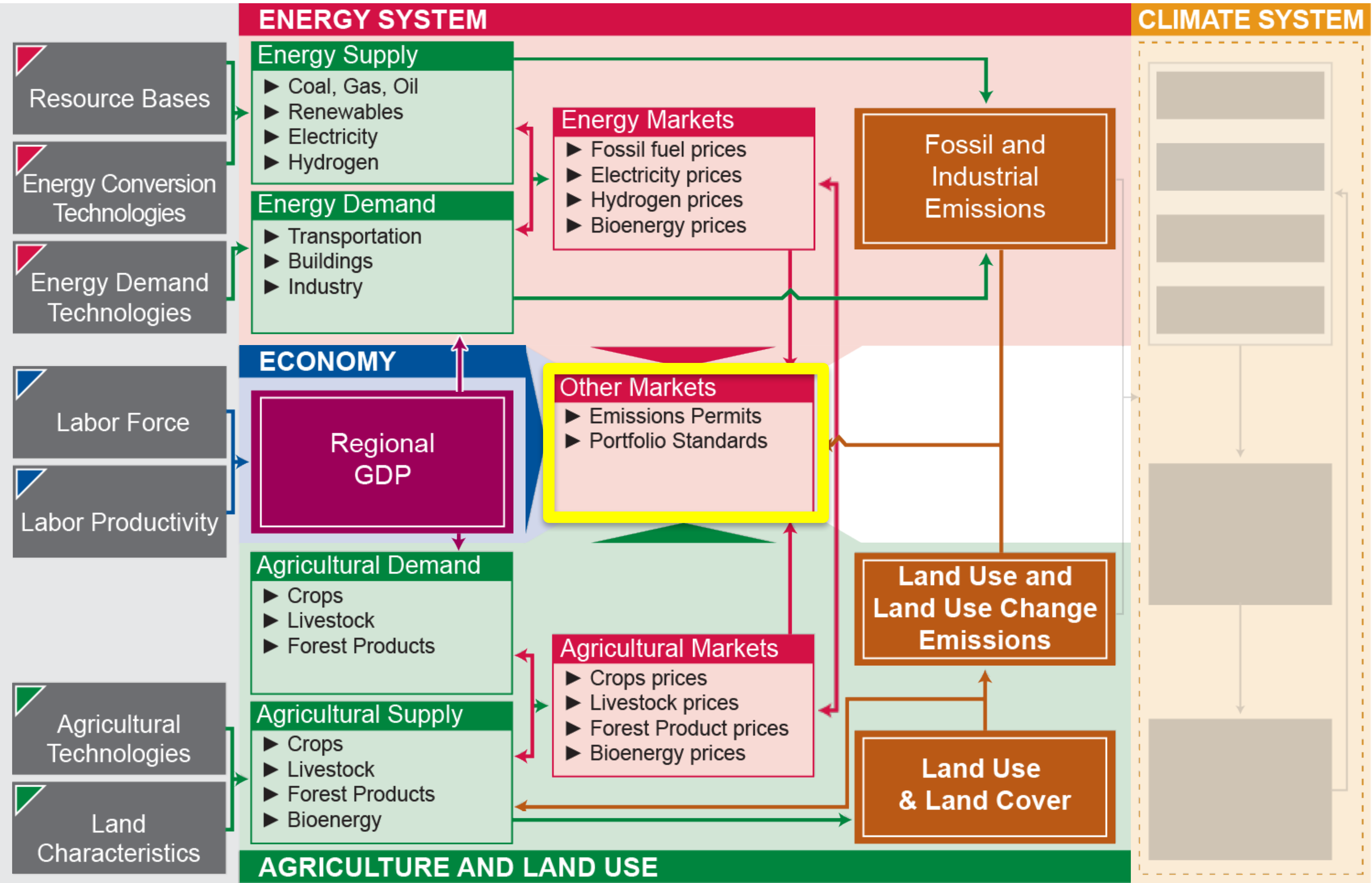


Emissions Policies

- Carbon or GHG prices:
  - Users can specify the price of carbon or GHGs directly
  - Emissions will vary depending on other scenario drivers
- Emissions constraints:
  - Users can specify the total amount of emissions (CO_2 or GHG)
  - Model will calculate the price of carbon needed to reach the constraint
- Climate constraints:
  - Users can specify a climate variable (e.g., concentration or radiative forcing) target for a particular year
  - Users determine whether that target can be exceeded prior to the target year
  - Model will adjust carbon prices in order to find the least cost path to reaching the target
  - (This type of policy increases model run time significantly)

Energy Policies

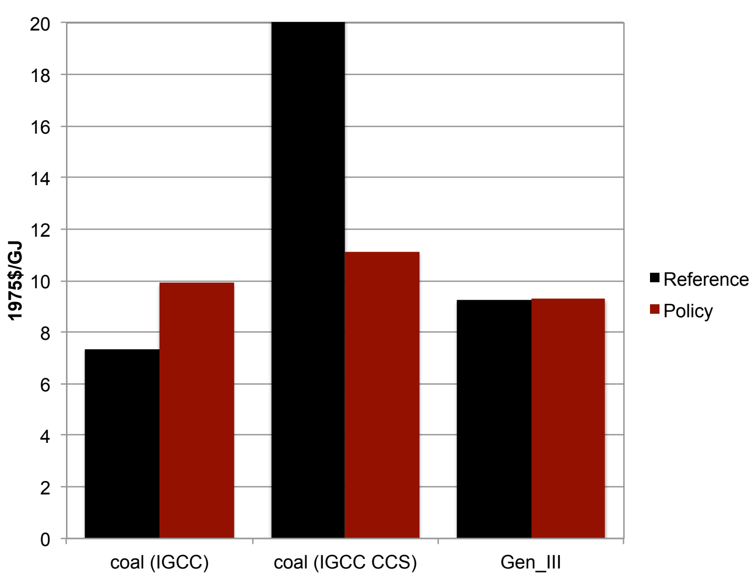
- We can impose constraints (lower & upper bounds) on energy consumption.
  - The model will solve for the tax (upper bound) or subsidy (lower bound) required to reach the given constraint.
  - Within an individual sector, these constraints can be share constraints (e.g., fraction of electricity that comes from solar power).
    - This allows us to model renewable portfolio standards and biofuels standards.
  - Across sectors, these must be quantity constraints.

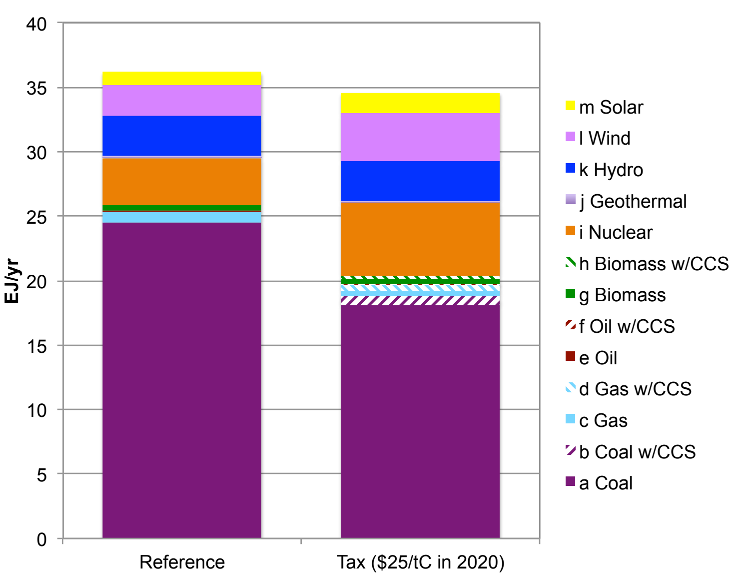
Land-Use Policies

- REDD:
  - In this policy, we set aside some land from economic competition. This land cannot be converted to crops, pasture, or any other land type.
  - Currently, this is the core assumption in GCAM when running a carbon policy.
    - We have protected 90% of non-commercial ecosystems.
- Valuing carbon in land:
  - In this policy, we assume that land use change emissions are taxed at the same rate as fossil fuel and industrial emissions.
  - Land owners receive a subsidy proportional to their carbon content.
- Bioenergy constraints (upper or lower):
  - We can also constrain biomass to a particular level. This is implemented in GCAM as a tax or subsidy on bioenergy consumption. The tax/subsidy is adjusted until the constraint is met.
- Bioenergy taxes:
  - We can impose a tax on bioenergy that is linked to the carbon price.

Other Markets: The Effect of Emissions Policy on the Energy System

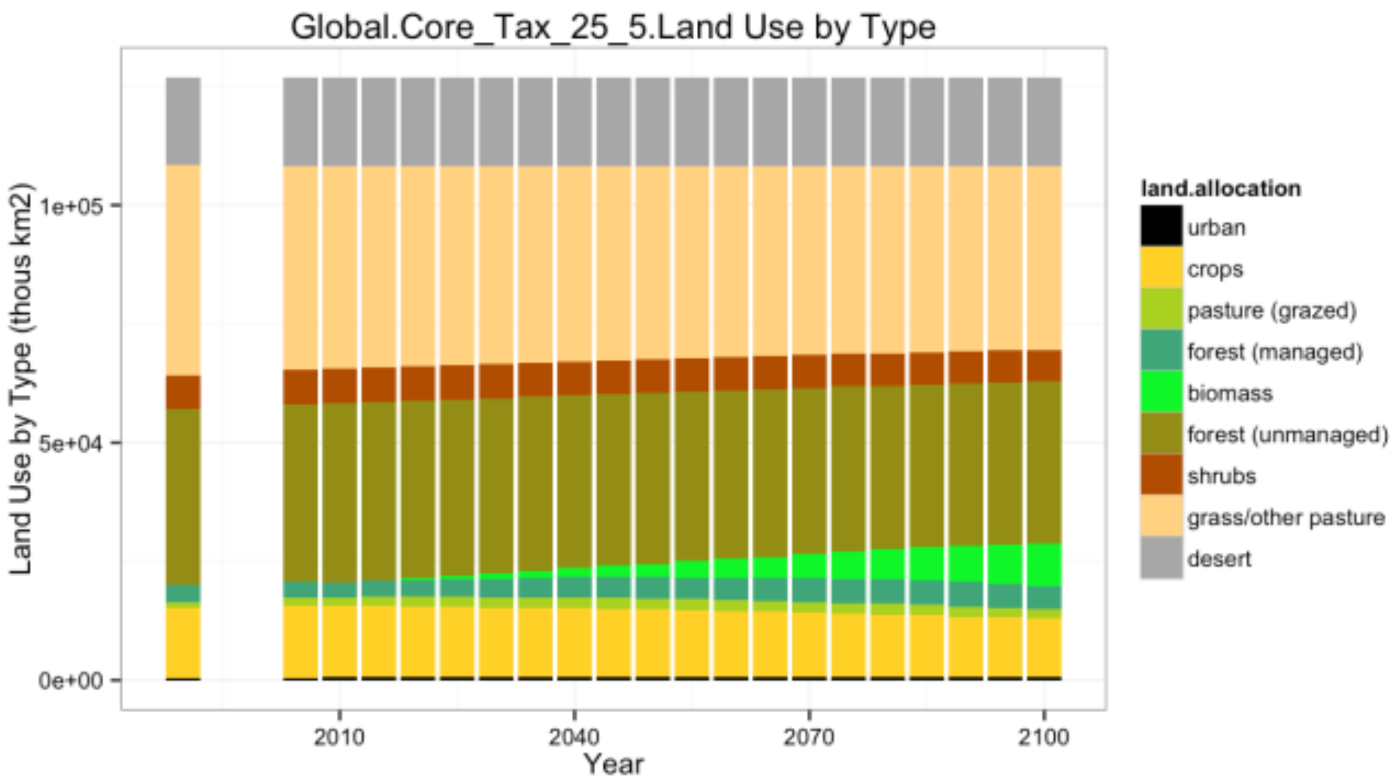
- Imposing an emissions policy affects the cost of energy production for carbon-intensive fuels. This induces a shift toward lower emitting technologies.





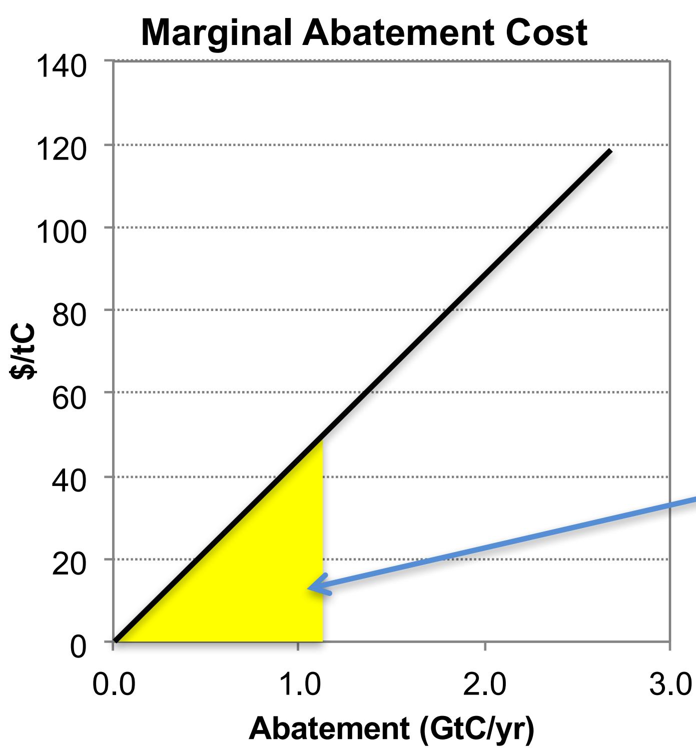
Other Markets: The Effect of Emissions Policy on the Agriculture & Land-Use System

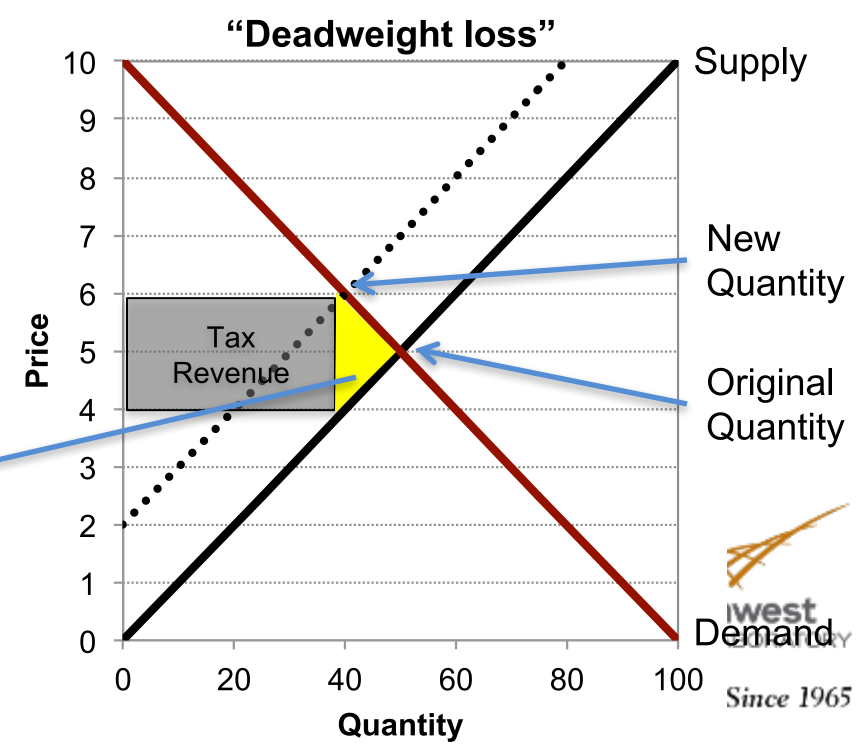
- Under the default assumption in GCAM, 90% of non-commercial ecosystems are protected in GCAM. This means that they cannot be used for crop or bioenergy production.



Other Markets: Climate Policy Cost

- GCAM can compute the cost of a climate policy endogenously.
- The cost metric used is the area under the marginal abatement cost (MAC) curve. This area under the MAC curve commonly referred to as “deadweight loss” (i.e., the change in producer and consumer surplus.)
- Currently, we are not modeling this cost as affecting GDP in GCAM.





Frequently Asked Questions

- Question:
  - Does the GCAM reference scenario include other climate and energy policies?
- Answer:
  - To the extent that these exist in the base year, they will be calibrated into the GCAM reference scenario.
  - However, we do not explicitly include any proposed climate or energy policies in the reference scenario.

Trade

2017

Marshall Wise

Pacific Northwest NATIONAL LABORATORY

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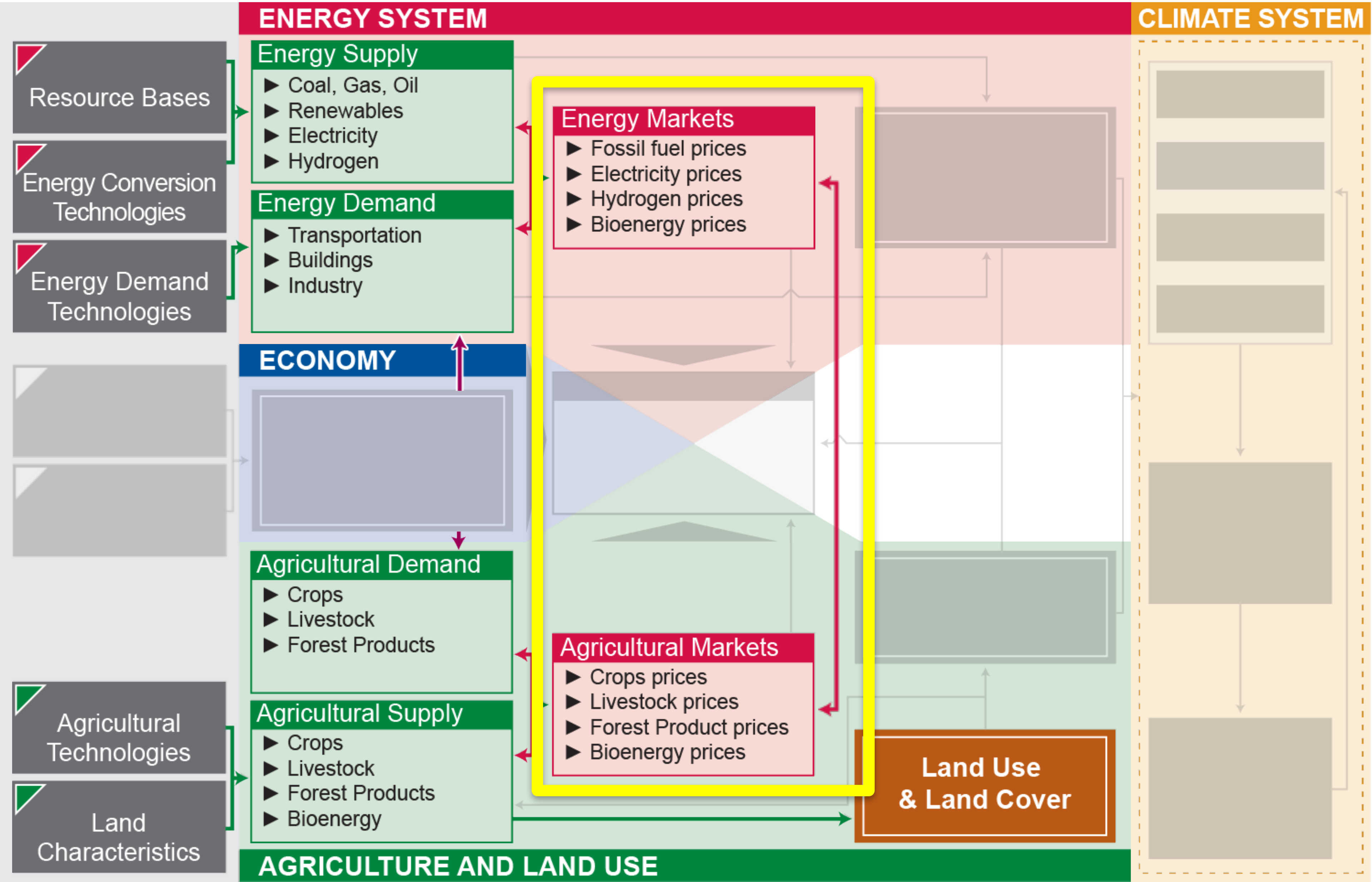
The Global Change Assessment Model



Current Approach to Modeling Trade

- In general, we model Heckscher-Ohlin trade. (e.g., global markets)
- This means that for many products, we assume that trade occurs freely into and out of global markets. These products include coal, gas, oil, bioenergy, food, and fiber.
  - A region's net trade position is dynamic depending on economics, technical change, demand growth, resources, and other changing factors.
  - In simplest terms – given a global market price – each region computes demand and production, and net imports are the difference.
  - No modeled preferences for products from specific regions.
- For other products, we have fixed or static interregional trade. These products include solar, wind, geothermal, meat, and dairy.
  - For some products, like solar resources, trade is physically impractical if not infeasible.
  - For other products such as beef, our basic economic modeling approach makes dynamic trade complicated, and the fixed trade assumption based on historical data is a conservative approach.

New Approaches in Development for Regional Markets/Trade in GCAM (Not in Release Model)

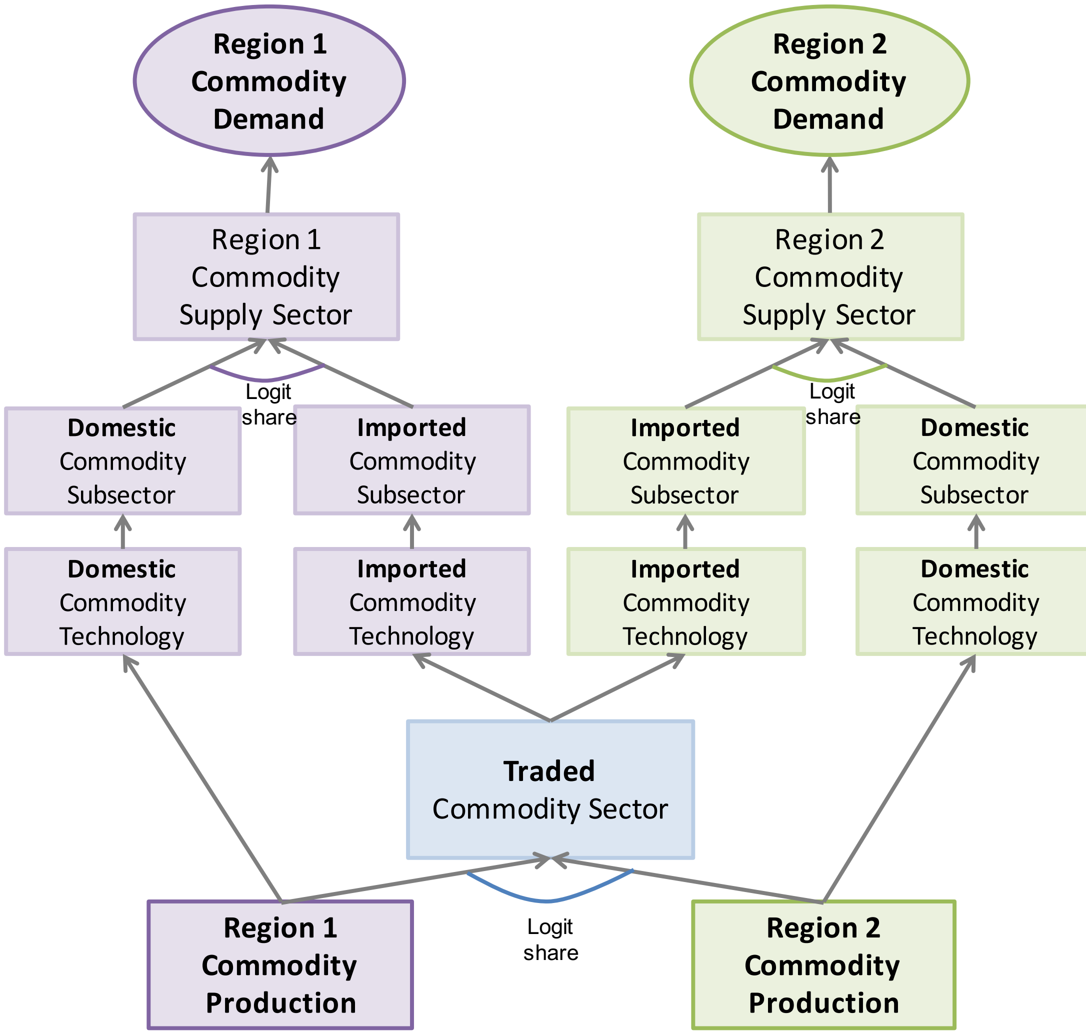
- We have implemented and are testing an approach for crops markets for dynamically combining regional markets in a global trade markets.

- Approach is based on modeling dynamic regional gross trade to and from a global (or at least multi-regional) market for each traded crop.
  - Regional gross imports and exports calibrated to Base Year data.
  - Regional preferences for domestic crops are calibrated but actual consumption is dynamic based on future economics
  - Unlike some Armington implementations where products are regionally-differentiated, there can be changes of regional net product import/export positions in response to economics.
  - Can consider impacts of inter-regional transportation costs/trade limits.

- Crop prices will be be different by region with regionally-specific conditions affecting their paths.
  - Important for impacts of ag changes on regional food demand.
  - Better representation of regional crop production technology/costs.

New Approaches in Development for Regional Markets/Trade in GCAM (Not in Release Model)

Snapshot of 2-region trade example



New Approaches in Development for Regional Markets/Trade in GCAM (Not in Release Model)

- Much recent development supported by EPA OTAQ.

- Regional markets and aspects like preference for domestic production will have an impact on many results such as food prices, bioenergy production, and regional land use change (and therefore global LUC).

- Status and plans.
  - More testing and vetting required.
  - It does require adding many more market equations that need to be solved – potentially adding run time or difficulty solving.
  - You may notice some of these features are in place in release model for modeling unconventional oil production.
  - Similar approach could be used for fossil fuel trade.
  - Similar approach can be implemented to allow trade in the "secondary products" in GCAM (e.g., refined liquids, beef) for which we now assume fixed trade amounts.

Emissions

2017

Steve Smith

Emissions: Modeling in GCAM

In an IAM we need to represent future emission trajectories and how those trajectories might vary under different drivers and policies.

CO_2: GCAM is a process model for CO_2 emissions and reductions

- Emissions depend on specific technologies, whose use is explicitly determined by the model, and can be modified through carbon prices.
- The GCAM, in effect, produces a Marginal Abatement Curve for CO_2

Non-CO_2 GHGs: are modeled as

$$Emissions = Em\_factor \bullet Activity\_Level \bullet \left(1 - MAC(Carbon\text{-}Price)\right)$$

Air pollutant emissions: (SO_2, NO_x, etc.) are modeled as:

$$Emissions = Em\_factor \bullet Activity\_Level \bullet \left(1 - Em\_Controls(GDP_{per-capita})\right)$$

Non-CO_2 emissions (both GHGs & air pollutants) originate from many sources and can be controlled using multiple abatement technologies

- This is too much detail for us to include explicitly at the process level
- We calibrate to base year inventories and use parameterized functions for future emissions controls and Marginal Abatement Cost (MAC) curves to change emission factors over time.
- Technology shifts still play a role, since emission factors differ between technologies.

Marginal Abatement Cost (MAC) Curves

While for CO_2 GCAM explicitly includes reduction technologies, this is generally not the case for other emissions.

So we include in core GCAM MAC curves for non-CO_2 GHGs.

```xml
<scenario>
   <world>
      <region name="USA">
         <supplysector name="comm cooling" nocreate="1">
            <subsector name="electricity" nocreate="1">
               <stub-technology name="electricity" nocreate="1">
                  <period year="1975">
                     <Non-CO2 name="HFC134a">
                        <input-emissions>0</input-emissions>
                        <output-driver/>
                        <emissions-unit>Gg</emissions-unit>
                        <mac-control name="Refrigeration and Air Conditioning">
                           <mac-reduction tax="0">0.434</mac-reduction>
                           <mac-reduction tax="5">0.437</mac-reduction>
                           <mac-reduction tax="10">0.471</mac-reduction>
                           <mac-reduction tax="15">0.589</mac-reduction>
                           <mac-reduction tax="32">0.589</mac-reduction>
                           <mac-reduction tax="66">0.722</mac-reduction>
                           <mac-reduction tax="129">0.722</mac-reduction>
                           <mac-reduction tax="243">0.768</mac-reduction>
                           <mac-reduction tax="486">0.768</mac-reduction>
                           <mac-reduction tax="1093">0.768</mac-reduction>
                        </mac-control>
                     </Non-CO2>
                     <Non-CO2 name="HFC143a">
                        <input-emissions>0</input-emissions>
```

Note that some MAC curves indicate cost-effective reductions at zero carbon price. These are assumed to be phased in in the reference case scenario in GCAM core (as of Sept 2017 these are phased in over a couple decades).

Emissions: Base Year Emissions

GCAM tracks emissions for a number of greenhouse gases and air pollutants

- CO_2, CH_4, N_2O, CF_4, C_2F_6, SF_6, HFC23, HFC32, HFC43-10mee, HFC125, HFC134a, HFC143a, HFC152a, HFC227ea, HFC236fa, HFC245fa, HFC365mfc, SO_2, BC, OC, CO, VOCs, NOx, NH_3
- We calculate CO_2 from fossil fuel & industrial uses, as well as from land-use change

CO_2:

- *Energy system*: we read in global carbon contents for fossil fuels (e.g., coal, gas, oil). These are chosen so we match global emissions from CDIAC in the base year. These carbon contents are used to compute emissions in all years (including the base year).
- *LUC*: we read in carbon density, growth parameters, and historical land allocation and compute emissions in all years (including the base year).

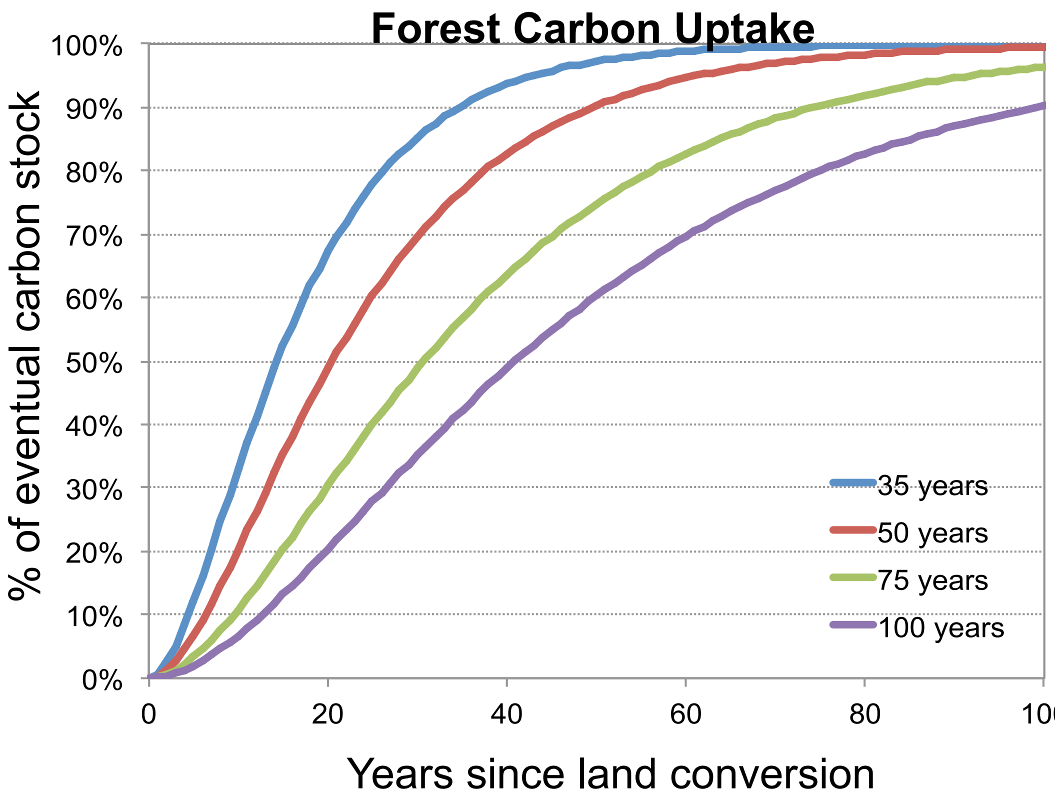
Non-CO_2:

- 2005 emissions calibrated to match the EDGAR* data set (except BC & OC, where we use RCP inventories). In some cases (e.g., electricity), we supplement EDGAR with EPA to get technology-specific emissions.
- *We plan to update GCAM calibration to be more flexible and calibrate to the newly released CEDS historical emissions dataset, or other datasets as needed.* *globalchange.umd.edu/ceds*

Emissions: Vegetation CO_2 Emissions

- First, we determine the total change in carbon stock for each land type and region.
  - Δ C Stock = [Land Area (t)]*[C density (t)] - [Land Area (t-1)]*[C density (t-1)]

- Then, we allocate that change across time.
  - If change in land area decreases the carbon stock (e.g., deforestation), then all carbon is released into the atmosphere instantaneously.
  - If the change in land area increases the carbon stock (e.g., afforestation), then carbon accumulates slowly over time, depending on an exogenously specified mature age.
    - The mature age varies by land type and region.



Emissions: Soil CO_2 Emissions

- First, we determine the total change in carbon stock for each land type and region.
  - Δ C Stock = [Land Area (t)]*[C density (t)] - [Land Area (t-1)]*[C density (t-1)]

- Then, we allocate that change across time.
  - Whether carbon stock increases or decreases, we use the same formula.
    - $SoilCarbon(t) = SoilCarbon(0) + \Delta SoilCarbonStock_{i,j} \cdot (1 - e^{-\lambda t})$
  - The half life, λ, varies by region.
  - In general, colder regions have longer soil carbon half lives.

Emissions: Non-CO_2 Drivers

Energy System

- Emissions in the energy system can be driven by input (e.g., fuel consumed by a particular technology) or output (e.g., fuel or service produced by a particular technology).
- Emissions information is technology-specific. As a result, different technologies that produce the same output can have different emissions per unit of activity.
- For most gases and species, we model drivers of emissions in detail. However, for some F-gases, the driver data (e.g., fire extinguishers) depends only on GDP.

Agriculture

- Emissions in the agricultural system can be driven by output (e.g., for crop production) or land area (e.g., for open burning).
- Emissions information is crop and region specific in GCAM. However, inventory data is region specific, but not crop specific (or AEZ specific).

GCAM Non-CO_2 Emissions: Projections

Air Pollutant Emissions

- Projections currently use a global parameterization where emission factors decline as a function of GDP per capita
  - This species-specific parameterization captures the general trend of increasing pollutant controls over time.
  - This does not capture regional and technological heterogeneity. Future updates to this are planned.
  - *Note that the GCAM implementation of the SSP scenarios used a different approach, incorporating region, sector, and fuel specific pollutant emission factor pathways (Calvin et al 2016, Rao et al. 2016).*

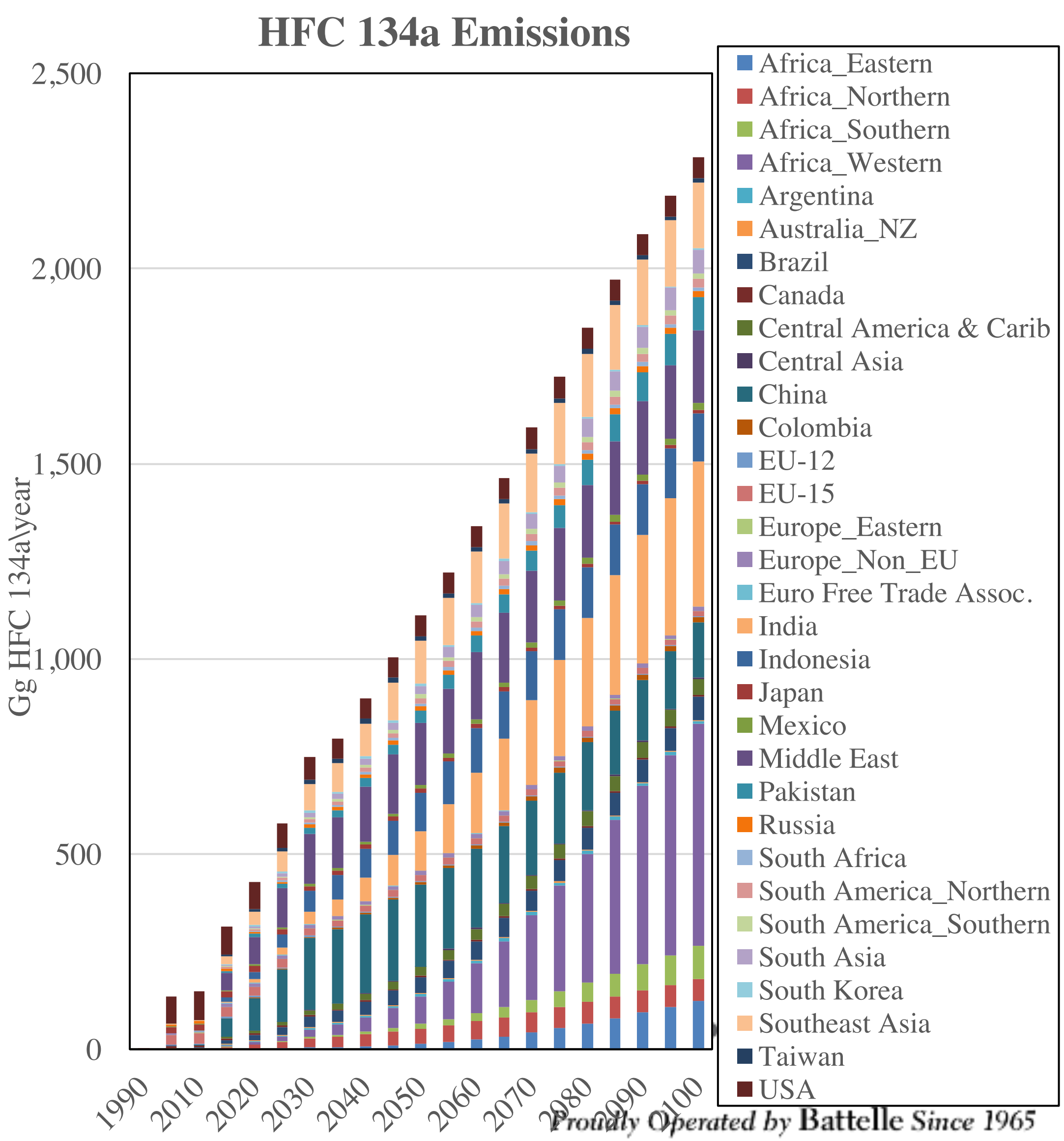
Non-CO_2 GHG Emissions

- GHG emission factors only change due to MAC curves
  - Where a MAC curve is present, the emissions factor changes in two ways
    - Below-zero (e.g. “no cost”) MAC mitigation (e.g. MAC reduction percentage is > 0 at zero carbon price) are applied in the reference case. (can be turned off by setting `no-zero-cost-reductions` to 1 within a MAC curve).
    - Under a carbon policy, the emission factor is reduced, as a function of the carbon price, as specified by the MAC curve.

Emissions: Fluorinated Gases

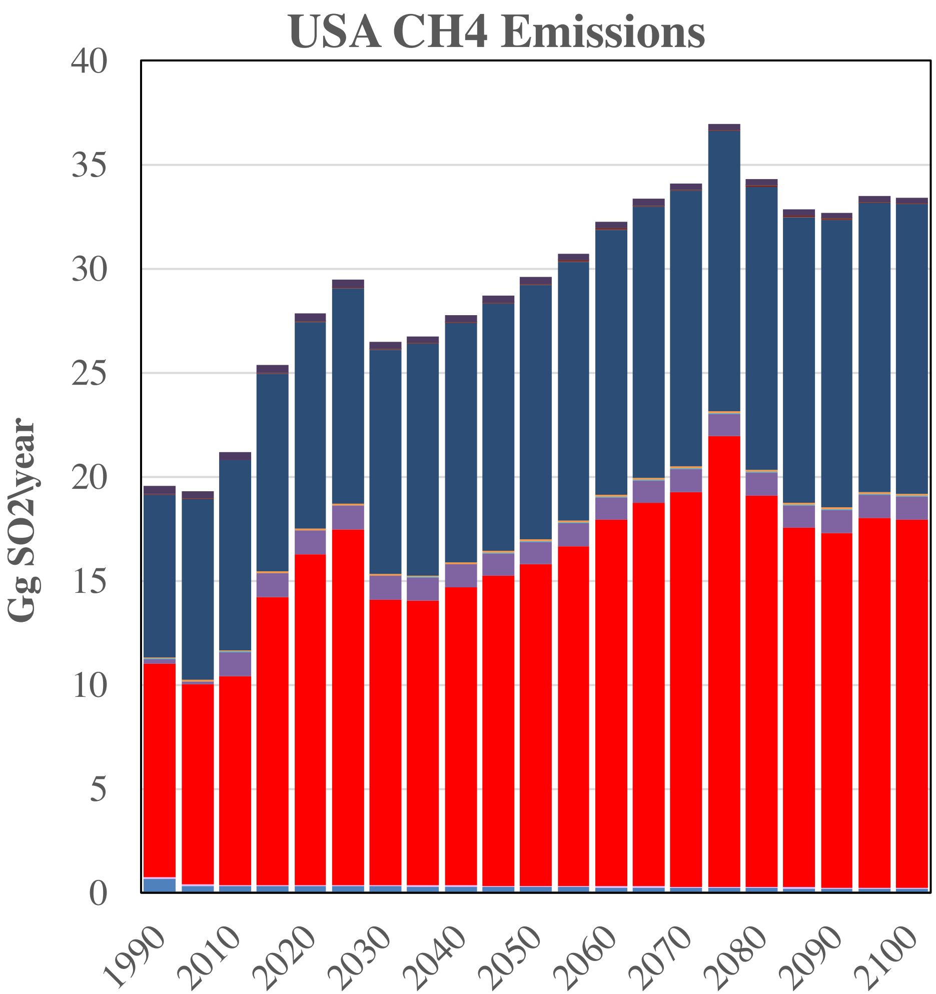
- Fluorinated gas emissions are linked either to the size of the industrial sector (e.g., semiconductors) or to GDP (e.g., fire extinguishers). As those drivers change, emissions will change. Additionally, we include abatement options based on the EPA's most recent MAC curves.

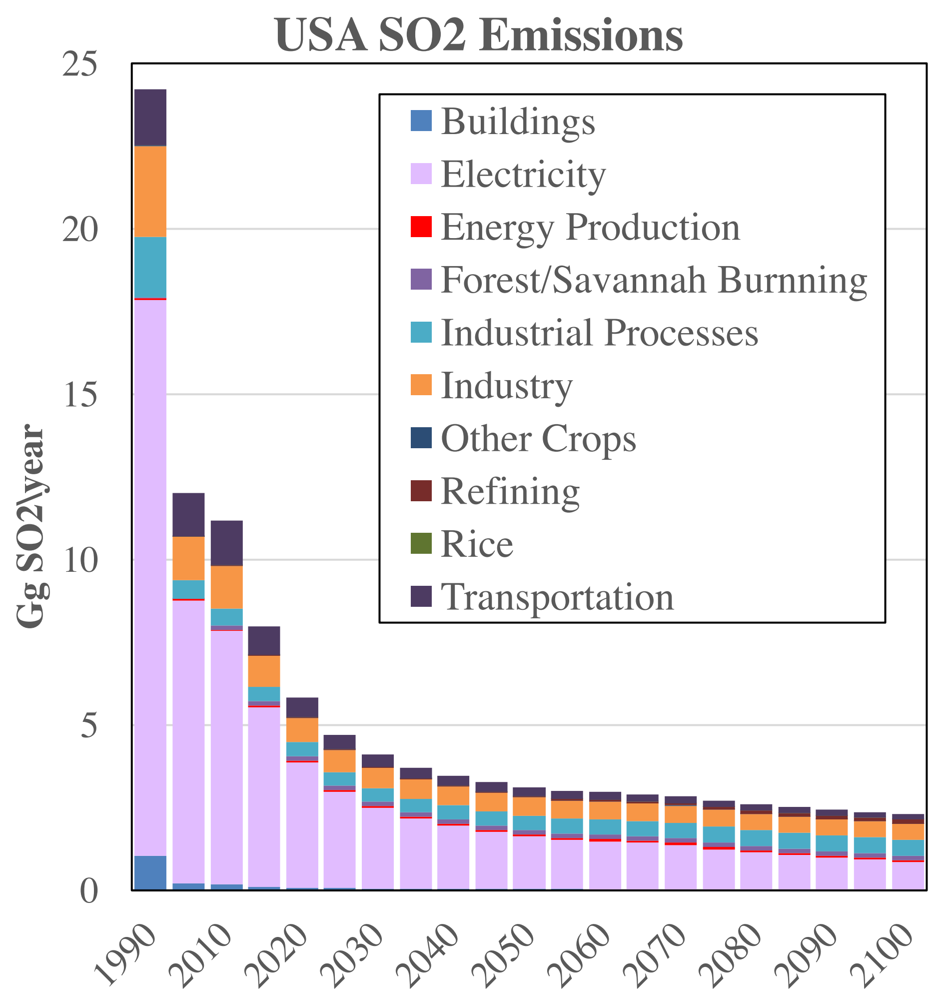
- For HFC134a from cooling (e.g., air conditioners), we make additional adjustments to emissions factors in the developing regions to reflect their continued transition from CFCs to HFCs (see EPA report).



Emissions: Results

Emissions are produced at a region level (32 regions for energy, 283 regions for agriculture & land-use).





GCAM Non-CO_2 Emissions: User Options

GHG Emissions

- Emissions prices of different GHGs can be linked together for a multi-gas policy using the `linked-ghg-policy` object (for example, `linked_ghg_policy.xml`). The parameter `price-adjust` is used to convert prices (e.g., 100 year GWP) and `demand-adjust` is used to convert demand units (e.g., to common units of carbon equivalents).
  - These can be changed by year if desired.
  - Setting price-adjust to zero means that there is no economic feedback for the price of this GHG. MAC curves, however, will still operate. This can be changed separately for energy/industrial/urban CH_4, agricultural CH_4 (CH4_AGR), and CH_4 from agricultural waste burning (CH4_AWB), LUC CO_2 emissions (e.g. CO2_LUC).
  - Note that you must first create the policy (e.g., a <ghgpolicy> objects) and then you define how this links to any emissions (through <linked-ghg-policy> objects).

This flexibility allows CO_2-only, CO_2-equivalent, or non-CO_2 markets/constraints for various “baskets” of emissions as needed.

New GCAM Non-CO2 User Options

These options have been added to the core model as of 9/13/17.

- MAC curves can be set for any emission species. (e.g., CH_4-only market, NO_x market, etc.)
  - Note that it generally does not make sense to set up a emissions market unless the model has a direct way to reduce emissions! (e.g. you've added relevant MAC curves.)
- Below zero MAC reductions are phased in over several years (default 25 years, with optional user-defined time period).
- GHG objects can be added/changed via user input in any time period (currently GHG objects must first appear in 1975 and cannot be changed).
  - This also means that GHG objects can be removed after a given year by reading in a blank GHG object for that gas.
- New `linear-control` object allows user to specify that an emission factor will go to a user-defined value over a specified time period.

Example: Creating an emissions policy

1) Frist, read in an emissions policy.
   - This must be done first so as to set up a market in GCAM.
     - Examples: Fixed tax, target forcing

```
<world>
    <region name="USA">
        <ghgpolicy name="GHG">
            <market>global</market>
            <isFixedTax>1</isFixedTax>
            <fixedTax year="2020">10</fixedTax>
            <fixedTax year="2035">20.8</fixedTax>
            <fixedTax year="2050">43.2</fixedTax>
            <fixedTax year="2065">89.9</fixedTax>
            <fixedTax year="2080">186.8</fixedTax>
            <fixedTax year="2095">388.3</fixedTax>
            <fixedTax year="2100">495.6</fixedTax>
        </ghgpolicy>
    </region>
    <region name="Canada">
        <ghgpolicy name="GHG">
            <market>global</market>
        </ghgpolicy>
    </region>
```

- Include every region you want to be included.
- Give your policy a name (e.g. “fred”)

2) Read in the linked policy XML
   - This file tells GCAM what gases are part of the market

Example: linked_ghg_policy.xml

```xml
<scenario>
  <world>
    <region name="USA">
      <linked-ghg-policy name="CO2">
        <price-adjust fillout="1" year="1975">1</price-adjust>
        <demand-adjust fillout="1" year="1975">3.666666667</demand-adjust>
        <market>global</market>
        <linked-policy>GHG</linked-policy>
        <price-unit>1990$/tC</price-unit>
        <output-unit>MtC</output-unit>
      </linked-ghg-policy>
      <linked-ghg-policy name="CH4">
        <price-adjust fillout="1" year="1975">5.727272727</price-adjust>
        <demand-adjust fillout="1" year="1975">21</demand-adjust>
        <market>global</market>
        <linked-policy>GHG</linked-policy>
        <price-unit>1990$/GgCH4</price-unit>
        <output-unit>TgCH4</output-unit>
      </linked-ghg-policy>
      <linked-ghg-policy name="N2O">
        <price-adjust fillout="1" year="1975">84.54545454</price-adjust>
        <demand-adjust fillout="1" year="1975">310</demand-adjust>
        <market>global</market>
        <linked-policy>GHG</linked-policy>
        <price-unit>1990$/GgN2o</price-unit>
        <output-unit>TgN2O</output-unit>
```

3.6666 gCO_2/gC

Name of emission species.

Unit conversion for prices.

- If = 0 policy cost does get added to technologies that emit that species.
- Converts linked market price to units of $/tCH4

Unit conversion for adding up emission amounts.

Same market as used in setting up the policy.

Name of policy

Note that this GCAM default file includes economic feedbacks for all emission species. This is not always what happens in actual policies. For example, in many current systems agricultural emissions are offsets only – e.g., they get paid to reduce emissions, but never pay for emissions otherwise. (so for this, price-adjust would be set to zero).

Climate System

2017

Corinne Hartin

Pacific Northwest
NATIONAL LABORATORY

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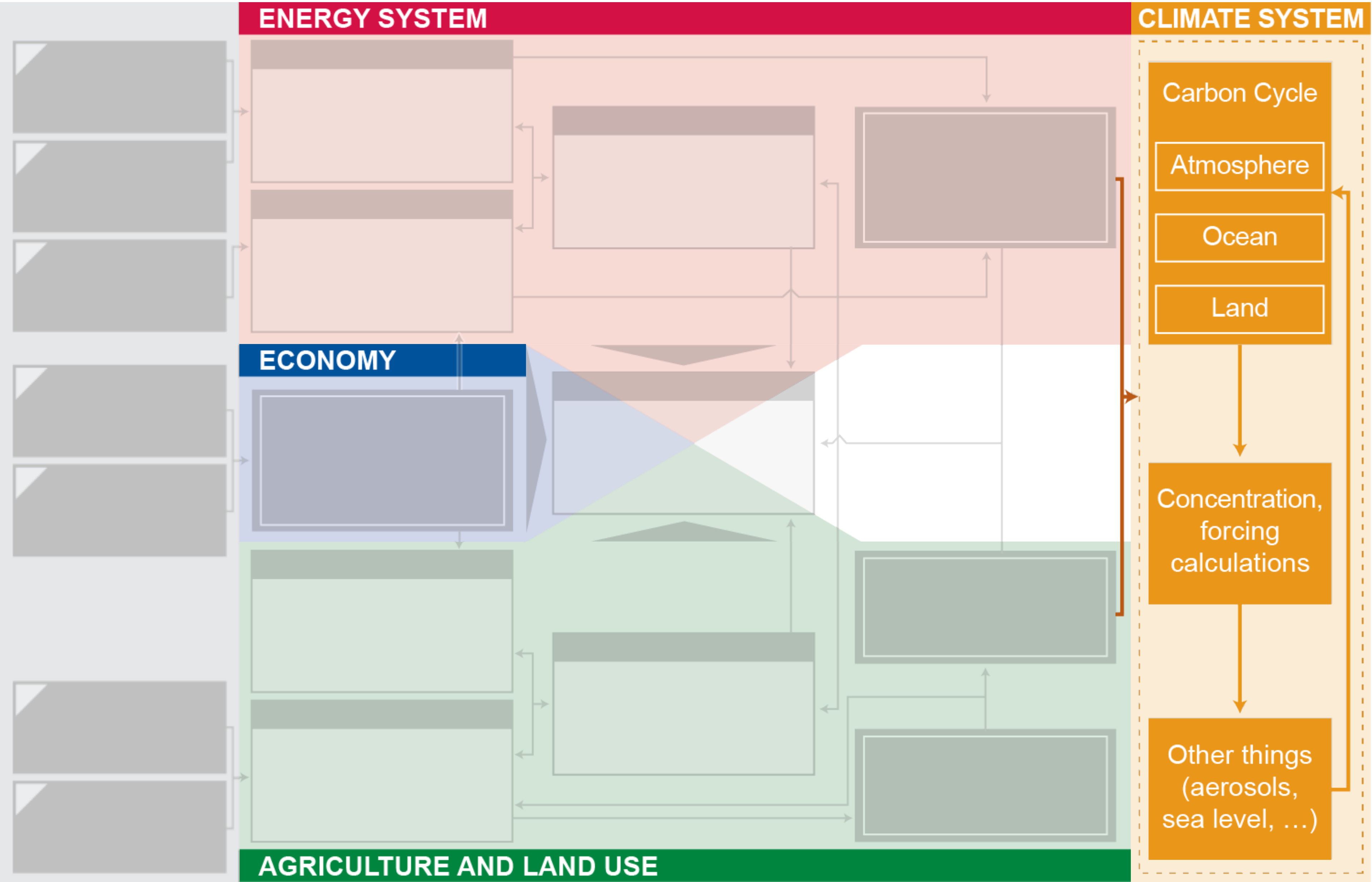
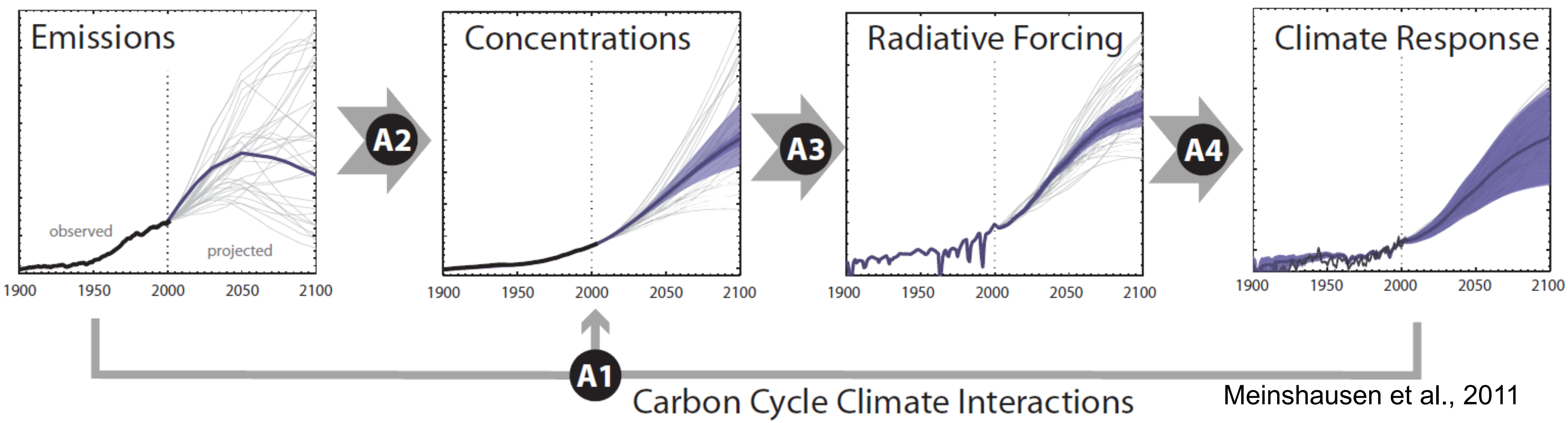
The Global Change Assessment Model



The Climate System: Approach

- GCAM has the option to use MAGICC 5.3 or ***Hector v1.1.2*** to compute climate related outputs
- Inputs:
  - GCAM passes emissions to the climate model
  - Fossil fuel & Industrial CO_2, Land-Use Change CO_2, CH_4, N_2O, SF_6, C_2F_6, CF_4, HFC125, HFC134a, HFC143a, HFC227ea, HFC245fa*, SO_2, CO, NO_x, NMVOCs, BC, OC
- Outputs:
  - MAGICC and Hector compute concentrations and radiative forcing
  - Computes atmospheric CO_2, temperature change, air-land/air-sea fluxes, SLR



Meinshausen et al., 2011

Why develop a new simple climate model?

- MAGICC
  - Used across many scientific and policy communities – instrumental in the IPCC
  - Many strengths
  - Old code to work with
  - Not open source, legal issues unclear
- Developed Hector
  - Free and open-source – community model
    - www.Github.com/JGCRI/hector
      - Option to incorporate other versions of Hector
  - Easy to use and well documented
    - Hartin et al., 2015 - GMD
    - Hartin et al., 2016 - BGS

Hector philosophy and structure

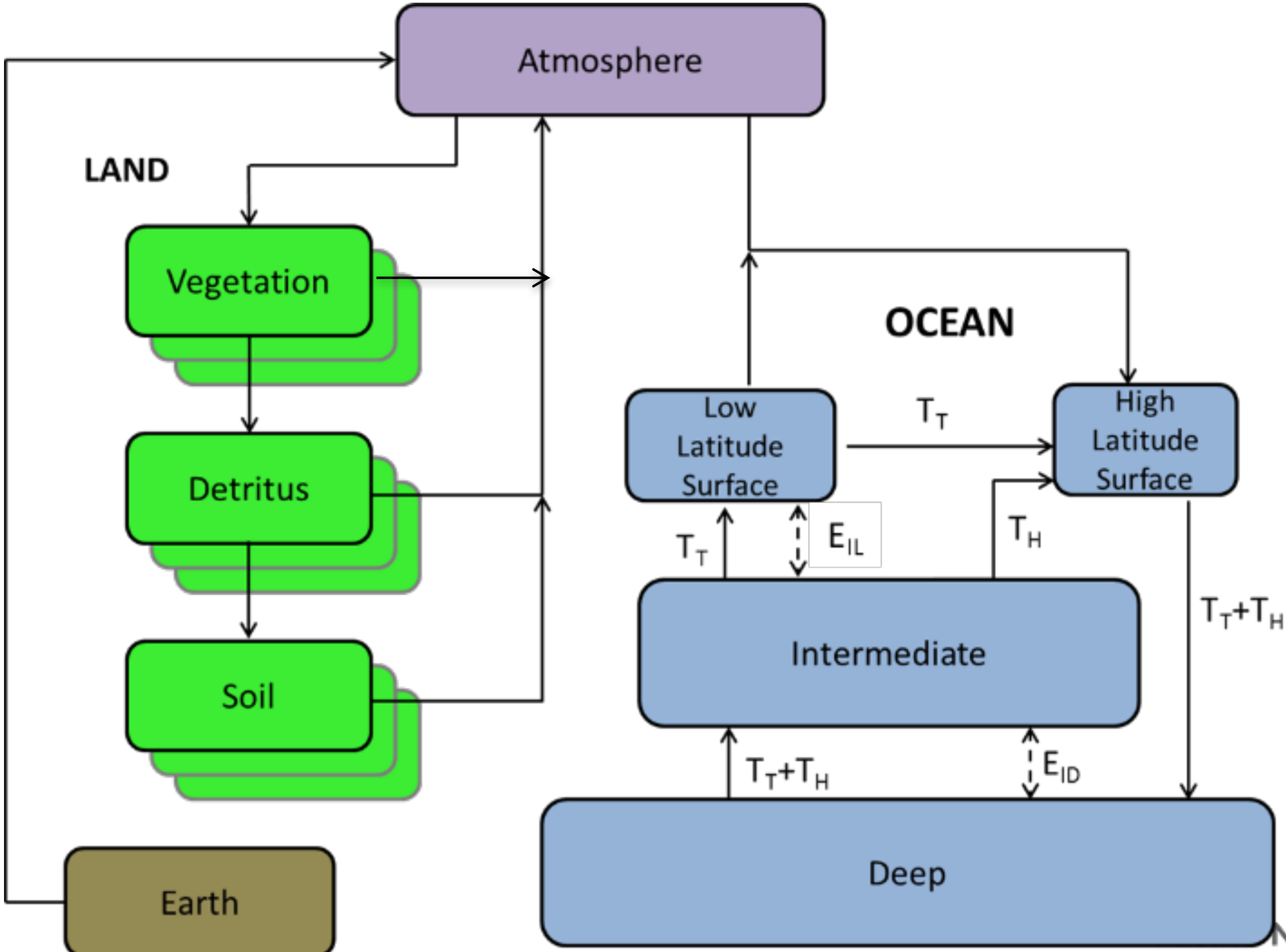
- Complexity only where warranted
- Modular
  - Components can be enabled/disabled via inputs
    - E.g. you can test two different ocean submodels against each other
- Modern, clean structure
  - E.g. coupler enforces unit checking between submodels

Sample Input File

```
; Config file for hector model: RCP4.5
[core]
run_name=rcp45
startDate=1745
endDate=2100
do_spinup=1              ; if 1, spin up model before running (default=1)
max_spinup=5000          ; maximum steps allowed for spinup
(default=2000)

[onelineocean]
enabled=0                ; putting 'enabled=0' will disable any component
ocean_c=38000, Pg C

[ocean]
enabled=1                ; putting 'enabled=0' will disable any component

spinup_chem=0            ; run surface chemistry during spinup phase?
tt  = 72000000            ; 7.2e7 thermohaline circulation, m3/s
tu  = 49000000           ; 4.9e7 high latitude overturning, m3/s
twi = 12500000            ; 1.25e7 warm-intermediate exchange, m3/s
tid = 200000000          ; 2.0e8 intermediate-deep exchange, m3/s

[simpleNbox]
; Initial (preindustrial) carbon pools
atmos_c=588.071                    ; Pg C in CO2, from Murakami (2010)
veg_c=550                          ; Pg C
detritus_c=55                      ; Pg C
soil_c=1782                        ; Pg C
```

Initial values for the ocean and land components

Hector: Science

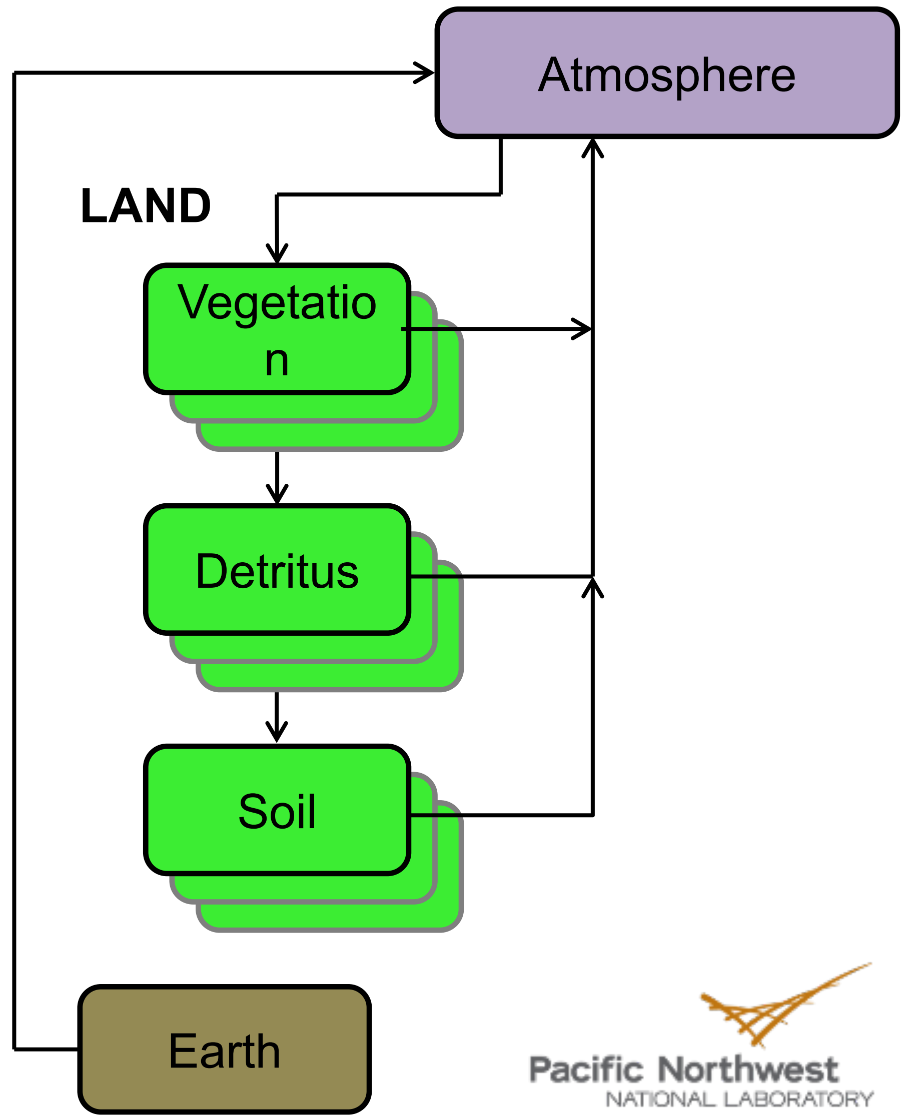


Hector: Atmosphere

- Well mixed globally averaged atmosphere
- Forced with emissions from RCP scenarios
  - CO_2 – anthropogenic & LUC
  - BC/OC
  - CH_4/N_2O
  - 26 halocarbons
  - Sulphate aerosols
  - Volcanic emissions
- Calculate:
  - Stratospheric H_2O
  - Tropospheric O_3
- Radiative forcing
  - include both indirect and direct effects on radiative forcing

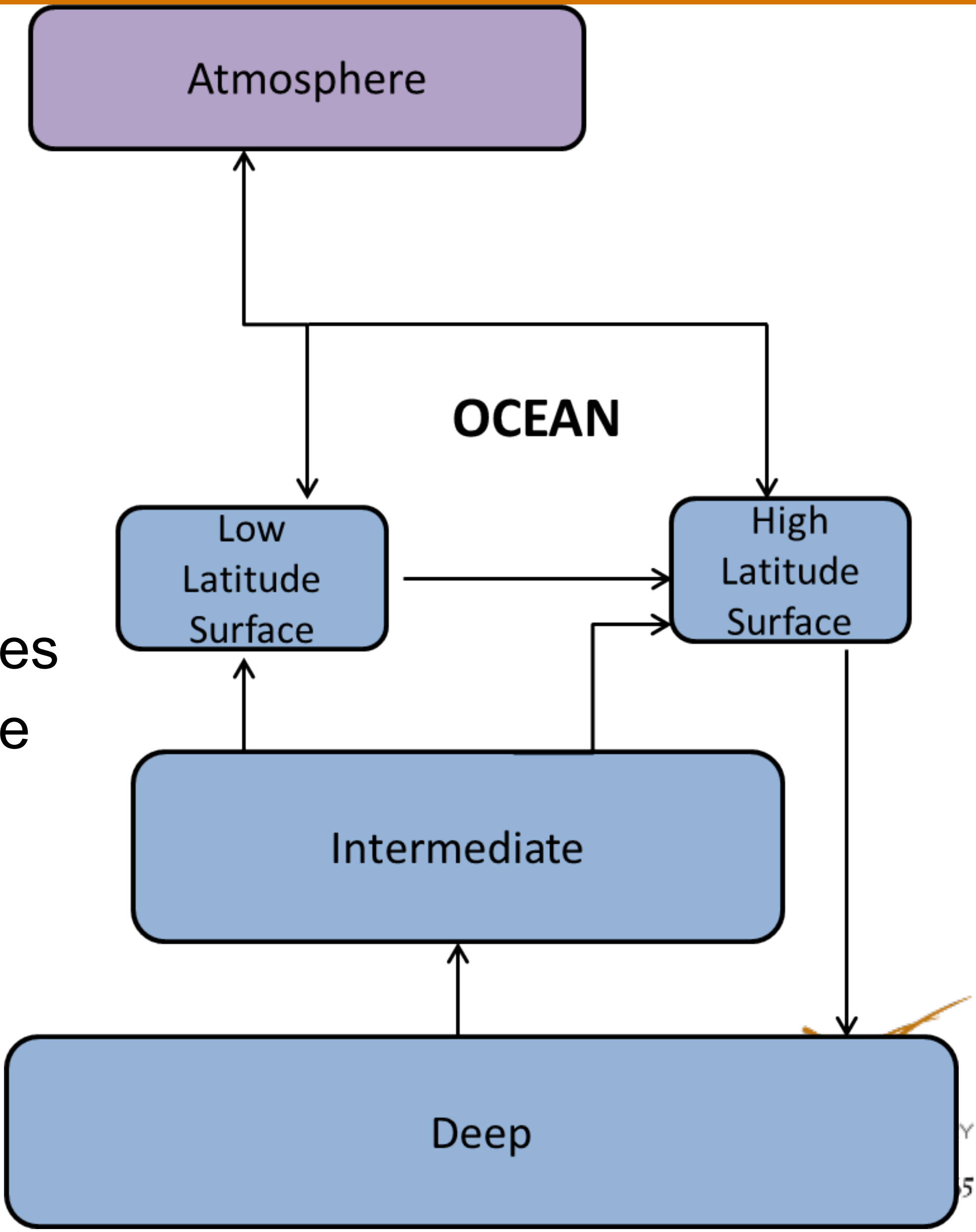
Science: Land

- A classic simple design: five boxes
- NPP, R_H, litter fluxes scaled by global temperature and CO_2
- Optional biomes – ex. Boreal and tropical
- Continual mass balance to check for 'leaks'

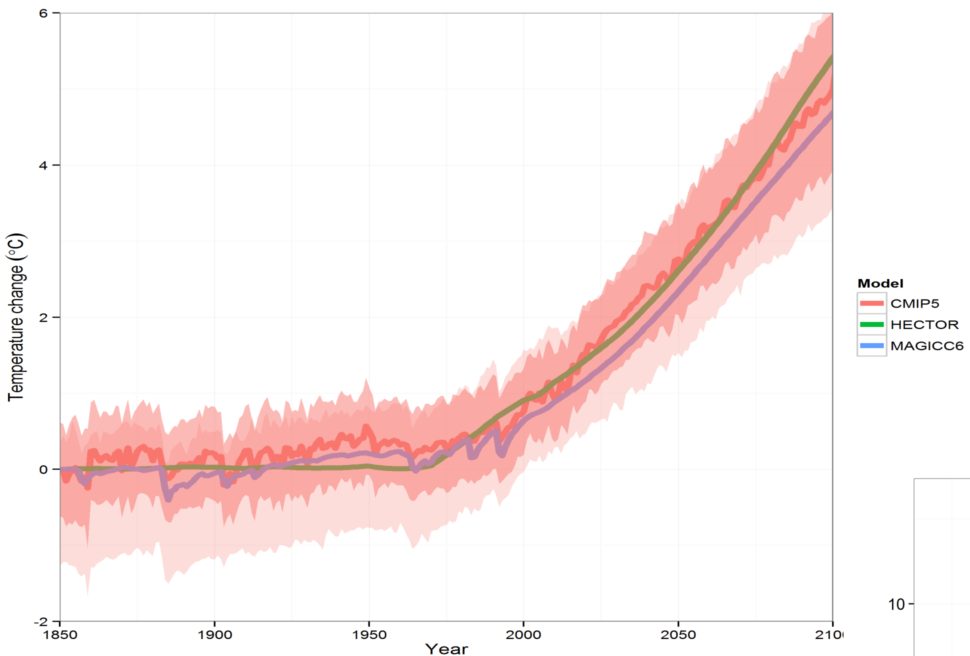


Science: Ocean

- 4 boxes
  - 2 surface boxes (100m)
  - Intermediate box
  - Deep box (~3777m)
- Advection and water mass exchange
- Heat uptake in surface boxes
- Carbon chemistry in surface boxes (e.g., atmosphere-ocean flux, pH, $CaCO_3$ saturations)

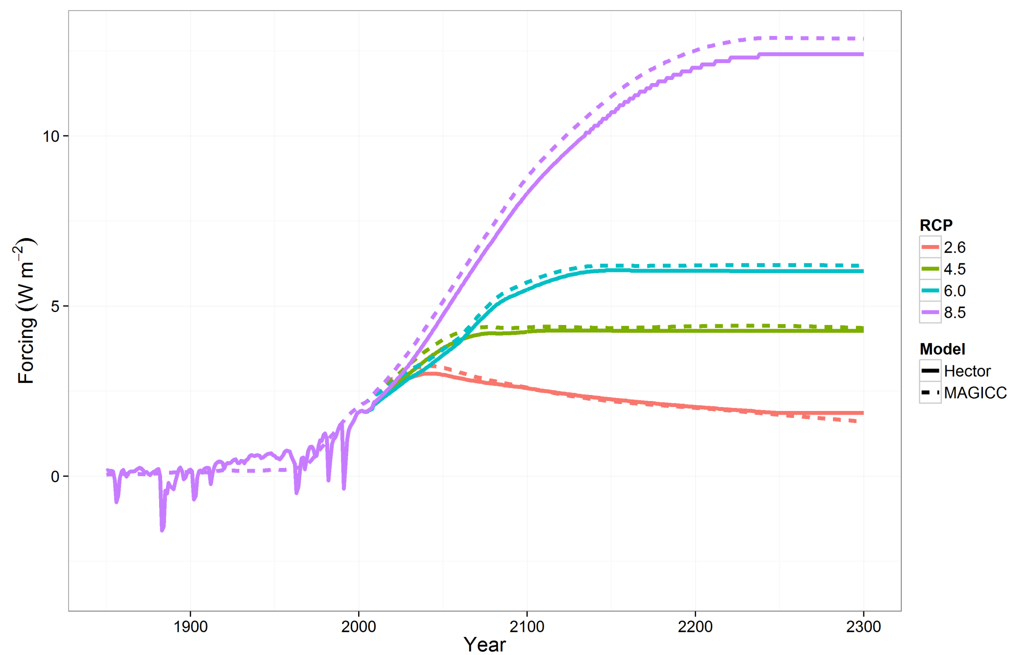


The Climate System: Results



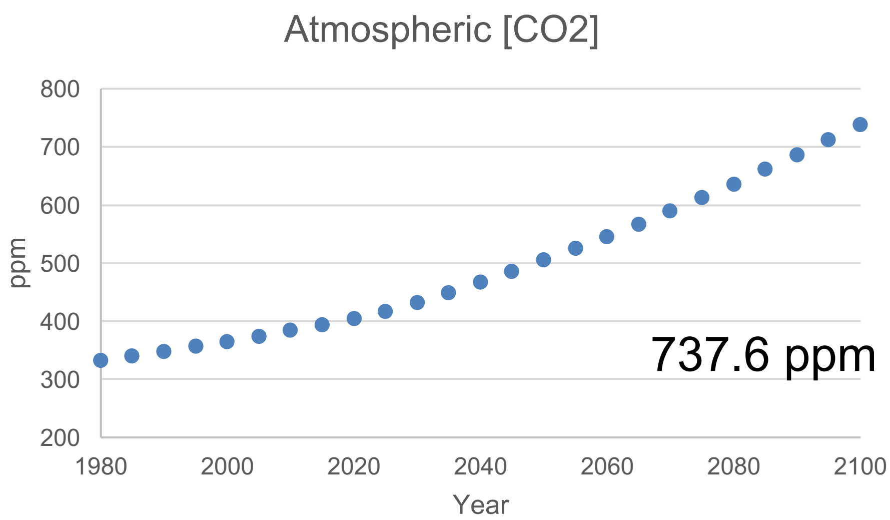
Atmospheric Temperature – RCP8.5

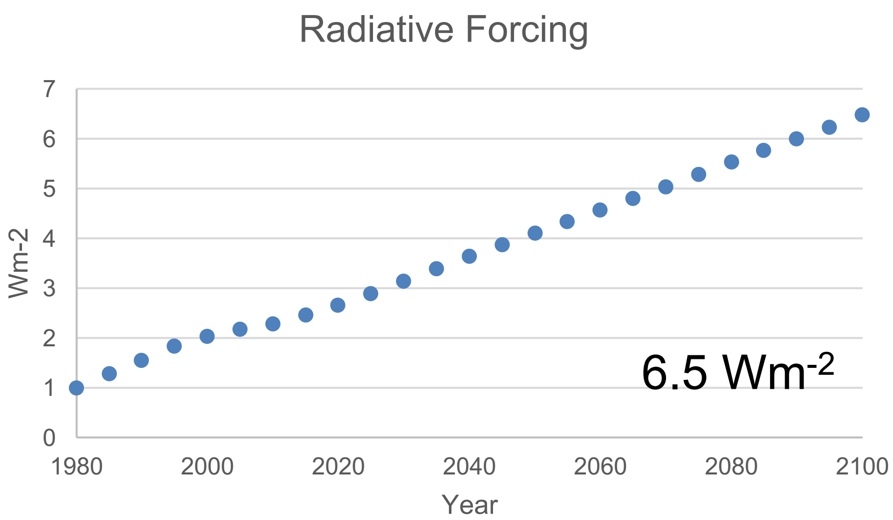
Radiative Forcing

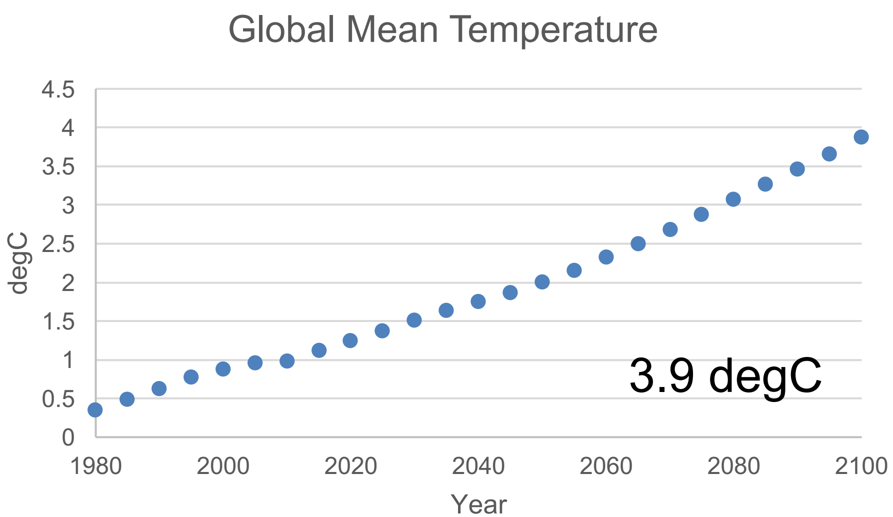


Hartin et al., 2015 - GMD

GCAM Reference Scenario







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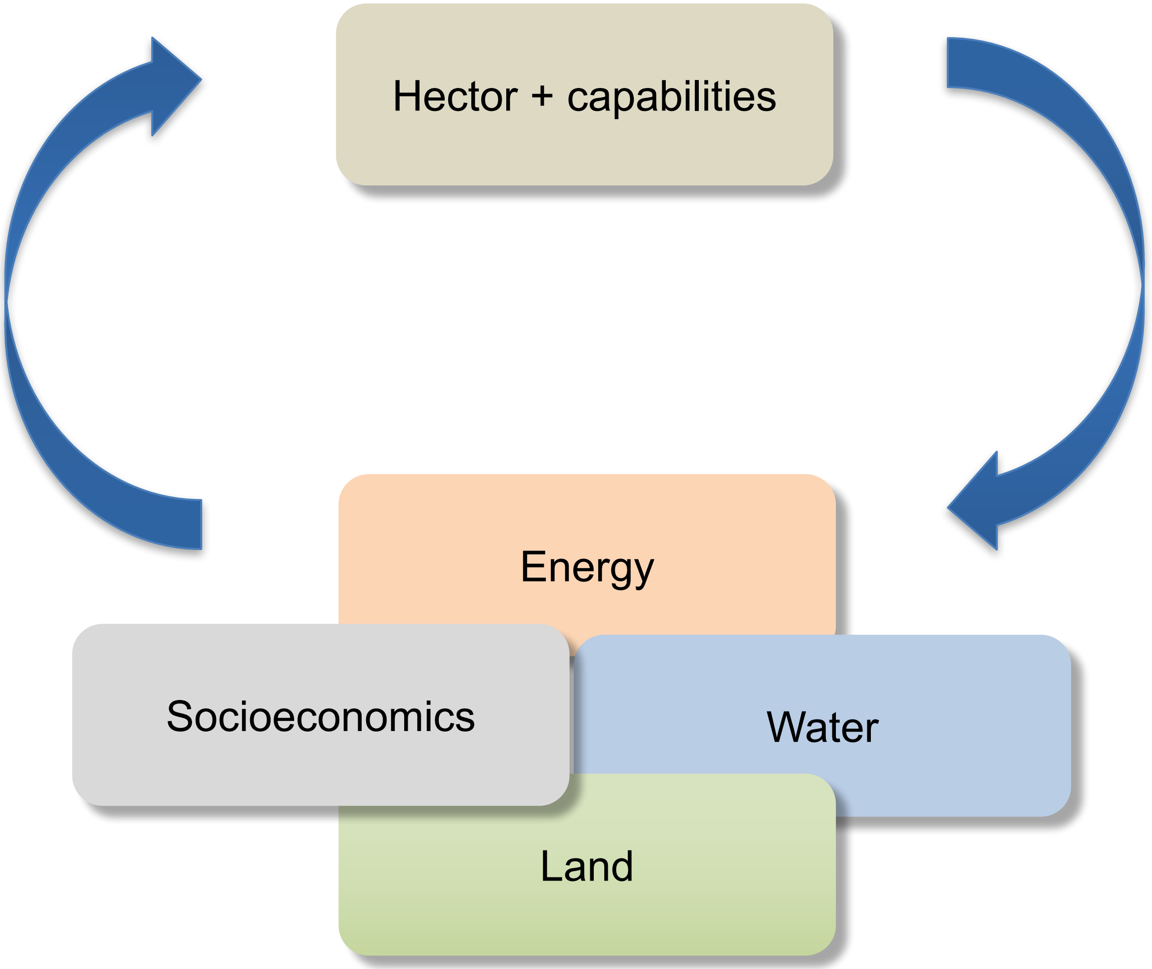
GCAM integration of Hector



QUESTIONS?