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GCAM Overview

October 17, 2018

Proudly Presented by the GCAM Team

U.S. DEPARTMENT OF ENERGY BATTELLE

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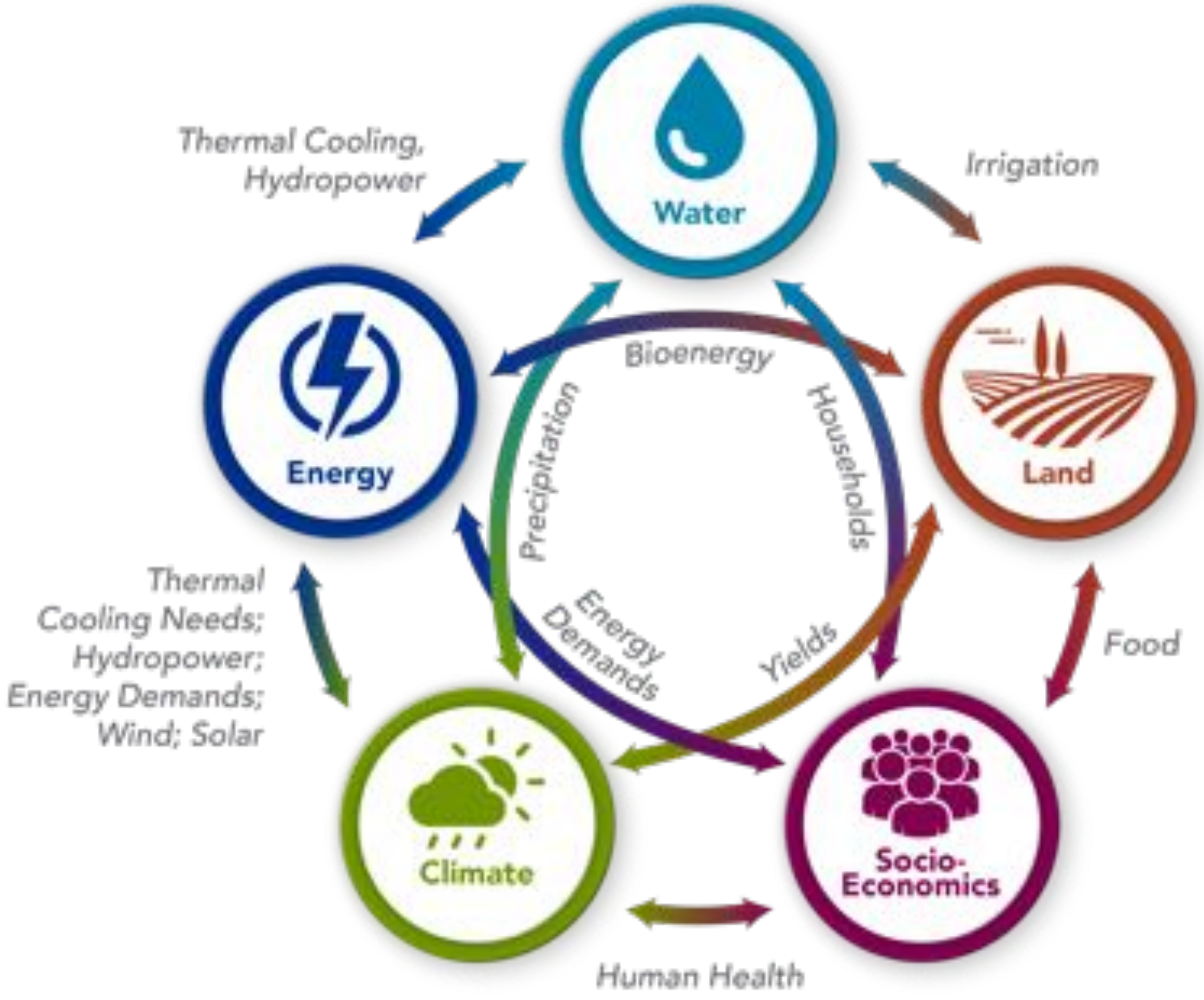
The Energy Sector in GCAM

GCAM explores the interactions between multiple systems



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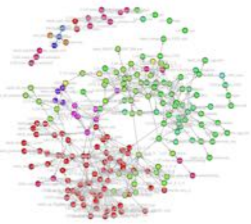
The GCAM ecosystem is a suite of models and tools

Data Development

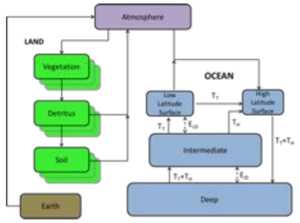
GCAM DS



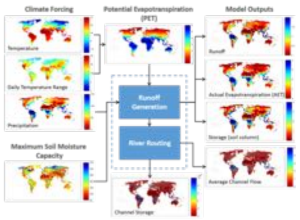
Moirai

Single System

Hector



Xanthos

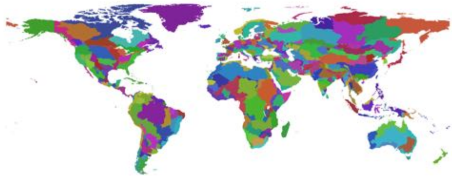


Dynamic Integration

GCAM-core

32 Energy Economy Regions

235 Water Basins

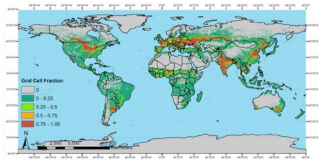


384 Land Regions

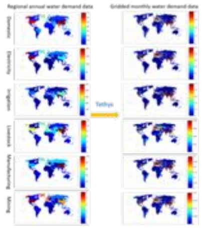
Province-Level Energy Economy Regions

Disaggregation

Demeter

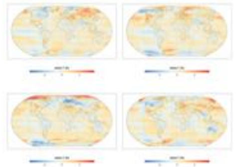


Tethys

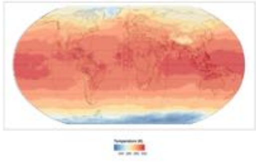


Statistical Emulators

fldgen



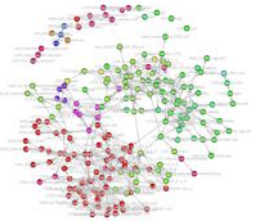
dnnclim



The GCAM ecosystem is a suite of models and tools

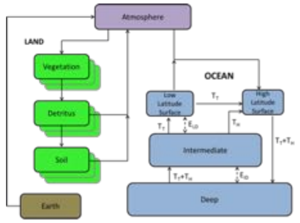
Data Development

GCAM DS



Single System

Hector

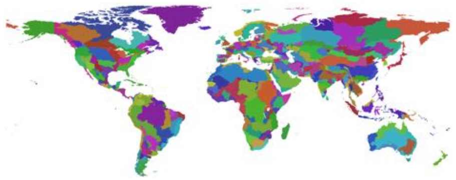


Dynamic Integration

GCAM-core

32 Energy Economy Regions

235 Water Basins



384 Land Regions

An Overview of GCAM

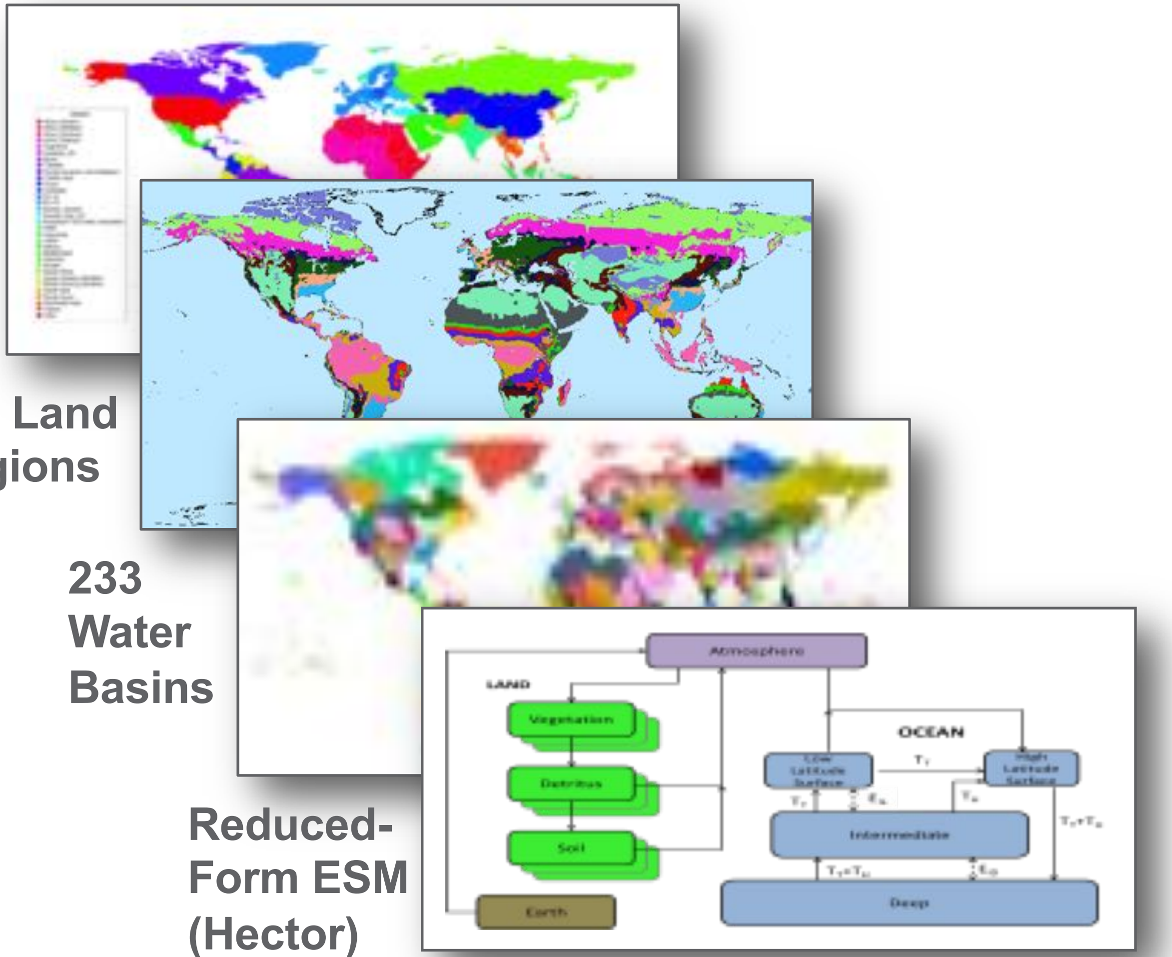
Global Coverage

32 Energy & Economy Regions

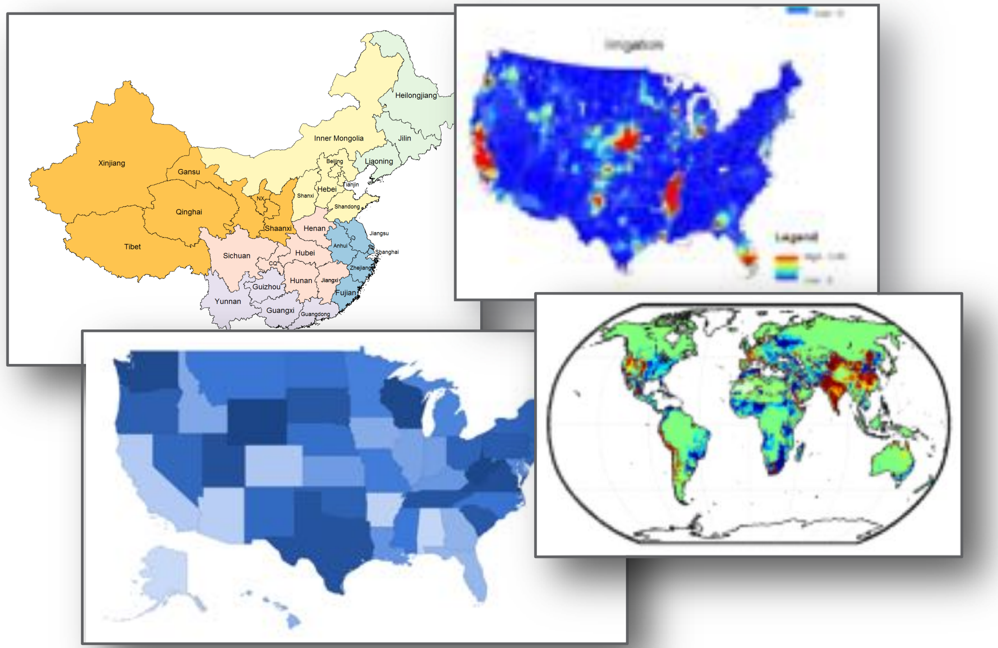
283 Land Regions

233 Water Basins

Reduced-Form ESM (Hector)



Flexible Scale



Market Equilibrium Solution

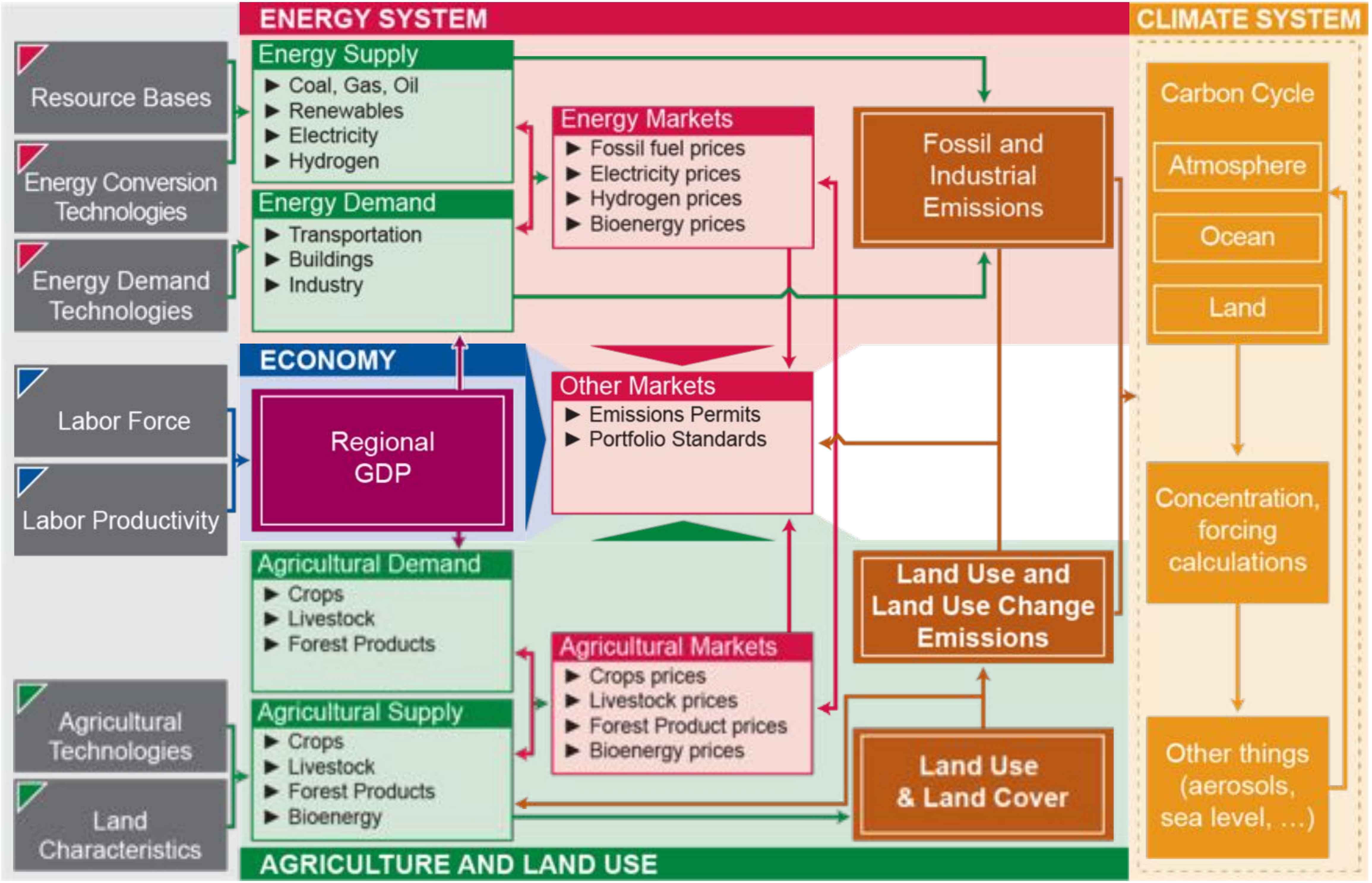
Community Model

http://jgcri.github.io/gcam-doc/toc.html

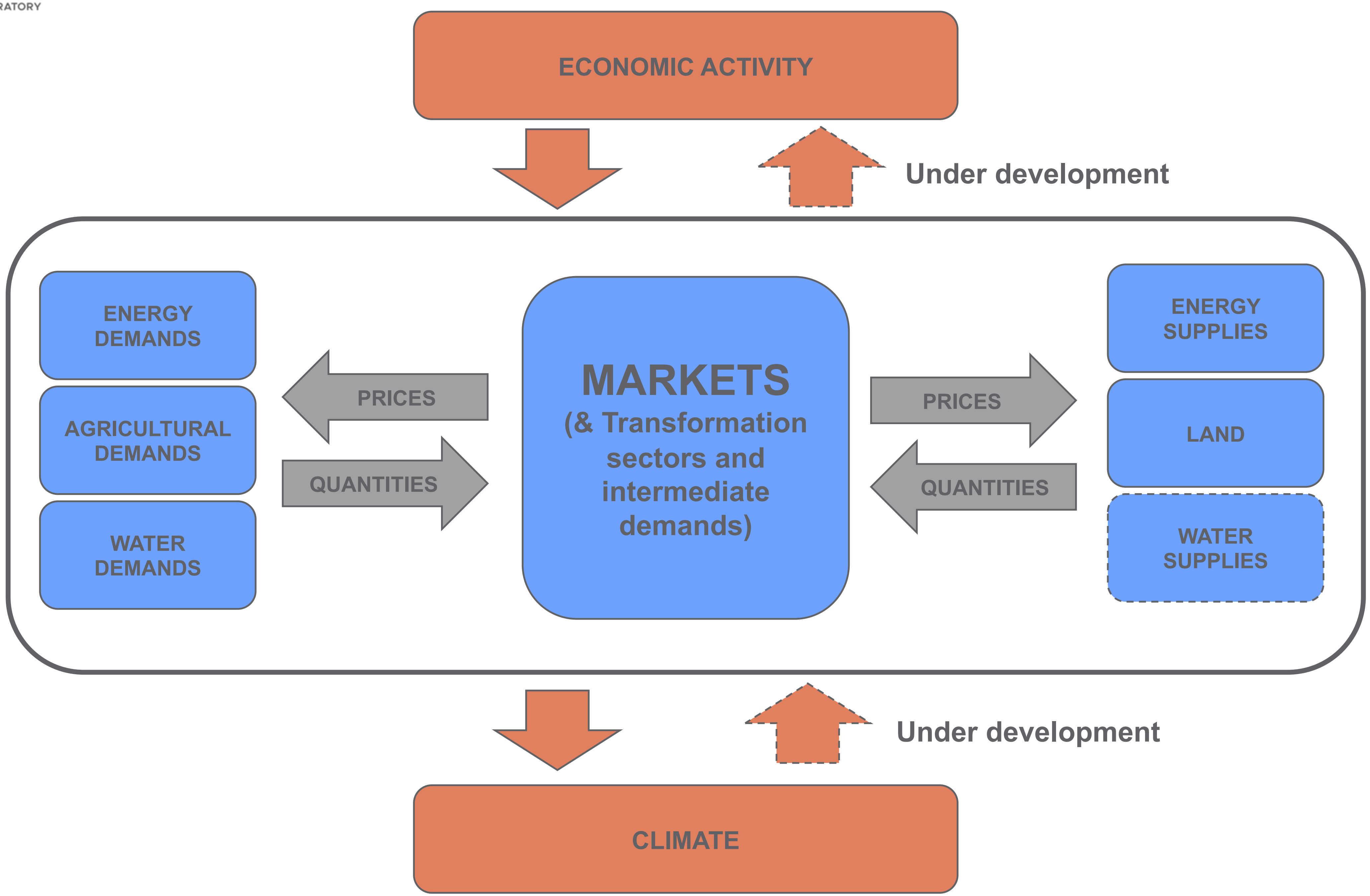
Flexible Time Scale

GCAM Core runs at 5 years; capability to run at one year; ancillary models run at finer scale

What's inside the GCAM Core?

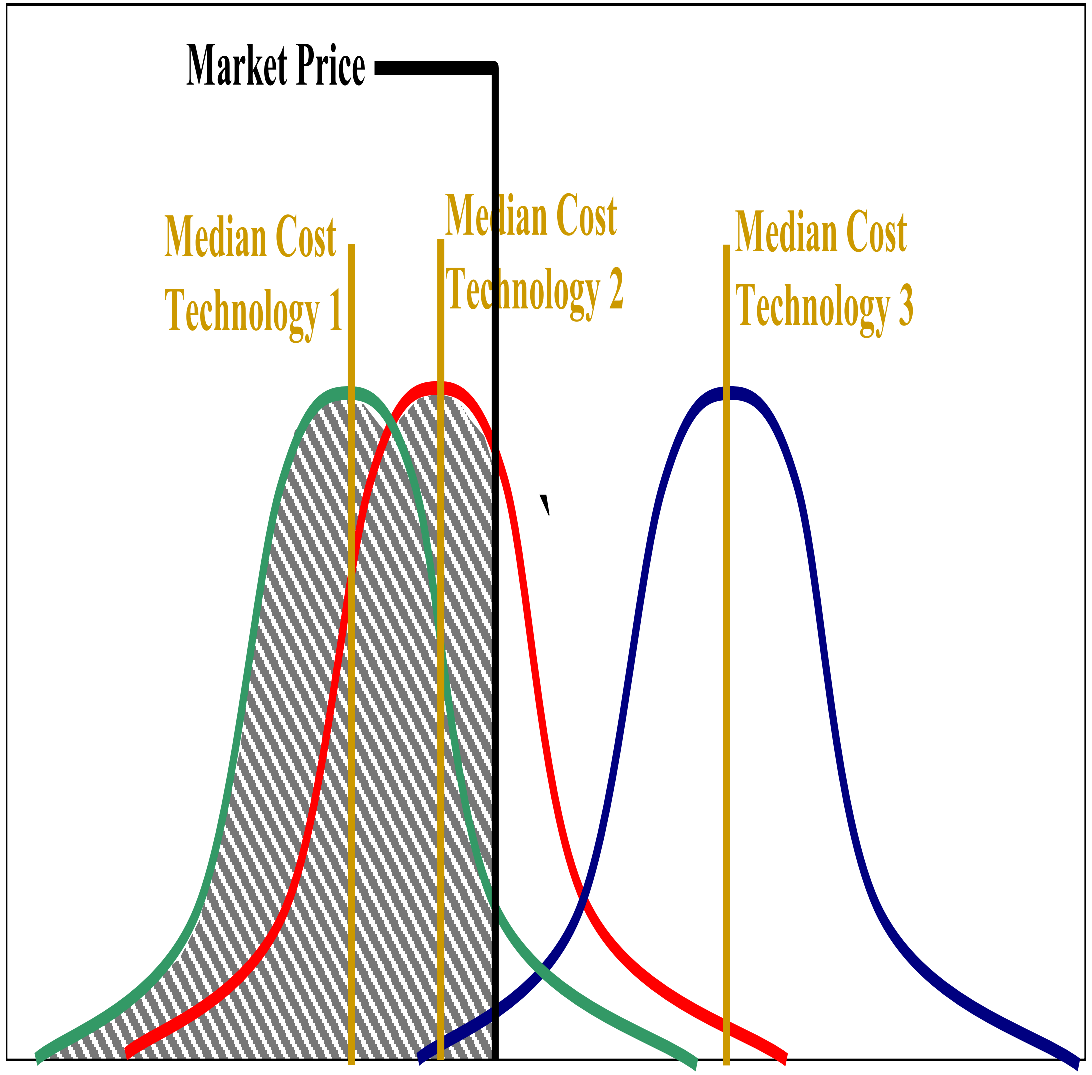


Market Equilibrium in GCAM



Logit Choice Mechanism for Decision Making

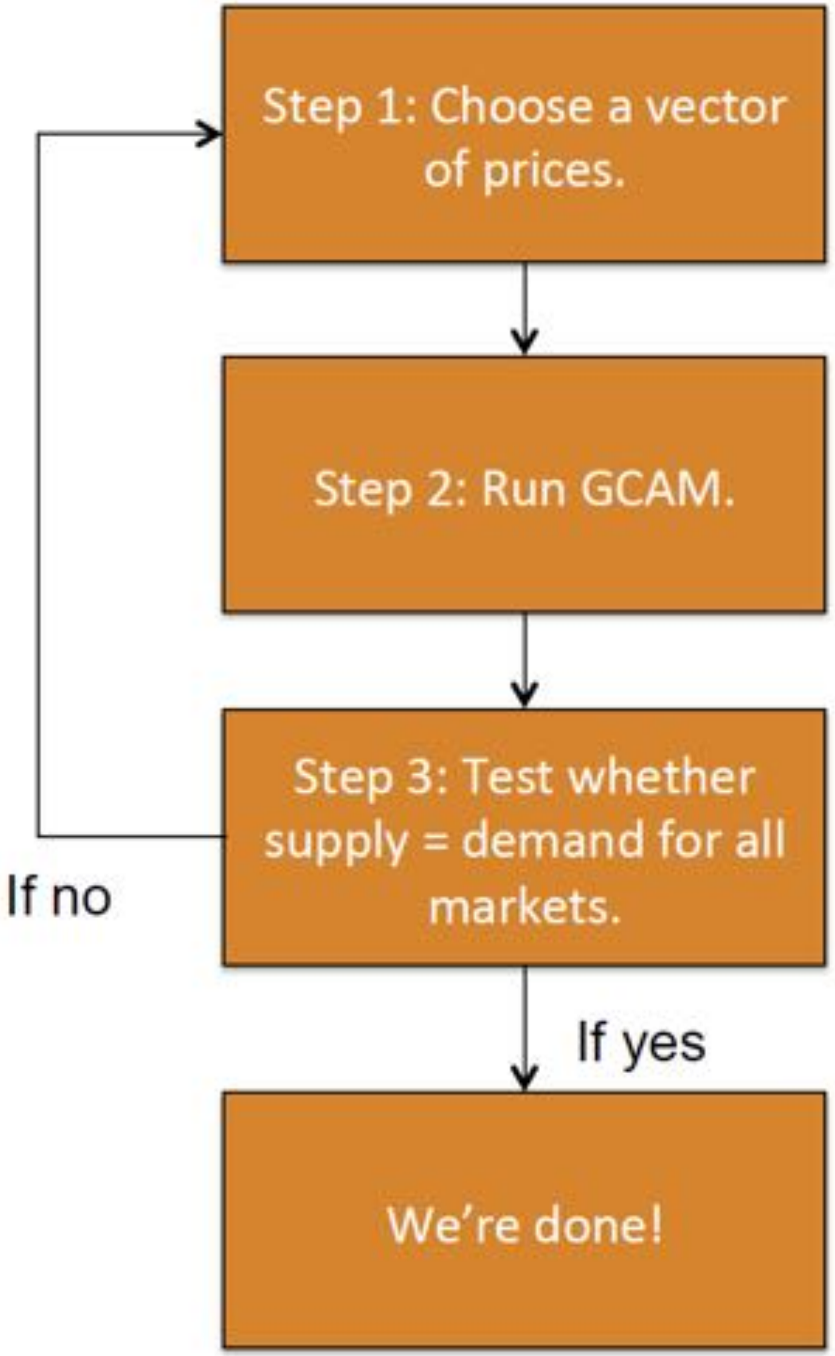
A Probabilistic Approach



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

- Calibrated logit approach 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.
- Historical calibration influences future competition through the “share-weight” (α)

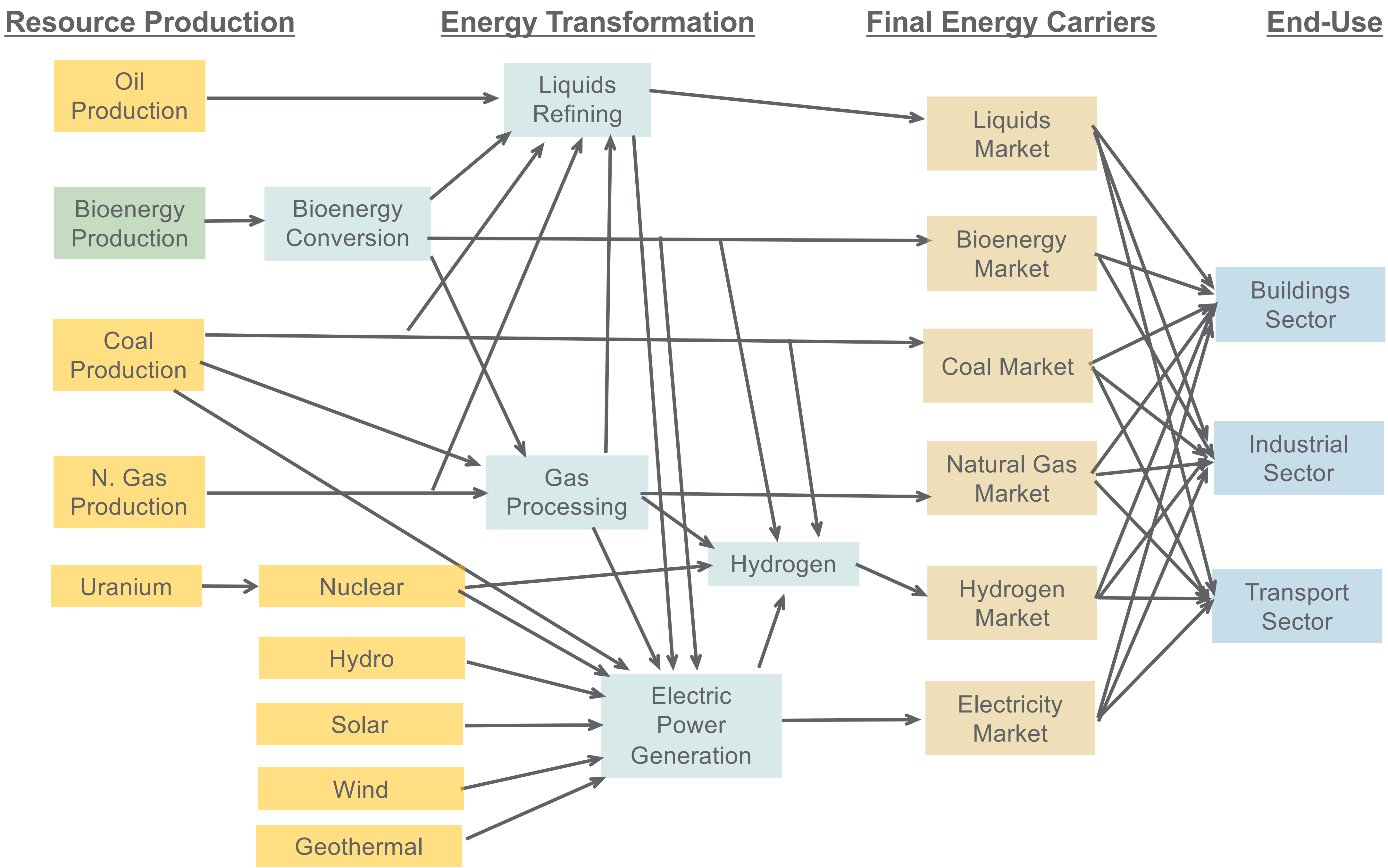
Solution Approach



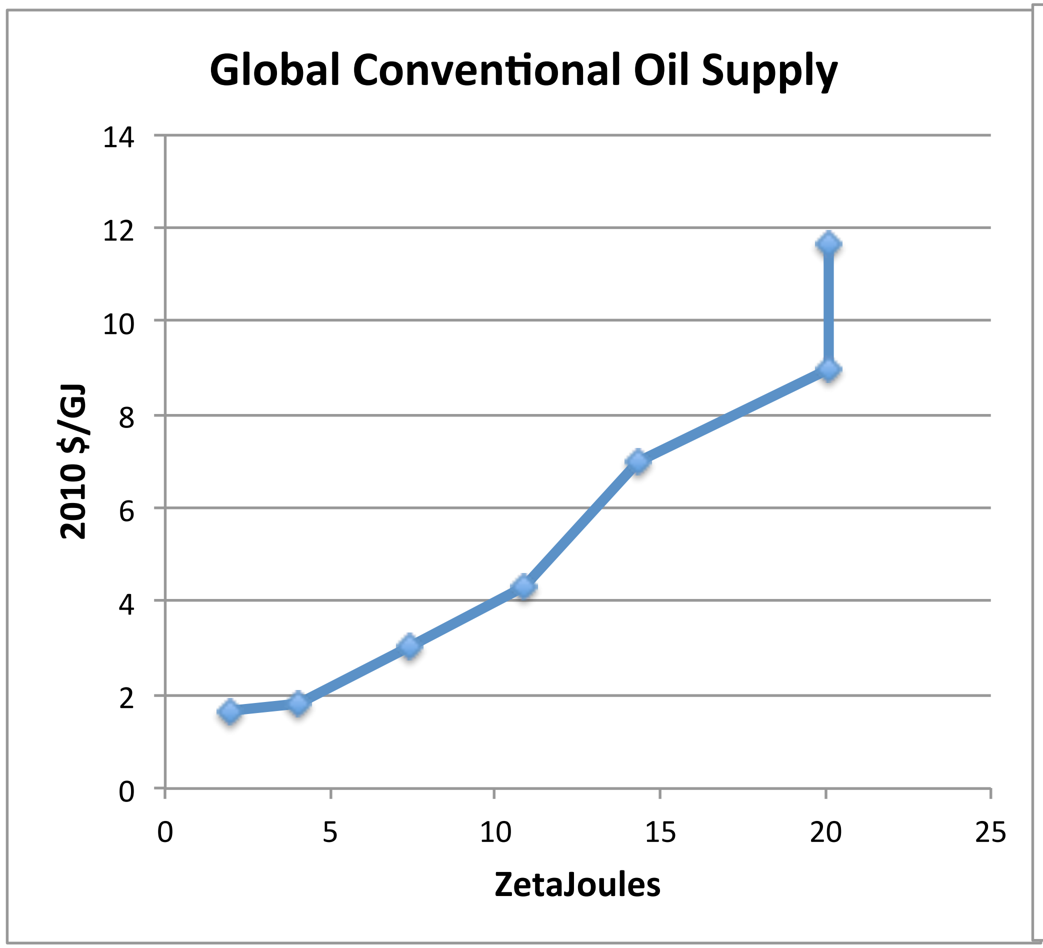
2 + 2 = 5?

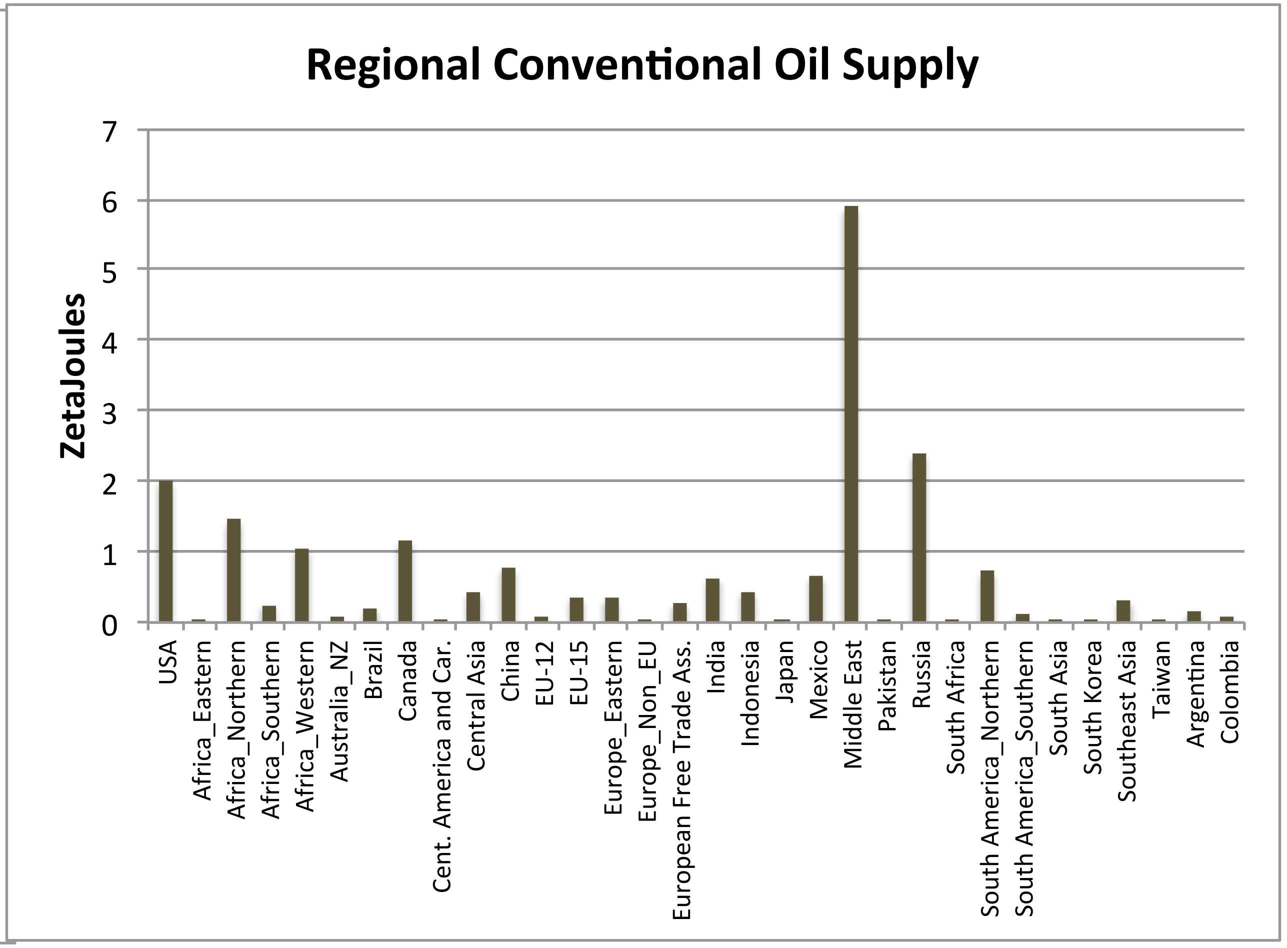
The Energy Sector in GCAM

The Energy System: Structure



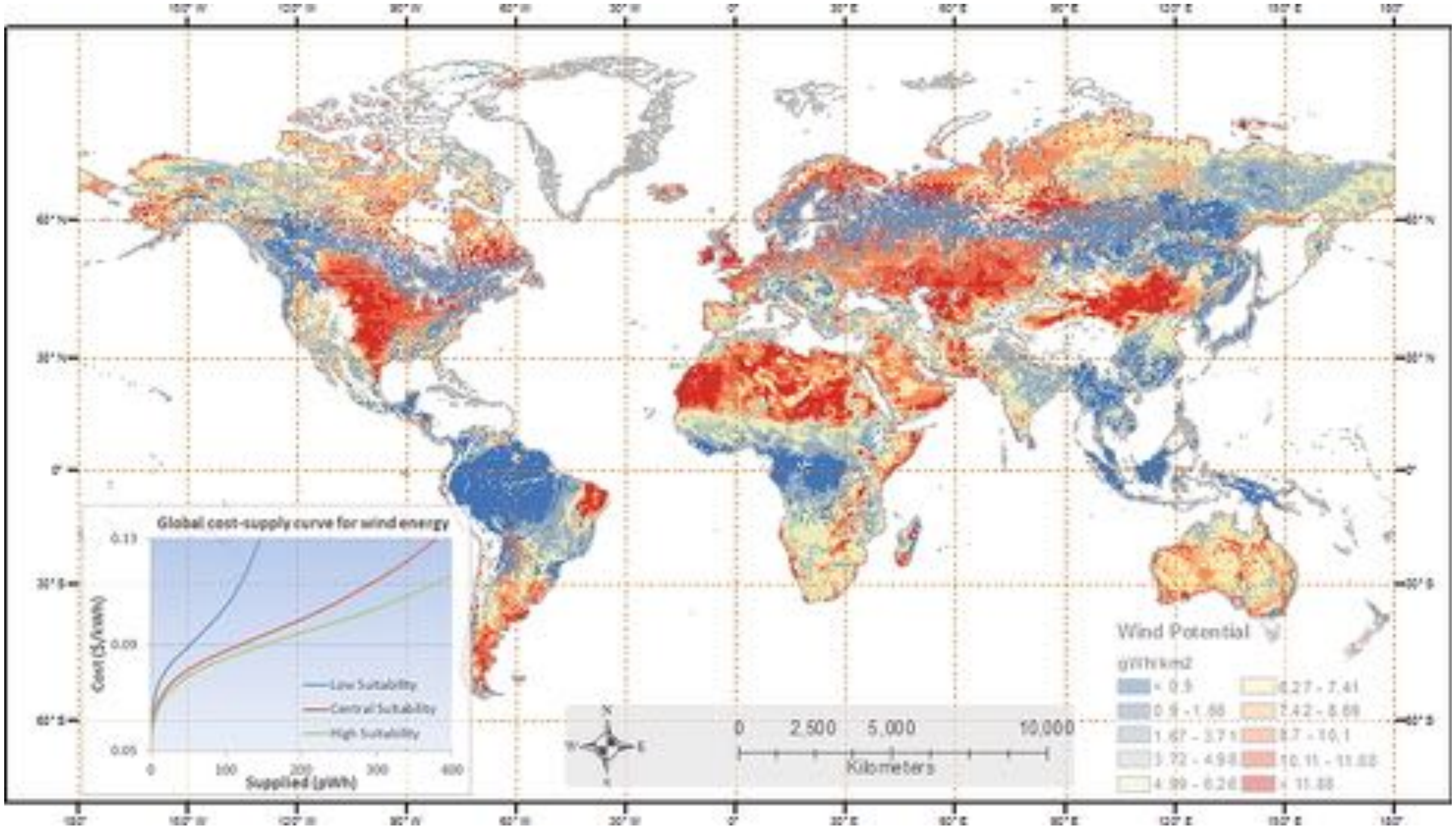
Depletable Resources: Conventional Oil





- Conventional oil, unconventional oil, natural gas, and coal resource supply curves derived from Rogner (1997) global assessment.

Renewable Resources: Wind



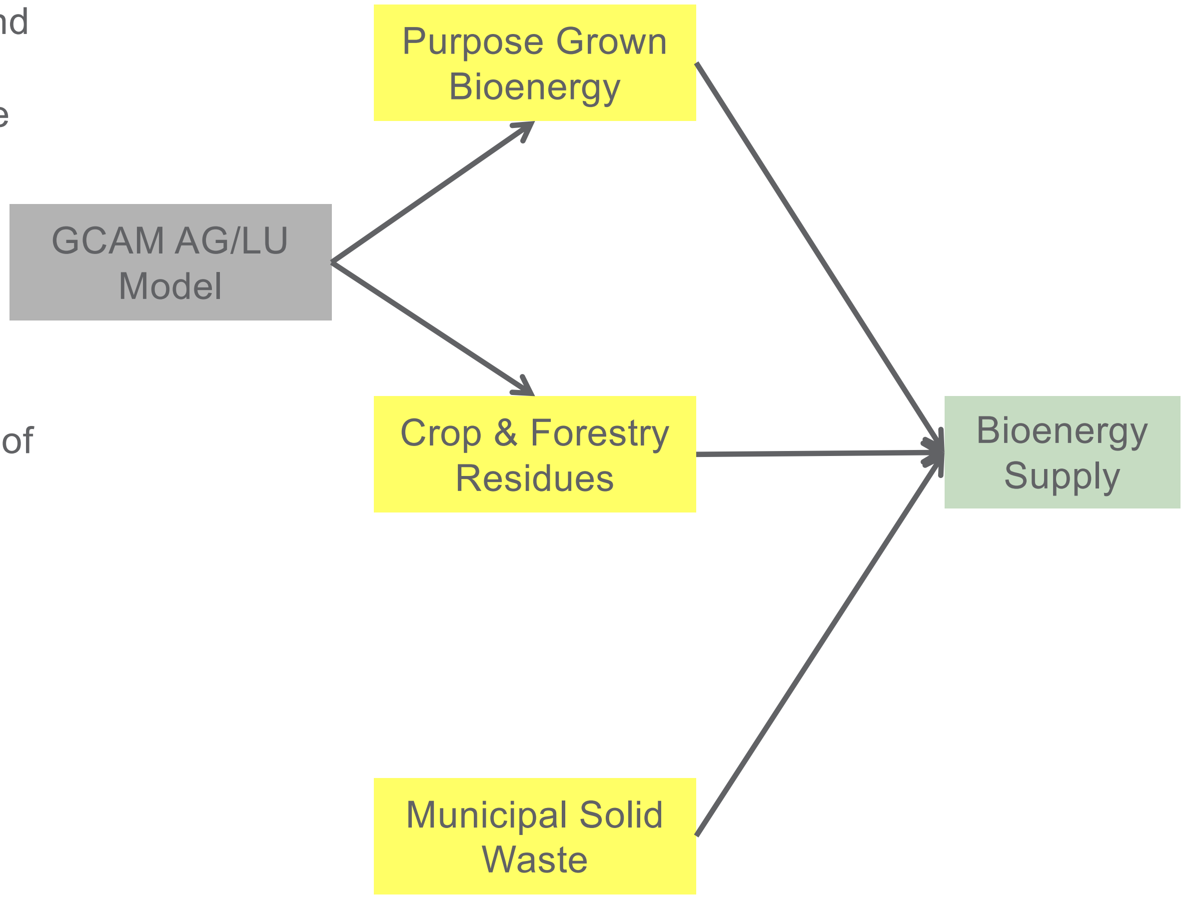
$$Q = maxSubResource * \frac{P^{CurveExponent}}{(MidPrice^{CurveExponent} + P^{CurveExponent})}$$

Bioenergy

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

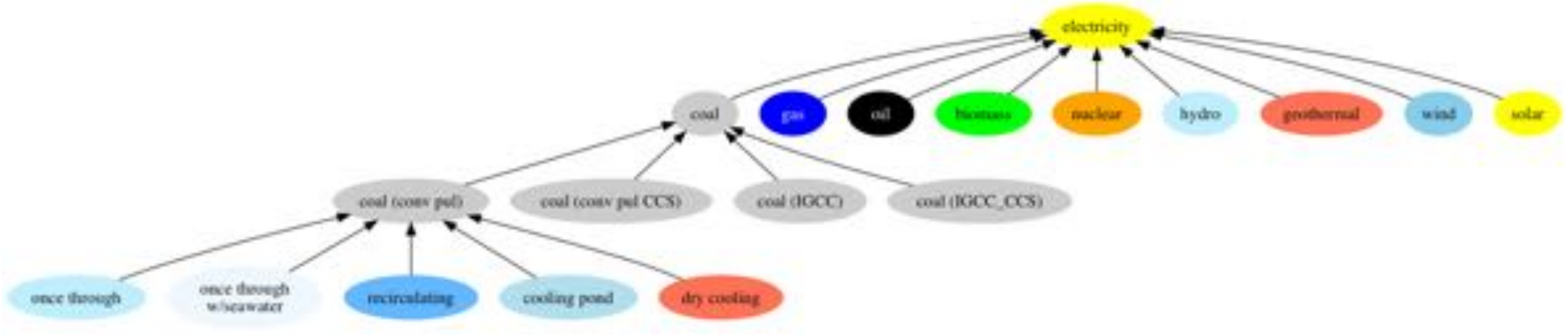
Crop & Forestry Residues:
- Potential production depends on crop production in ag model
- Fraction harvested depends on the price of bioenergy; higher prices lead to more production
- Some amount of residue must remain on the field for erosion control

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.

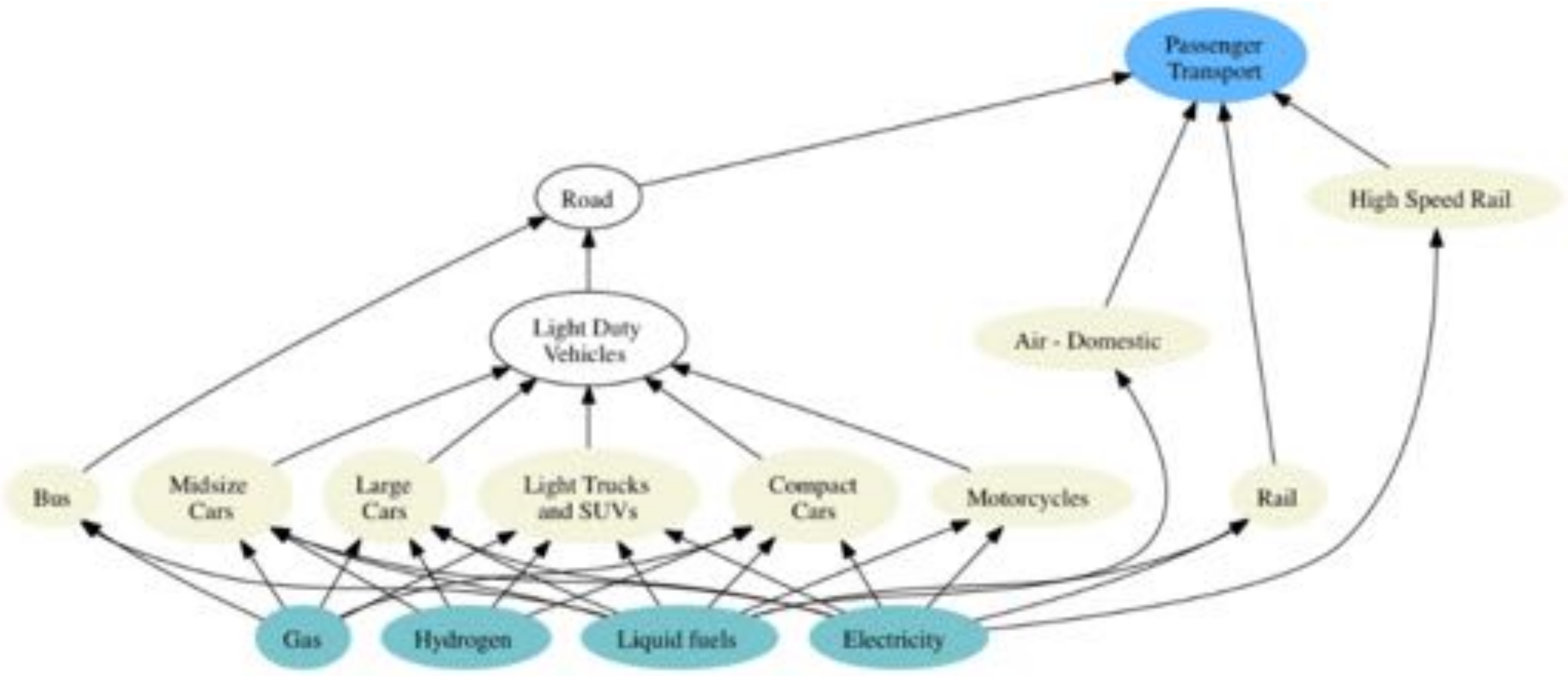
Energy Transformation: Electric Power Sector



- 3 levels of nesting
  - Fuel (coal, gas, etc)
  - Technology (e.g., efficiency level, CCS)
  - Cooling system (thermo-electric techs only)
- Logit choice competition at each nest based on relative levelized costs of electricity generation
  - Capital + fixed O&M + variable O&M
  - Fuel costs, including emissions penalties
  - Backup-related costs for intermittent technologies

Final energy demands: Transportation

- Passenger, freight, international aviation, and international shipping
  - Represented in physical units (passenger-km, tonne-km)



Final energy demands: Transportation (Key Exogenous Inputs)

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- By technology
  - Energy intensity
  - Load factor
  - Non-fuel costs
  - Calibration data

$$P_{j,i,r,t} = \frac{P_{f,r,t} * I_{j,i,r,t} + N_{j,i,r,t}}{L_{j,i,r,t}}$$

P: price
r: region
i: mode
j: technology
t: time period
I: fuel intensity
N: non-fuel cost
L: load factor

- By mode (passenger only)
  - Average speed
  - Valuation of time travelling

$$P_{i,r,t} = \sum_{j=1}^{N} (\alpha_{j,i,r,t} * P_{j,i,r,t}) + \frac{W_{r,t} * V_{i,r,t}}{S_{i,r,t}}$$

α: share of tech j within mode i
W: wage rate
V: time valuation
S: speed

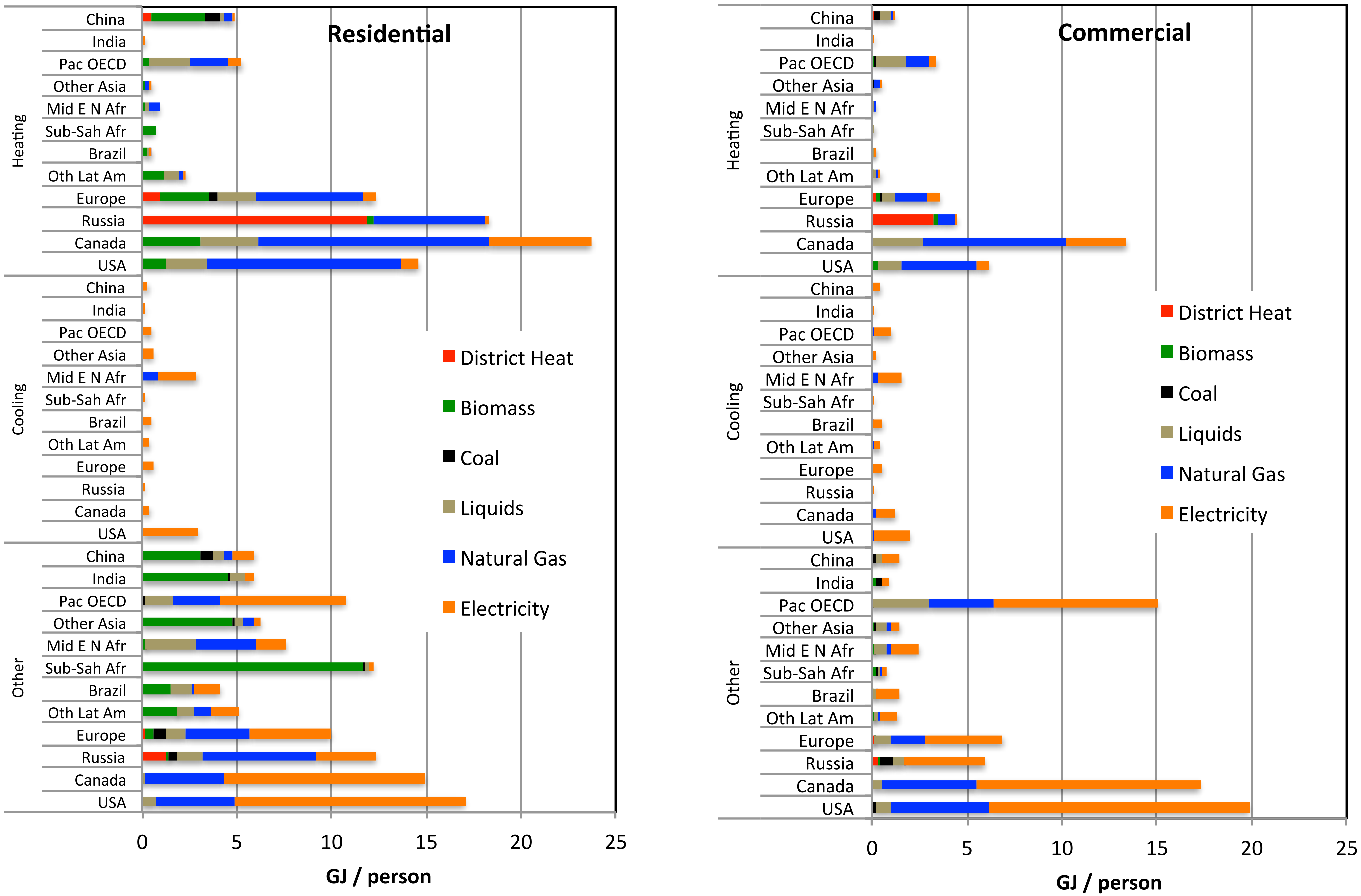
- By sector
  - Income elasticity
  - Price elasticity

$$D_{r,t} = D_{r,t-1} (\frac{Y_{r,t}}{Y_{r,t-1}})^{\alpha} (\frac{P_{r,t}}{P_{r,t-1}})^{\beta} (\frac{N_{r,t}}{N_{r,t-1}})$$

D: demand
Y: per-capita income
P: price
N: population

Final energy demand: Buildings

Per-capita Residential and Commercial Energy Use in 2010



Final energy demands: Buildings
(Key Exogenous Inputs)

- By technology
  - Efficiency
  - Non-fuel cost
  - Calibration data
- By service
  - Satiation level
  - Degree days
  - Shell conductance

$$d_H = k_H(HDD \cdot \eta \cdot R - IG)\left[1 - exp\left(-\frac{ln2}{\mu_H}\frac{i}{P_H}\right)\right]$$

$$d_C = k_C(CDD \cdot \eta \cdot R + IG)\left[1 - exp\left(-\frac{ln2}{\mu_C}\frac{i}{P_C}\right)\right]$$

d: demand
H, C: heating, cooling
h: calibration coefficient
HDD, CDD: degree days
η: shell conductance
R: floor to surface ratio
IG: internal gain heat
i: per-capita income
μ: per-capita income at mid-point of satiation fn

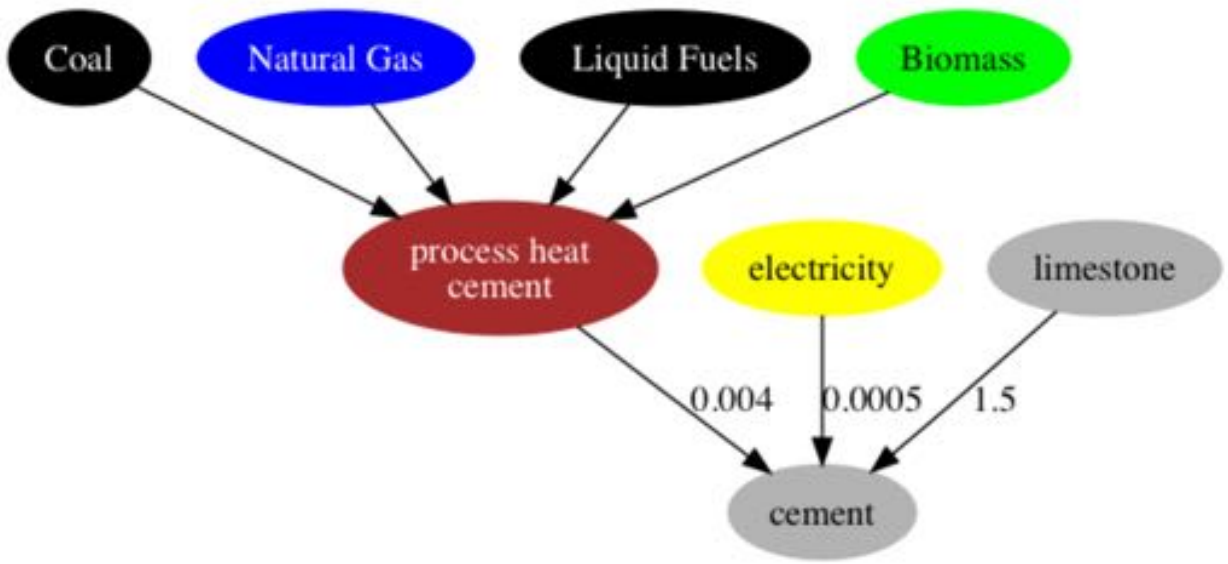
- By sector
  - Floorspace satiation level

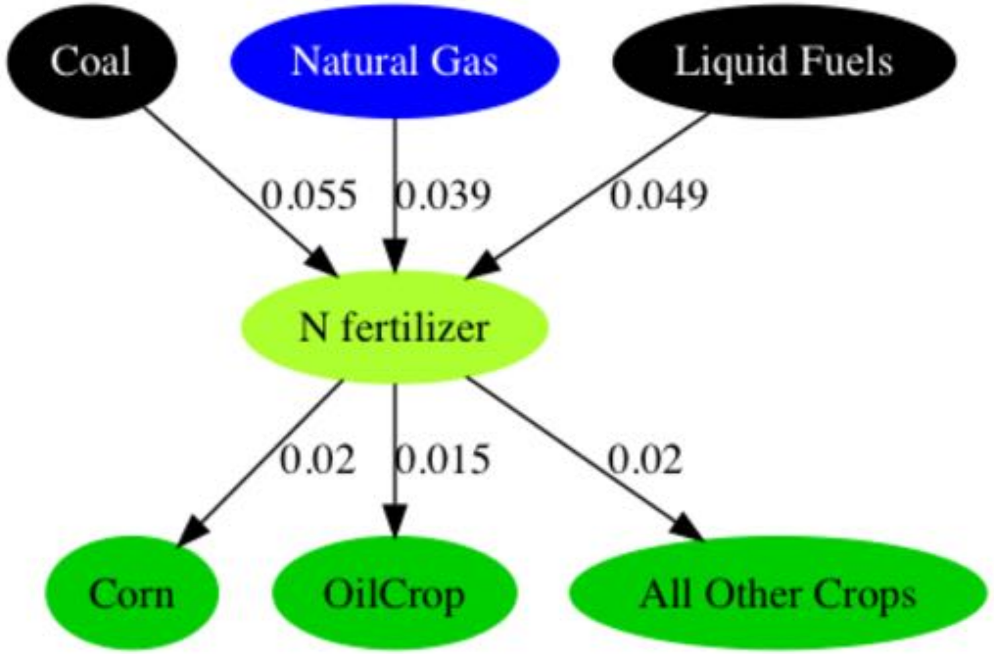
$$d_t = (s - a)\left[1 - \exp\left\{-\frac{ln2}{\mu} I_t \left(\frac{P_t}{P_0}\right)^{\varepsilon}\right\}\right] + a$$

s: satiation level
a: minimum floorspace
P: floorspace price

Final energy demand: Industry

- Most of the industrial sector is modeled in aggregate form
  - Energy demand ~ GDP
- Cement
  - Process-based representation, in physical units
  - Exogenous final demand quantity
- N fertilizer
  - Process-based representation, in physical units
  - Demands driven by inputs to crop production in AgLU





The Water Sector in GCAM

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The Land Sector in GCAM

Inputs and Outputs

Inputs

- Harvested area in historic period
- Land cover in historic period
- Production in historic period
- Consumption in historic period
- Cost of production
- Fertilizer application rates
- Water coefficients
- Carbon density, mature age
- Emissions factors
- Income elasticity of demand
- Price elasticity of demand
- Technical change
- Logit parameters

GCAM

Outputs

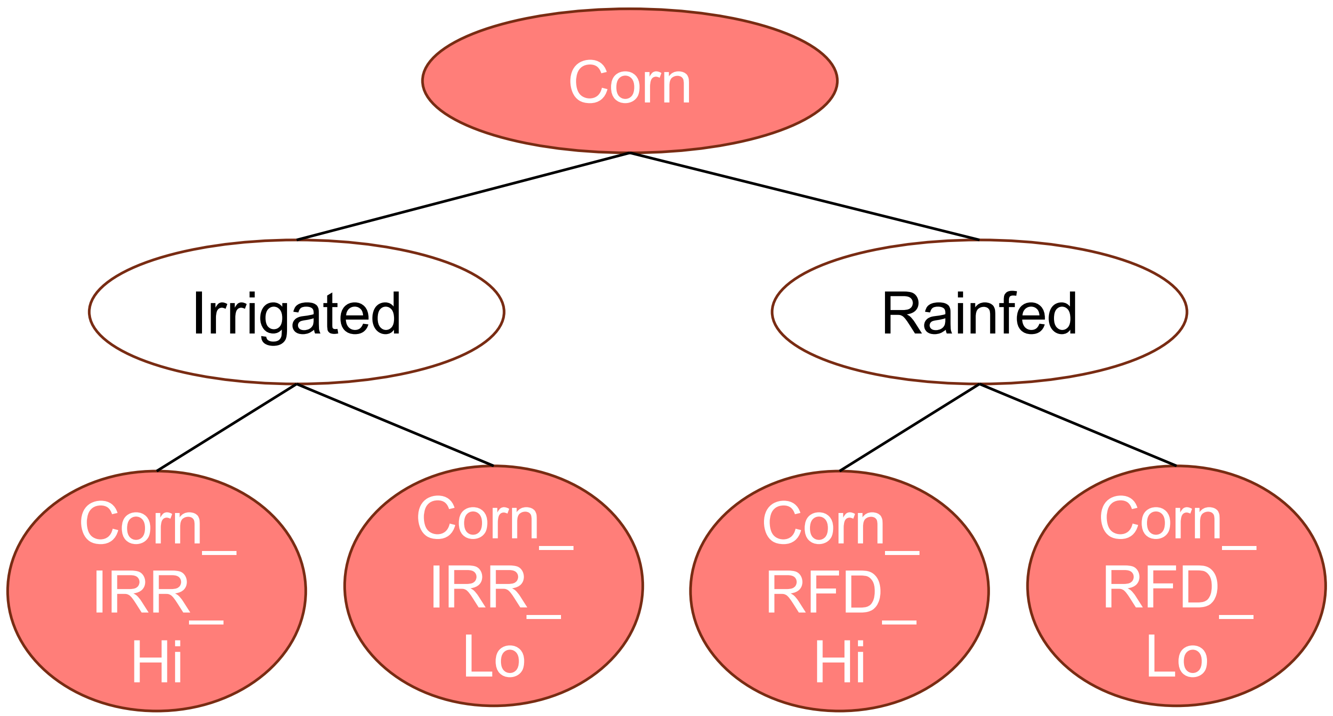
- Production
- Consumption
- Land use, land cover
- Yield
- Price
- Fertilizer use
- Water withdrawals
- Water consumption
- Land use change emissions
- Other land emissions

Agricultural Demand

- GCAM currently models supply and demand for 13 crops, 6 animal categories, and bioenergy.

- We account for both food and non-food demand, including animal feed.
  - Demand for a given commodity changes over time in response to income, its price, and the price of substitutes.
  - Food, feed, and energy uses of crops are price responsive, but the price elasticity of demand for food is relatively small.
  - Demand is modeled at the 32 region level.

Agricultural Technologies



- For each crop, we have four different technologies, each with a different yield, cost, and base year allocation.
- Changes in price or cost will alter the shares of each technology, enabling price-induced intensification.

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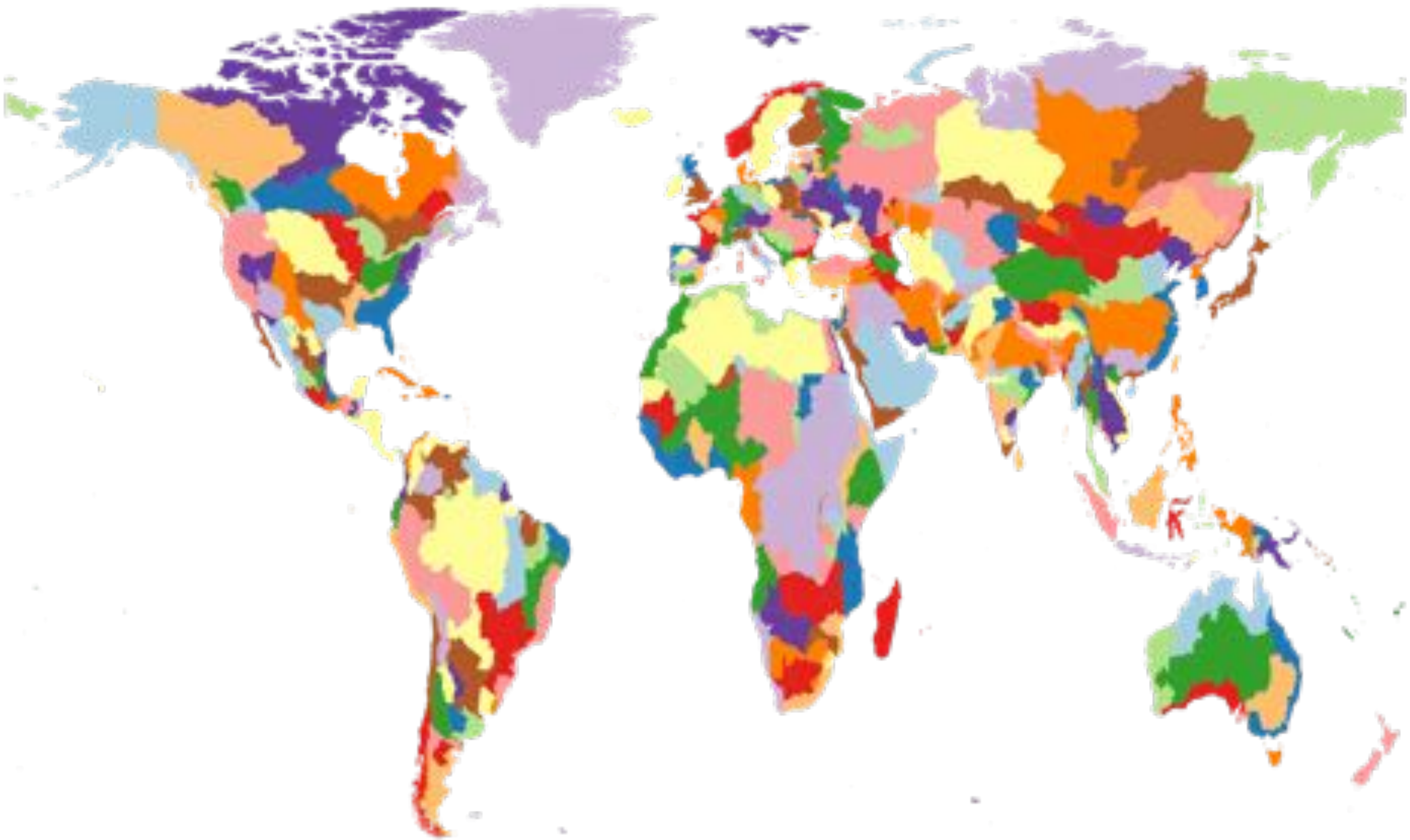
Land Use Regions



GCAM v5 has 384 land use regions, formed by the intersection of geopolitical regions and water basins.

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Land Use and Land Use Change

- The world is divided into **384** 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 384 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

Agricultural Supply

- Yield for each land type/management practice 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 type/management practice's share of area in its region is the probability its profit is the highest in that region.
- Supply = land * yield

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

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The Socioeconomics and Trade in GCAM

Representing Economic Activity

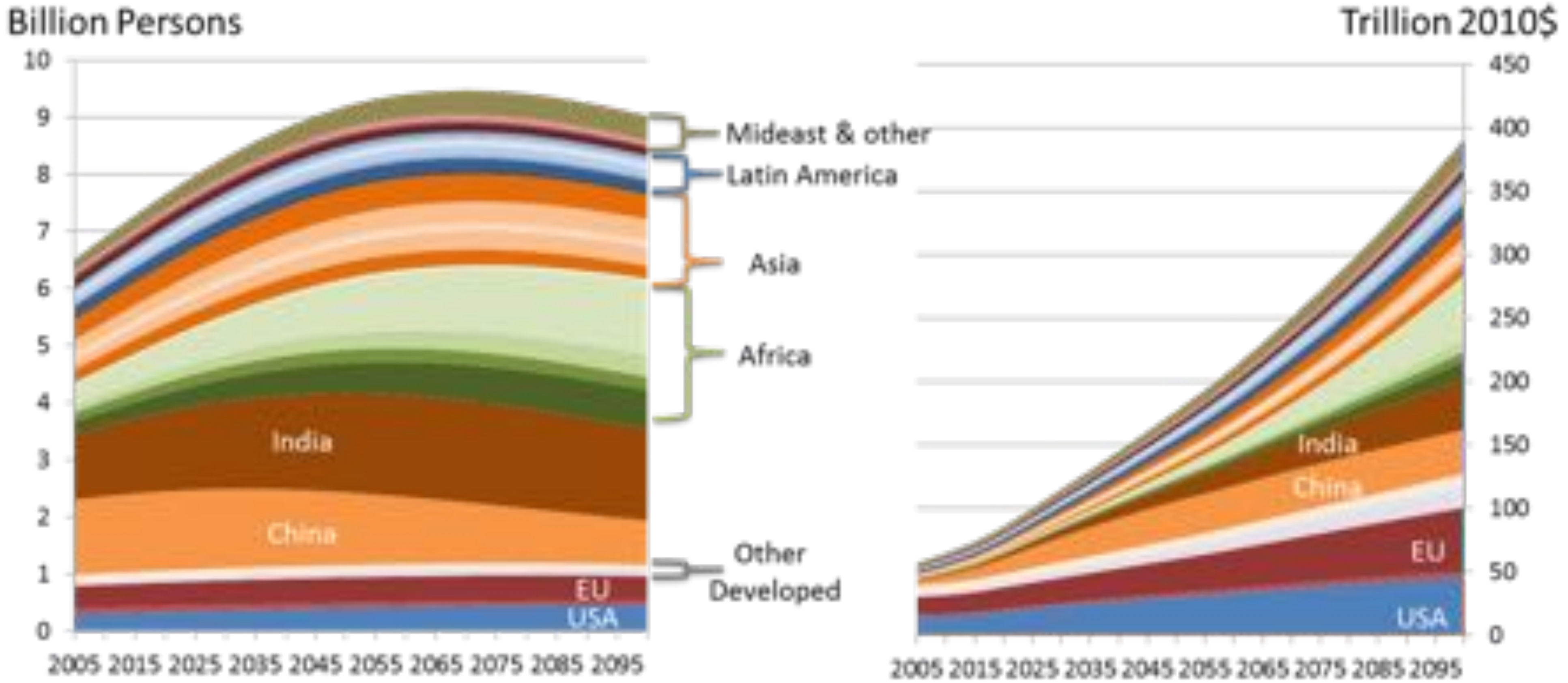
- GDP is a driver in GCAM, based on population and labor productivity, both of which can grow over time

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

- Where:
  - r = region, t = model period, t_step = years in model period
  - POP = population
  - g = annual rate of growth of per capita income

Socioeconomic projections for core version

- GDP and population are based on the Middle of the Road scenario from Shared Socioeconomic Pathways (SSPs).
- These projections are modified in the near-term to reflect near-term trends
- The core version of the model does not explicitly include other SSP assumptions beyond population and GDP, however the full GCAM SSPs are available as part of the release



Trade In GCAM

- Heckscher-Ohlin
  - Commodities such as coal, gas, oil, bio-energy, Corn, Rice, etc are each traded in a single global market.
  - Each region will see the same global price and independently decide how much each will supply and demand of each commodity given that price.
  - A region's net trade position is dynamic depending on economics, technical change, demand, growth, resources, etc.
- Fixed Inter-Region Trade
  - Some commodities such as meat and dairy and trade volumes are simply held fixed at their historical value for the rest of the simulation.
- No Trade of Secondary energy goods
  - Note that secondary energy products such as Electricity or Refined Liquids are assumed to not be traded at all between the 32 GCAM regions.

Emissions in GCAM

GCAM Emissions

GCAM projects emissions 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

Future emissions are determined by the evolution of drivers (such as energy consumption, land-use, and population) and the mix of technologies. How this is represented in GCAM varies by emission type.

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

- CO_2 emissions depend on specific technologies, whose use is explicitly determined by the model.
- The GCAM, in effect, produces a Marginal Abatement Curve for CO_2 as a carbon-price is applied within the model.
- Land-Use Change emissions are tracked separately
  - The above-ground (e.g. vegetation) carbon-content of land converted to forest exponentially approaches an exogenously-specified, region-dependent value.
  - Changes in the carbon content of soils due to land-use change also exponentially approach an equilibrium value

GCAM GHG Emissions: non-CO_2 GHGs

Non-CO_2 greenhouse gases: are modeled as

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

Non-CO_2 GHG emission factors only change due to exogenously specified Marginal Abatement Cost (MAC) curves, which encapsulate the technological detail for abatement that is not otherwise explicitly represented in GCAM.

- Below-zero (e.g. “no cost”) MAC mitigation is phased in even in reference cases.
- Under a carbon policy, the emission factor is reduced, as a function of the carbon price, as specified by the MAC curve.

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GCAM Air Pollutant Emissions

Air Pollutant Emissions (SO_2, NO_x, etc.) are modeled as:

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

Projections use a global parameterization where emission factors decline as a function of GDP per capita

- This species-specific parameterization captures the general global trend of increasing pollutant controls over time.
- This does not capture regional and technological heterogeneity.
- *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).*

Emissions: Base Year Emissions

- CO_2
  - Energy system: we read in global carbon contents for fossil fuels (e.g., coal, gas, oil). These are consistent with values from CDIAC. 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. Additional information for fluorinated gases is from Velders et al.
  - *We are in the process of updating 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*

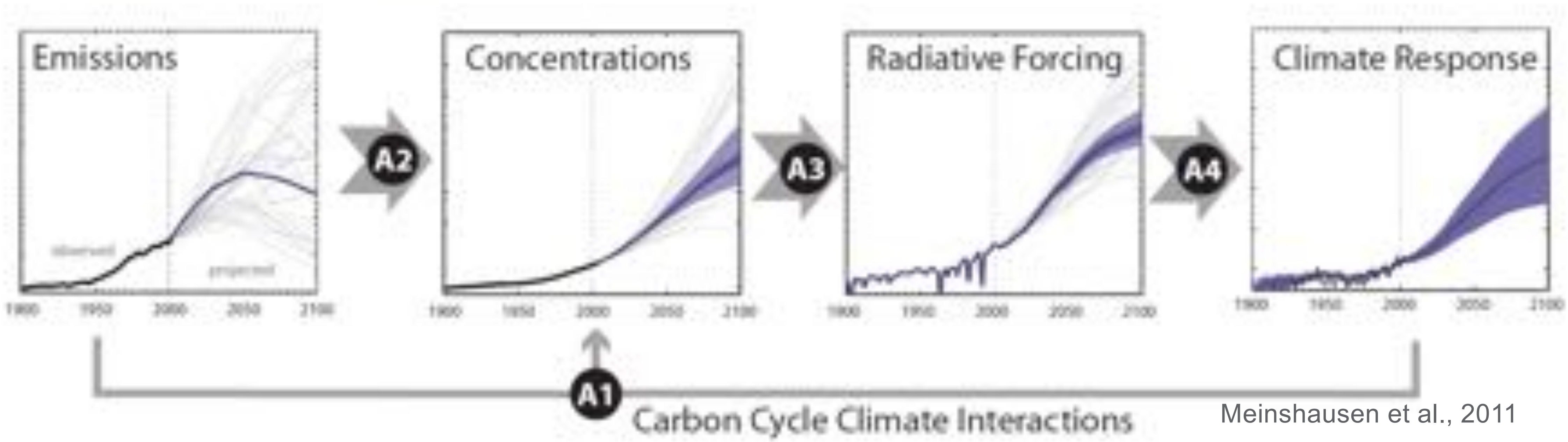
Emissions: Non-CO2 Drivers

- 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 and Land-Use
  - 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 generally not crop specific (or land-class specific) other than for rice production.

The Earth System in GCAM

The Climate System: Approach

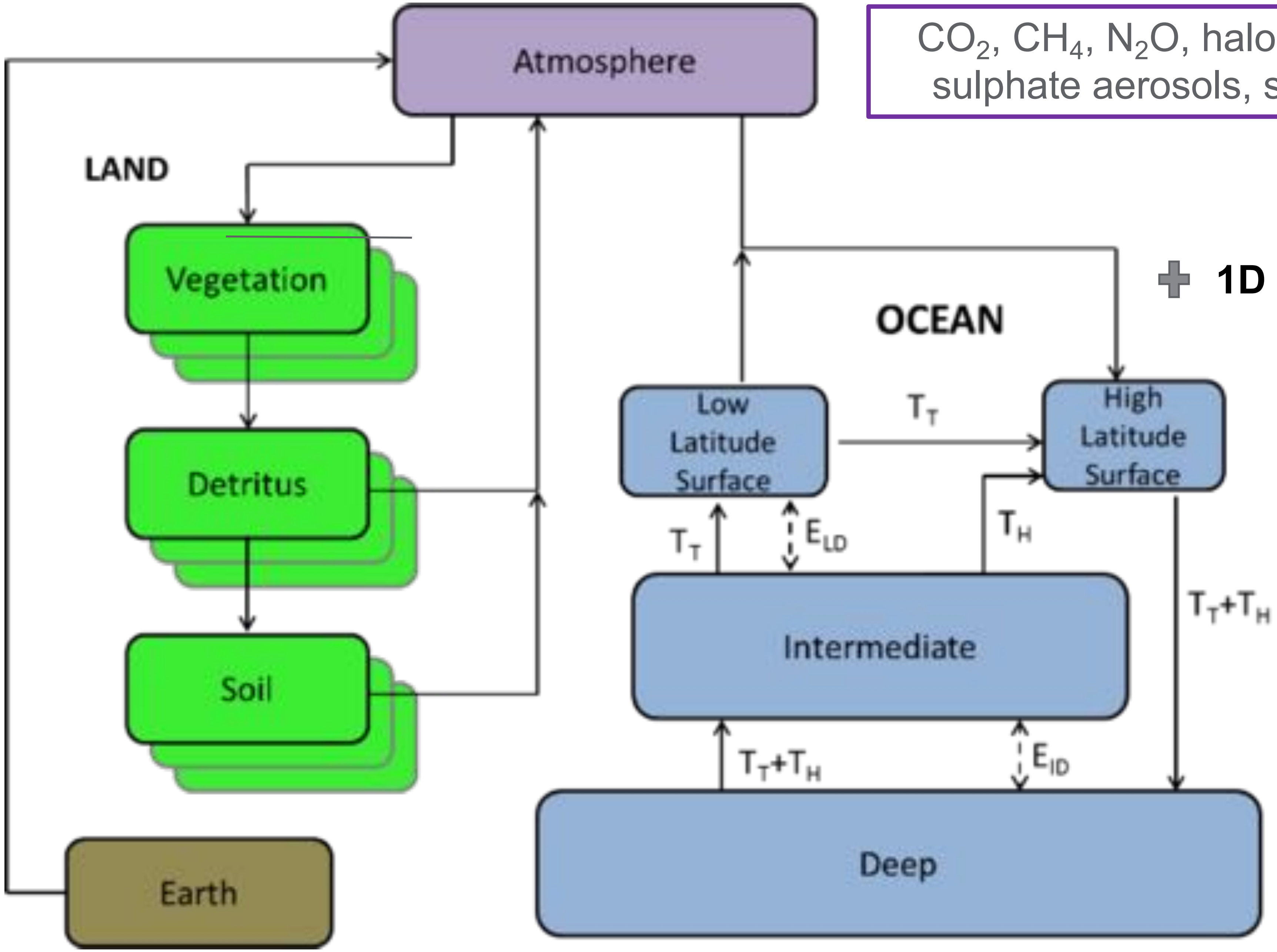
- By default, GCAM now uses the **Hector** (no longer MAGICC) simple carbon/climate model to compute climate related outputs.
- GCAM passes emissions to the climate model
  - Fossil fuel & Industrial CO_2, Land-Use Change CO_2, CH_4, N_2O, 26 halocarbons, SO_2, CO, NO_x, NMVOCs, BC, OC
- Hector computes atmospheric CO_2 concentrations, radiative forcing (direct and indirect), temperature change, air-land/air-sea fluxes, SLR, …



Meinshausen et al., 2011

Overview of Hector's Climate and Carbon Cycle

NPP, R_H, carbon fluxes



CO_2, CH_4, N_2O, halocarbons, BC, OC, sulphate aerosols, strat H_2O, trop O_3

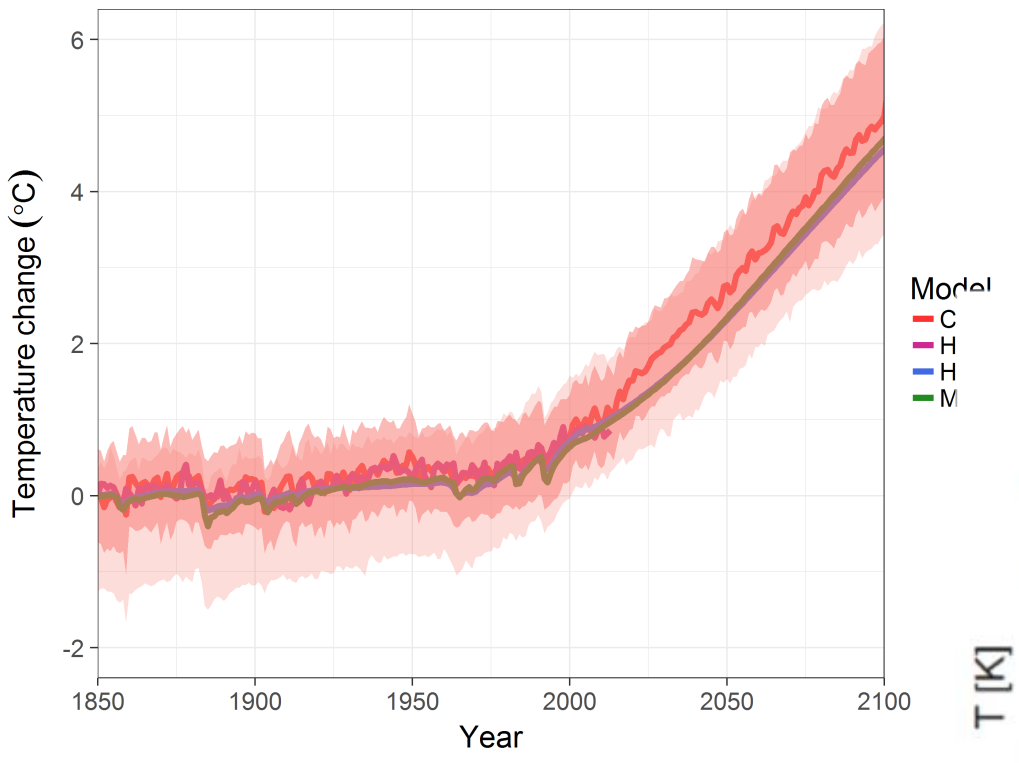
+ 1D diffusive ocean - DOECLIM

pH, $CaCO_3$ saturations, carbon fluxes, heat uptake, SLR

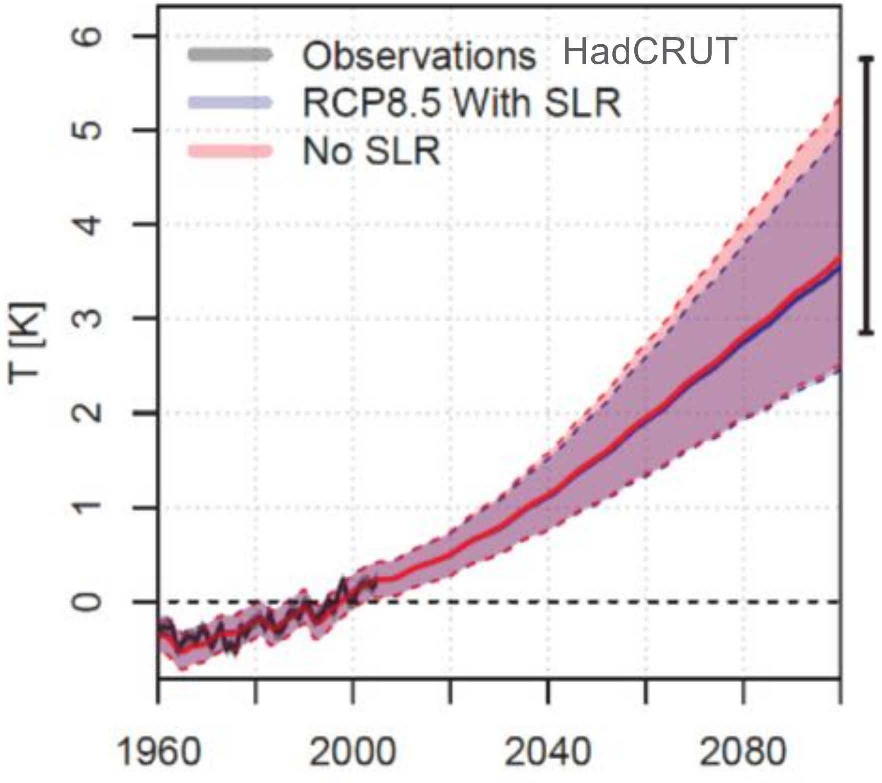
Hartin et al., 2015, 2016
www.Github.com/JGCRI/hector

Hector can track the CMIP5 median and individual models

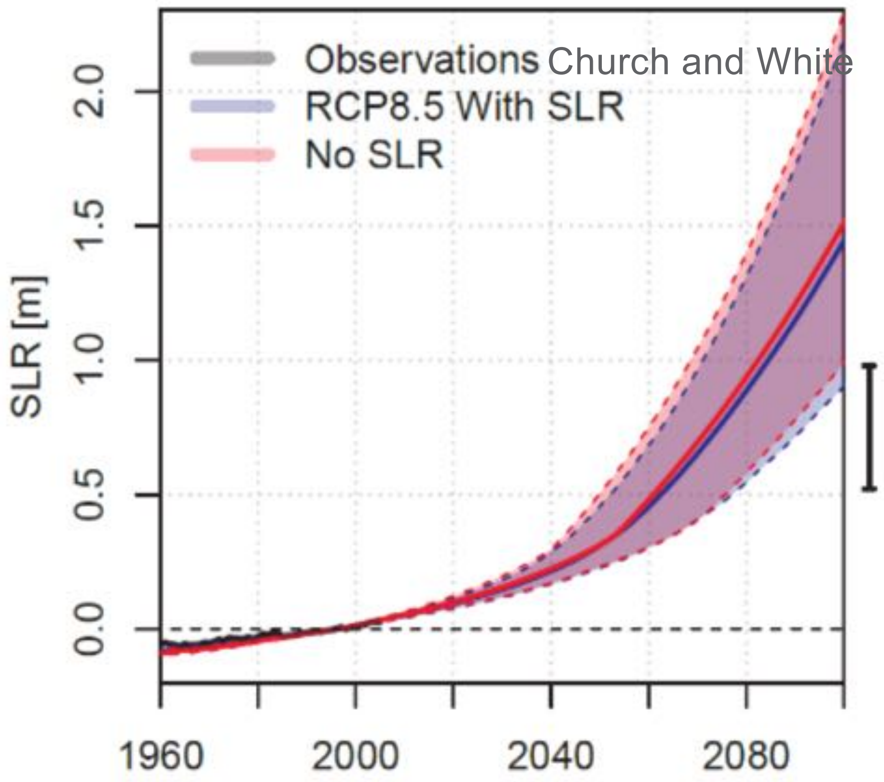
Atmospheric Temperature – RCP8.5



Global Mean Temperature



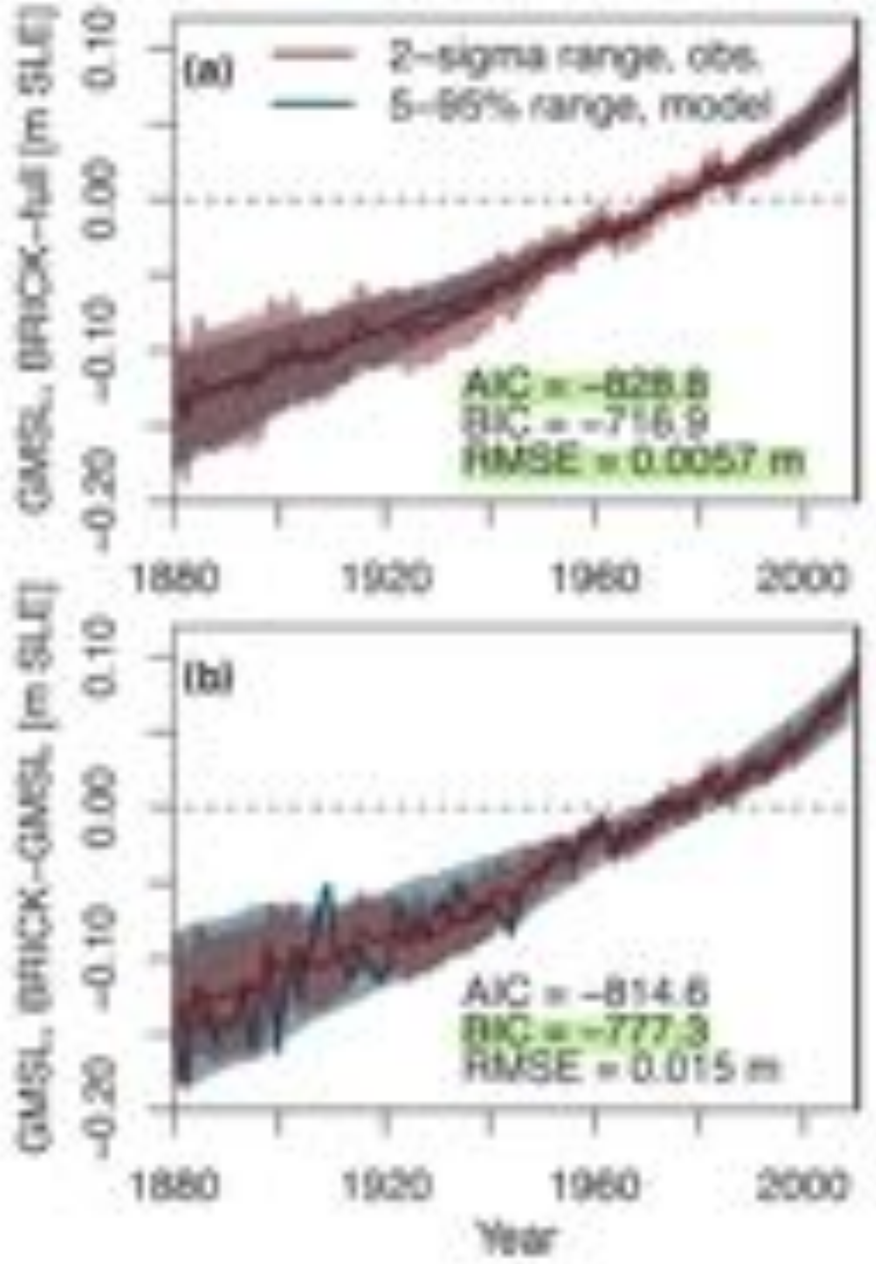
Global Sea-Level Rise



Vega-Westhoff in prep, 2018

Recent Hector developments

- Ben Vega-Westhoff and Ryan Sriver – UIUC
  - DOECLIM – ocean heat diffusion
  - BRICK – sea-level rise model
    - ✓Contributions from Greenland, Antarctica, ice sheets and thermal expansion
- Adria Schwarber (UMD)
  - Fundamental impulse tests



Recent Hector developments

- Hector can now be run as an R package
- One-line installation; help pages; vignettes
- Makes the stand-alone model much more accessible for many users
- Easy to run and integrate into e.g. sensitivity analyses
- Work by Robert Link; demos and vignettes by Alexey Shiklomanov

```
library(hector)
ini_file <- system.file(
  "input/hector_rcp45.ini",
  package = "hector"
)
core <- newcore(ini_file)
run(core)
results <- fetchvars(core, dates = 2000:2100)
head(results)
```

```
##   year variable    value     units
## 1 2000       Ca 362.2546 ppmv CO2
## 2 2001       Ca 363.8910 ppmv CO2
## 3 2002       Ca 365.5739 ppmv CO2
## 4 2003       Ca 367.3020 ppmv CO2
## 5 2004       Ca 369.1146 ppmv CO2
## 6 2005       Ca 371.0644 ppmv CO2
```

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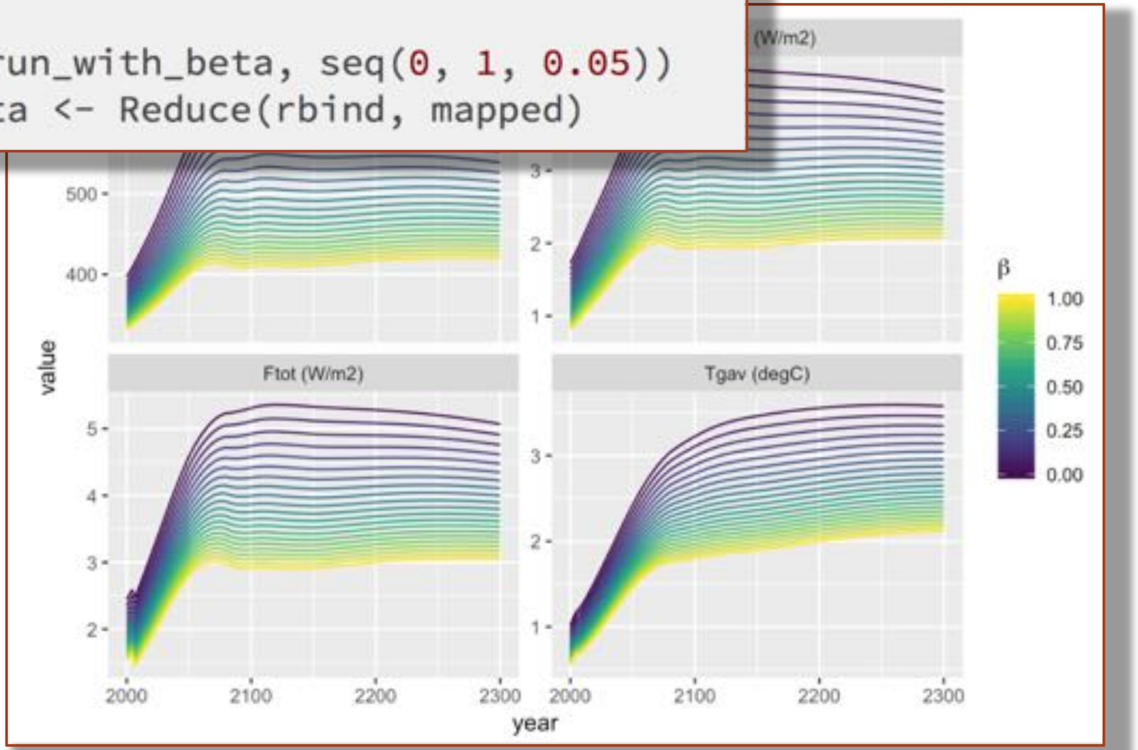
```r
run_with_beta <- function(value) {
  setvar(core, NA, BETA(), value, "(unitless)")
  reset(core)
  run(core)
  result <- fetchvars(core, 2000:2300)
  result[["beta"]] <- value
  result[["variable_unit"]] <- with(result, {
    sprintf("%s (%s)", variable, units)
  })
  result
}

mapped <- Map(run_with_beta, seq(0, 1, 0.05))
sensitivity_beta <- Reduce(rbind, mapped)
```



Implementing Policies in GCAM

Emissions-Related 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, GHGs, or any other substance)
  - 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-Related 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.

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Land-Related Policies

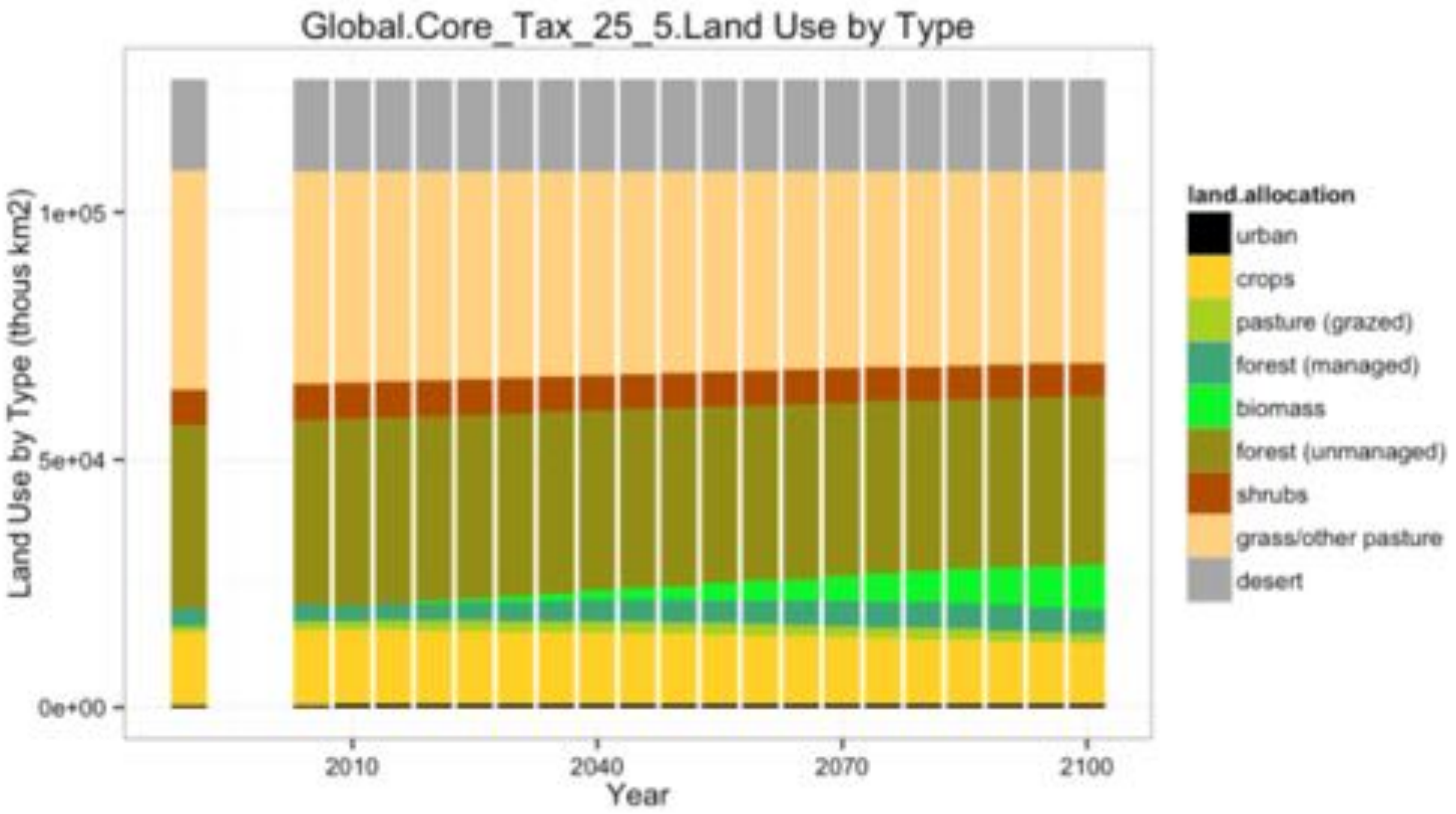
- Protected Lands (REDD):
  - With this policy, we can set aside some land, removing it from economic competition. This land cannot be converted to crops, pasture, or any other land type.
  - The default in GCAM is to protect 90% of all non-commercial ecosystems.

- Valuing carbon in land:
  - In a policy regime, we can choose to put a price on land-use change CO2 emissions that is equal to the price on fossil fuel and industrial CO2 emissions.
  - We model this policy as a subsidy to land-owners for the holding carbon stocks.

- Bioenergy constraints (upper or lower):
  - We can impose constraints on bioenergy within GCAM. Under such a policy, GCAM will calculate the tax or subsidy required to ensure that the constraint is met.
  - By default a bioenergy constraint in GCAM is imposed based on the amount of subsidy available for net negative emissions.

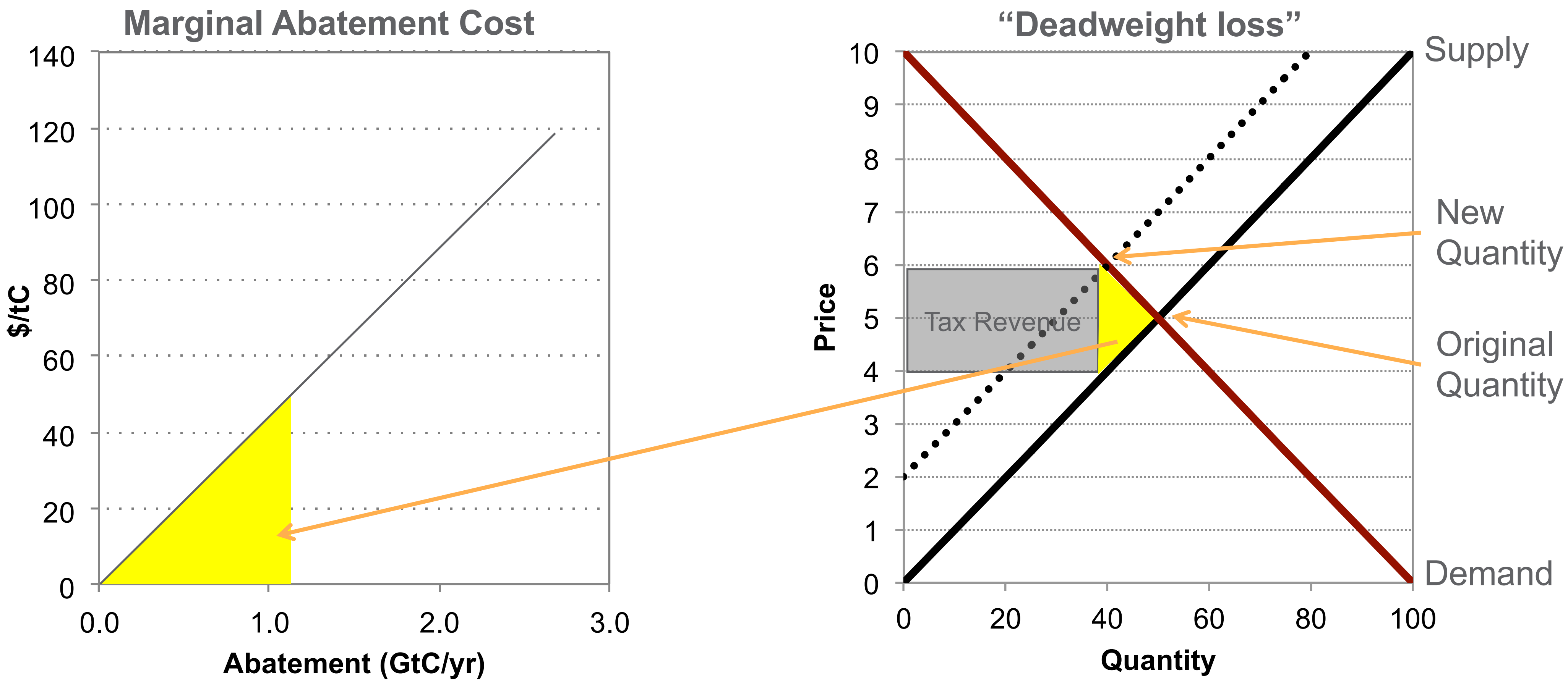
Land-Related Policies

- 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.



Policy Cost Calculation

- GCAM can compute the cost of a some policies.
- 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.



Treatment of Existing Policies in GCAM

- 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.

Thank you