Overview of the Global Change Assessment Model (GCAM)

THE JGCRI GCAM TEAM

Joint GCAM Community Modeling Meeting and GTSP Technical Workshop
Joint Global Change Research Institute
College Park, Maryland, USA
Thursday, October 13, 2016
Outline

- Brief introduction to Integrated Assessment Models
- Overview of GCAM
- Detailed information on GCAM’s
  - Socioeconomics,
  - Energy,
  - Agriculture and land use,
  - Policies,
  - Emissions
  - Climate
- Discussion
INTRODUCTION TO IA MODELS
What is an Integrated Assessment (IA) Model?

IAMs integrate representations of multiple human and natural Earth systems.

- IAMs provide insights that would be otherwise unavailable from disciplinary research.
- IAMs capture interactions between complex and highly nonlinear systems.
- IAMs provide natural science researchers with information about human systems such as GHG emissions, land use and land cover.
- IAMs support national, international, regional, and private-sector decisions.
The Global Change Assessment Model (GCAM) is a “High-Resolution” IA Model

<table>
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<tr>
<td>AIM</td>
<td>National Institutes for Environmental Studies, Tsukuba Japan</td>
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<td>GCAM</td>
<td>Joint Global Change Research Institute, PNNL, College Park, MD</td>
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<td>IGSM</td>
<td>Joint Program, MIT, Cambridge, MA</td>
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<td>IMAGE</td>
<td>PBL Netherlands Environmental Assessment Agency, Bildhoven, The Netherlands</td>
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<tr>
<td>MESSAGE</td>
<td>International Institute for Applied Systems Analysis; Laxenburg, Austria</td>
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<td>REMIND</td>
<td>Potsdam Institute for Climate Impacts Research; Potsdam, Germany</td>
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General Characteristics of High-Resolution, Global IA models

- High-resolution, global IA models are:
  - Global in scope,
  - Include representations of energy and agricultural/land use systems
  - Include all anthropogenic sources of emissions,
  - Include some representation of the climate system.

- However, there is significant variation across models as to their:
  - Spatial resolution
  - Inclusion of gases and substances
  - Energy system detail
  - Representation of agriculture and land-use
  - Economic assumptions
  - Degree of foresight
  - Sophistication of the climate model component
  - Degree of integration of model components
Integrated Assessment Research and Model Development is Problem Driven

1980’s

Projections of emissions and concentrations

energy-economy-climate
Integrated Assessment Research and Model Development is Problem Driven

1980’s
Projections of emissions and concentrations

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

Value of Technology

Cumulative Carbon Emissions and Cumulative Compliance Cost across Scenarios

Carbon Prices

Energy Systems
Integrated Assessment Research and Model Development is Problem Driven

1980’s
Projections of emissions and concentrations

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

2000’s
Mitigation and land use
Land Use Change
Emissions

Crop production and land use changes

ENERGY-ECONOMY-land-climate
Examples of Current Questions for the IA Community

- Type 1: Where are the NDCs taking us? How to implement and ramp up action? What’s actually realistic for different countries?

- Type 2: How will these mitigation activities link to the other societal goals (e.g., SDGs)? Will they be limited by energy-water-land constraints?

- Type 3: How can we plan investments and strategy taking into account climate impacts and a broad range of additional stressors and dynamics?

- Type 4: Where are the biggest future climate-related national security risks, domestically and internationally?

Can you help us interpret and understand this stuff? What’s the confidence in any of this?

Incorporating climate impacts, adaptation, and vulnerability

Increased “realism”, particularly with regards to regional dynamics
GCAM has a long history…

- GCAM was one of four models chosen to create the representative concentration pathways (RCPs) for the IPCC’s AR5.
- GCAM was one of six models chosen to create the shared socioeconomic pathways (SSPs).
- GCAM was one of three models used to create scenarios for Climate Change Science Program (CCSP).
- GCAM was a prominent tool for analysis in the Climate Change Technology Program (CCTP).
- GCAM has participated in virtually every major climate/energy/economics assessment over the last 20 years:
  - Every EMF study on climate
  - Every IPCC assessment
- GCAM has been used for strategic planning by energy and other private companies.
- GCAM is now used by research institutions and governments internationally.
The Global Change Assessment Model

- GCAM is a **global integrated assessment model**
- GCAM links **Economic**, **Energy**, **Land-use**, **Water**, and **Climate** systems
- Runs in **5-year time-steps**.
- Meant to analyze consequences of policy actions and interdependencies
- GCAM is a community model
- Documentation available at: [wiki.umd.edu/gcam](http://wiki.umd.edu/gcam)
- Used to evaluate impacts of these threads:
  - Socioeconomic development
  - Climate mitigation and impacts
  - Technology and resource developments
  - Energy policies
What do IA Models do?

Scenario Assumption
- Population
- Labor Productivity
- Technology Characteristics
- Policies

Model Equations, Relationships, and Parameters

Modeled Scenario
- Population
- Labor Productivity
- Technology Characteristics
- Policies
- Emissions
- Prices
- Energy Supplies and Demands
- Agricultural Production
- Land Use
- Concentrations and Temperature
What is GCAM?
What is GCAM?

- What does it do?
- How does it work?
- What kinds of questions can it answer?
- What’s new in this release?
What is GCAM?

- GCAM is a **global integrated assessment model**
- GCAM links Economic, Energy, Land-use, Water, and Climate systems

- Runs in **5-year time-steps**.
- Meant to analyze consequences of policy actions and interdependencies

- GCAM is an open-source community model
- Documentation available at: [wiki.umd.edu/gcam](http://wiki.umd.edu/gcam)
- Used to evaluate impacts of these threads:
  - Socioeconomic development
  - Climate treaty compliance
  - Technology and resource developments
  - Energy policies
What’s inside GCAM?

**ENERGY SYSTEM**
- **Energy Supply**
  - Coal, Gas, Oil
  - Renewables
  - Electricity
  - Hydrogen
- **Energy Demand**
  - Transportation
  - Buildings
  - Industry
- **Energy Markets**
  - Fossil fuel prices
  - Electricity prices
  - Hydrogen prices
  - Bioenergy prices

**ECONOMY**
- **Regional GDP**
- **Agricultural Demand**
  - Crops
  - Livestock
  - Forest Products
- **Agricultural Supply**
  - Crops
  - Livestock
  - Forest Products
  - Bioenergy
- **Agricultural Markets**
  - Crops prices
  - Livestock prices
  - Forest Product prices
  - Bioenergy prices

**CLIMATE SYSTEM**
- **Fossil and Industrial Emissions**
- **Land Use and Land Use Change Emissions**
- **Land Use & Land Cover**

**AGRICULTURE AND LAND USE**
- **Carbon Cycle**
- **Atmosphere**
- **Ocean**
- **Land**
- **Concentration, forcing calculations**
- **Other things (aerosols, sea level, ...)**
The Solver Algorithm

- Start with a vector of initial guess prices $\vec{P}$
- The main body of GCAM calculates demand disequilibrium $\vec{E}(\vec{P})$
  - This part can be run multithreaded.
- Solve: $\vec{E}(\vec{P}) = 0$
  - Broyden’s method solver.
  - Numerous heuristics to improve solver convergence.
  - Iteration step can be calculated either with LU decomposition or SVD (use the latter if you can).
- Result:
  - Equilibrium prices
  - Quantities, market shares, land use, resource depletion, etc.
Common question:
- Does GCAM include foresight?

Answer:
- For long-term investment decisions, we assume that decision-makers think about the future. That is, they may consider the costs and profits over the full lifetime of an electricity generation unit before building.
- However, we are myopic in that we use current prices when making these decisions.
- Decision-makers do not know future prices!

Frequently Asked Questions

► Common question:
  ■ Does GCAM optimize?

► Answer:
  ■ Not exactly.
  ■ GCAM is a market equilibrium model, so it adjusts prices until supplies and demands are equal.
  ■ However, GCAM assumes that producers maximize profit and consumers minimize cost.
  ■ And, under certain conditions, welfare economics tells us that market equilibria are (Pareto) optimal.
  ■ GCAM is not intertemporally optimizing.
What can you do with GCAM?

- **Prices and production quantities:**
  - Energy sectors
  - Transportation
  - Primary energy resources
  - Agricultural products

- **Land use**
  - Crops (by type)
  - Pasture
  - Unmanaged

- **Water demand**
  - Raw demand by sector
  - Response to scarcity

- **Greenhouse gases**

- **Economic cost of policies**
  - Economic loss
  - Income transfer
Deep Regional Dives in GCAM

2005 Electricity Demand by Province (TWh)
What’s new in GCAM?

- Hector is now the default climate model.
- Near-term population and GDP adjusted to match IMF projections for all included scenarios.
- Users can now configure GCAM to save only the results they plan to use.
- Updates to electricity and liquid fuel sector costs, reflecting recent literature.
- Various performance (i.e., speed) enhancements.
- Various minor bug fixes.
THE MACRO-ECONOMY IN GCAM

2016
Core GCAM structure: The Macro-economy
The Macro-economy in the present release version

\[ GDP_{r,t+1} = POP_{r,t+1} (1 + GRO_{r,t}) \uparrow tStep \left( \frac{GDP_{r,t}}{POP_{r,t}} \right) P_{r,t+1} + \alpha \]

- \( r = \text{region, } t = \text{time period} \)
- POP = population,
- GRO = rate of growth of per capita income
- P = aggregate price of energy service
- \( \alpha = \text{GDP feedback elasticity} \)

Note that the GDP feedback elasticity is set to zero in default mode.
GCAM 4.3 is moving to SSP2 population and GDP

- Middle of the Road scenario from Shared Socioeconomic Pathways:

- Near-term GDP growth is adjusted to reflect economic stagnation in several countries.

- Current release does not include other SSP assumptions beyond population and GDP.
The Global Change Assessment Model

**ENERGY SYSTEM**
- **Energy Supply**
  - Coal, Gas, Oil
  - Renewables
  - Electricity
  - Hydrogen
- **Energy Demand**
  - Transportation
  - Buildings
  - Industry

**CLIMATE SYSTEM**
- Energy Markets
  - Fossil fuel prices
  - Electricity prices
  - Hydrogen prices
  - Bioenergy prices
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)
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
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).
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
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 \([3]\).

\begin{itemize}
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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.
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: Electricity Generation

- Refined Liquids
- Bioenergy
  - Coal
- Natural Gas
- Nuclear
- Hydro
- Solar
- Wind
- Geothermal

Electric Power 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

\[ S_i = \frac{\alpha_i c_i^\sigma}{\sum_j \alpha_j c_j^\sigma} \]


Change in technology shares when tech 1’s cost increases by 20%
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.
The Energy System: Energy Demand

We have detailed representations of transportation & buildings in all regions.
Per capita transportation service demands (measured in km/yr) are a function of income and the prices of services.
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 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

**LDV Ownership rates**

**LDV age distribution in 2030**

**Weighted average transit speed**
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

![chart of residential heating and cooling energy use](chart.png)
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

![Image of bar chart showing energy use by region and year, with color-coded bars for different types of energy sources: electricity, heat, liquids, gas, coal, biomass.]
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

- Geothermal
- Solar
- Wind
- Hydro
- Biomass
- Nuclear
- Oil
- Gas
- Coal

Primary/Final Coefficient (EJ/yr)
- 1990: 0
- 2010: 1
- 2020: 2
- 2030: 3

Intensity
Frequently Asked Questions

**Common question:**
- Why are some of the energy prices in GCAM lower than recent history or other projections?

**Answer:**
- We are a long-term equilibrium model. We do not attempt to capture short-term market fluctuations or market behavior.
- In the case of oil, we do not sustain higher oil prices because the cost of substitutes (e.g., CTL, GTL) is lower than the current market price.
The Global Change Assessment Model

ENERGY SYSTEM

CLIMATE SYSTEM

ECONOMY

AGRICULTURE AND LAND USE

Agricultural Demand
- Crops
- Livestock
- Forest Products

Agricultural Supply
- Crops
- Livestock
- Forest Products
- Bioenergy

Agricultural Markets
- Crops prices
- Livestock prices
- Forest Product prices
- Bioenergy prices

Land Use & Land Cover
The Agricultural System: Demand

- GCAM currently models supply and demand for 12 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 (e.g., hay, alfalfa), roots & tubers, fruits & vegetables
  - Animals: beef, dairy, pork, poultry, sheep/goat, other
  - Forest: roundwood
  - Bioenergy: switchgrass, miscanthus, jatropha, willow, eucalyptus, corn ethanol, sugar 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 Agricultural System: Technologies

For each crop and region, we have started with 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
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

- Land
  - Tundra
  - Rock, Ice, Desert
  - Arable Land
  - Urban

- Non-Pasture
  - Grass and Shrubs
    - Grass land
    - Shrub land
  - Crops
  - Other arable land

- Pasture
  - Other Pasture
  - Intensively-Grazed Pasture
  - Commercial Forest
  - Forest

Gray = Exogenous
Green = Non-commercial
Red = Commercial
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 \( \times (p - c) \)) 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.
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%
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

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

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

Beef Consumption by Region

Global Beef Feed

- Scavenging_Other
- FodderHerb_Residue
- Pasture_FodderGrass
- FeedCrops
The Agricultural System: Results

Wheat Production by Region

Wheat Production in the USA
The Agricultural System: Results

Wheat Consumption by Use

Mt/yr

NonFoodDemand_Crops
FoodDemand_Crops
FeedCrops
The Agricultural System: Results

![Global Core Reference Land Use by Type](chart.png)

- **Land Allocation**
  - urban
  - crops
  - pasture (grazed)
  - forest (managed)
  - biomass
  - forest (unmanaged)
  - shrubs
  - grass/other pasture
  - desert

- **Years**: 2010, 2040, 2070, 2100

- **Land Use by Type**: thousands of km²

- **Scales**:
  - Y-axis: 1e+05, 5e+04, 0e+00
  - X-axis: 2010, 2040, 2070, 2100
The Global Change Assessment Model

ENERGY SYSTEM

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- Energy Demand
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  - Buildings
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ENERGY MARKETS

- Fossil fuel prices
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ECONOMY

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Agricultural Supply

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LAND USE & LAND COVER

Resource Bases

Energy Conversion Technologies

Energy Demand Technologies

Agricultural Technologies

Land Characteristics

AGRICULTURE AND LAND USE
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
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.

![Global fertilizer production by fuel](image)
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](chart.png)
Introduction to the Global Change Assessment Model (GCAM)

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► Brief introduction to Integrated Assessment Models

► Overview of GCAM

► Detailed information on GCAM’s
  ■ Economic assumptions,
  ■ Energy system,
  ■ Agriculture and land use system,
  ■ Emissions,
  ■ Policies,
  ■ Climate system, and
  ■ Solution algorithm.

► Frequently asked questions
POLICY MARKETS
The Global Change Assessment Model
Other Markets: Climate Policy

- **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 (CO₂ 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)
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.
Other Markets: Land-Use Policy

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

► Common 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
Current Approach to Modeling Trade

► In general, we model Heckscher-Ohlin trade. We have not focused on bilateral trade.

► 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.

► 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.
Interregional Trade: the case of Bioenergy

We model large scale bioenergy systems

- Collection and Processing
  - Pelletizing important to increase the energy density of the fuel and facilitate transportation
  - Average cost to transport to local collection facility and pelletize of $2.18/GJ (2005$)
    - 85% of cost is in pelletizing
    - compare to $1.33/GJ for Coal (Edwards).
  - International transport cost of $0.31/GJ (2005$) added to all regions (assumes large ocean bulk carriers)

(Van Vliet, 2009, consistent with Wolf 2006)
Future Goals and New Approaches in Development for Modeling Trade

- We have several recent efforts where we have either goals or plans to go beyond the simple global market approach.
  - Dynamically combine regionally differentiated product markets with global or multiregional markets.
  - Allow ability to model effect of regional isolation or difficulty in participating in inter-regional markets (e.g., short-term constraints to imports).
  - Unlike some Armington implementations, allow long-term dynamic change of regional product import/export positions in response to economics.

- We have initial implementations differentiating demand from domestic and global (or extra-regional) markets.
  - Combines intra-regional production as currently modeled with statistical (logit) parametric sharing of interregional trade in global market.
  - Still requires more development and vetting, possibly simplifying.
  - Natural gas production and markets to address need for LNG for global.
  - Would allow dynamic trade in current fixed trade products like beef.
  - Project task for DOE to model trade limits/implications of climate impacts on food demand in vulnerable regions.
EMISSIONS
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.

**CO₂**: GCAM is a process model for CO₂ 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 CO₂

**Non-CO₂ GHGs**: are modeled as

\[ Emissions = Em\_factor \times Activity\_Level \times (1 - MAC(Carbon\_Price)) \]

**Air pollutant emissions**: (SO₂, NOₓ, etc.) are modeled as:

\[ Emissions = Em\_factor \times Activity\_Level \times (1 - Em\_Controls(GDP_{per\text{-}capita})) \]

Non-CO₂ 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.
Emissions: Base Year Emissions

GCAM tracks emissions for a number of greenhouse gases and air pollutants
- CO$_2$, CH$_4$, N$_2$O, CF$_4$, C$_2$F$_6$, 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 the newly released CEDS historical emissions dataset, which currently extends to 2014.* globalchange.umd.edu/ceds
First, we determine the total change in carbon stock for each land type and region.

\[ \Delta \text{C Stock} = [\text{Land Area (t)}] \times [\text{C density (t)}] - [\text{Land Area (t-1)}] \times [\text{C density (t-1)}] \]

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: Forest Carbon Uptake

- 0%
- 10%
- 20%
- 30%
- 40%
- 50%
- 60%
- 70%
- 80%
- 90%
- 100%

% of eventual carbon stock

Years since land conversion

- 35 years
- 50 years
- 75 years
- 100 years

% of eventual carbon stock vs. Years since land conversion graph.
Emissions: Soil CO$_2$ Emissions

First, we determine the total change in carbon stock for each land type and region.

\[ \Delta \text{C Stock} = \text{[Land Area (t)]} \times \text{[C density (t)]} - \text{[Land Area (t-1)]} \times \text{[C density (t-1)]} \]

Then, we allocate that change across time.

- Whether carbon stock increases or decreases, we use the same formula.
  \[ \text{SoilCarbon}(t) = \text{SoilCarbon}(0) + \Delta \text{SoilCarbonStock}_{i,j} \cdot (1 - e^{-\lambda t}) \]
- The half life, \( \lambda \), 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).
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).

This flexibility allows CO$_2$-only or CO$_2$-equivalent markets/constraints for various “baskets” of emissions as needed.
New GCAM Non-CO2 User Options

*These will be part of the next incremental release.*

- MAC curves can be set for any emission species. (e.g., CH$_4$-only market, NO$_x$ market, etc.)
- Below zero MAC reductions 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).
- MAC curves can be set to operate only before a specific vintage year (useful for combining pollutant emission MAC curves with new source standards).
- New linear-control object allows user to specify that an emission factor will go to a user-defined value over a specified time period.
CLIMATE
The Climate System: Approach

- GCAM default climate module is now Hector with the option to run MAGICC5.3
- Inputs:
  - GCAM passes emissions to the climate model
  - Fossil fuel & Industrial CO$_2$, Land-Use Change CO$_2$, CH$_4$, N$_2$O, SF$_6$, C$_2$F$_6$, 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
- 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
Hector: open and object-oriented architecture

- Initialization
  - Input data are routed to model components via the model core

- Spin up
  - the carbon cycle is in equilibrium before the main run starts

- Main run
Hector: open and object – oriented architecture

- Components have a defined interface (API)
- They register their dependencies and capabilities with the core
  - e.g., sea level rise depends on temperature
- Core orders components by their dependencies
- Components query the core for data
  - Core routes request to appropriate component

As the model runs

During initialization

SLR

Core

X

Temperature

Temperature please

Core

SLR

Someone needs sea level rise

Yes, it's already been calculated...here

Okay

Here's sea level rise

I warned you I'd need temperature for this

Hello

during initialization

SLR

Core

X

Temperature please

Core

SLR

Someone needs sea level rise

I warned you I'd need temperature for this

Hello

During initialization

SLR

Core

X

Temperature please

Core

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During initialization

SLR

Core

X

Temperature please

Core

SLR

Someone needs sea level rise

Yes, it's already been calculated...here

Okay

Here's sea level rise

I warned you I'd need temperature for this

Hello
; 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
k = 0.2 ; ocean heat uptake efficiency (W/m2/K)

[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
Hector: Science
Hector: Atmosphere

- Well mixed globally averaged atmosphere
- Forced with emissions from RCP scenarios
  - CO$_2$ – anthropogenic & LUC
  - BC/OC
  - CH$_4$/N$_2$O
  - 26 halocarbons
  - Sulphate aerosols
  - Volcanic emissions
- Calculate:
  - Stratospheric H$_2$O
  - 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 CO$_2$ – RCP8.5

Radiative Forcing

Hartin et al., 2015 - GMD
The Climate System: Results

Atmospheric Temperature – RCP8.5

Ocean pH – RCP8.5
GCAM integration of Hector

- Energy
- Socioeconomics
- Water
- Land
- Climate – Hector + capabilities
QUESTIONS?