Modeling Energy-Water-Land Impacts in the Global Change Assessment Model (GCAM)

JAE EDMONDS & KATE CALVIN **FOR THE GCAM TEAM**

Workshop on Climate Change Impacts and Integrated Assessment (CCI/IA)
Snowmass, CO

24 July 2014

U.S. DEPARTMENT OF ENERGY | Office of Science

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GCAM evolution has always been *PROBLEM DRIVEN and linked to Energy AND Earth System Science.*

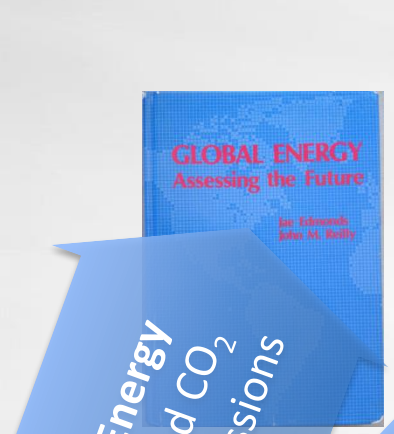
1980's

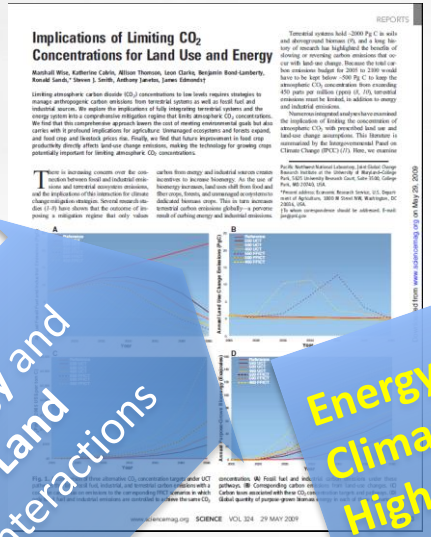
What will be the *future* fossil fuel contribution to C in the **atmosphere**?

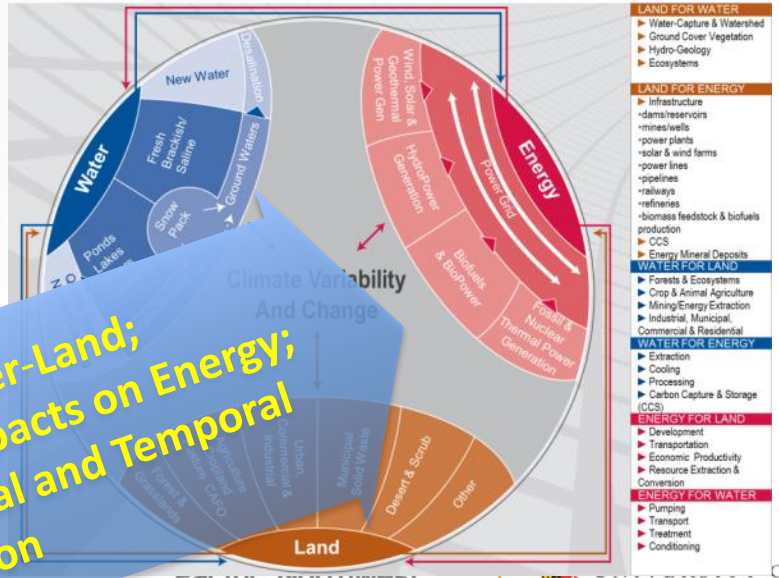
2000's

What are the potential *future* **energy** implications of **land biosphere & atmosphere** interactions?

GCAM is evolving to address a new set of problems: *climate impacts on the interconnected energy, water and land system in a world that may or may not be simultaneously mitigating GHG emissions, at temporal, spatial, and sectoral scales appropriate to science and decision-support problems.*







Energy and CO_2 Emissions

Energy and **Land** Interactions

Energy-Water-Land; Climate Impacts on Energy; High Spatial and Temporal Resolution

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GCAM Is Rapidly Evolving

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GCAM has evolved to become a modeling system with multiple interoperable modules, temporal and spatial scales, and modes of application in response to evolving challenges.

Tackling new problems such as climate impacts on the energy-water-land nexus means that GCAM has evolved to:

- **Employ high-resolution data inputs,**
- **Reconcile and transform data to appropriate analytical scales,**
- **Employ interoperable modules and models, and**
- **Produce output products, at appropriate space, time, sectoral, and technological resolutions.**

GCAM is a Multi-scale Model With Adaptive Resolution

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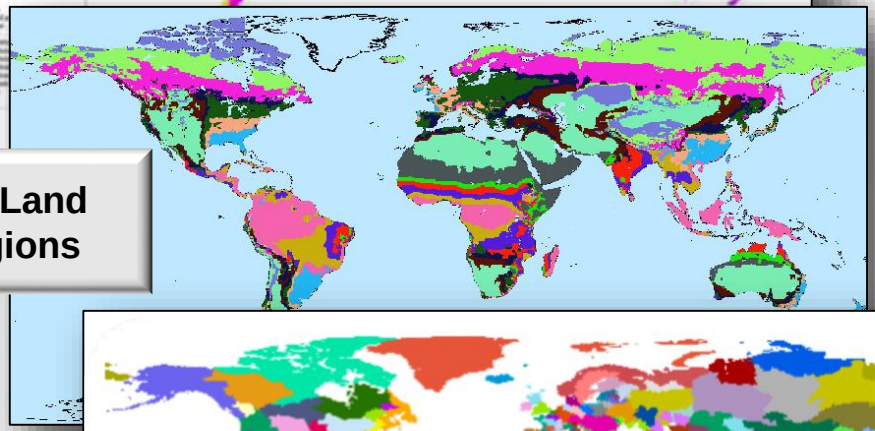
50-State Energy Economy Regions

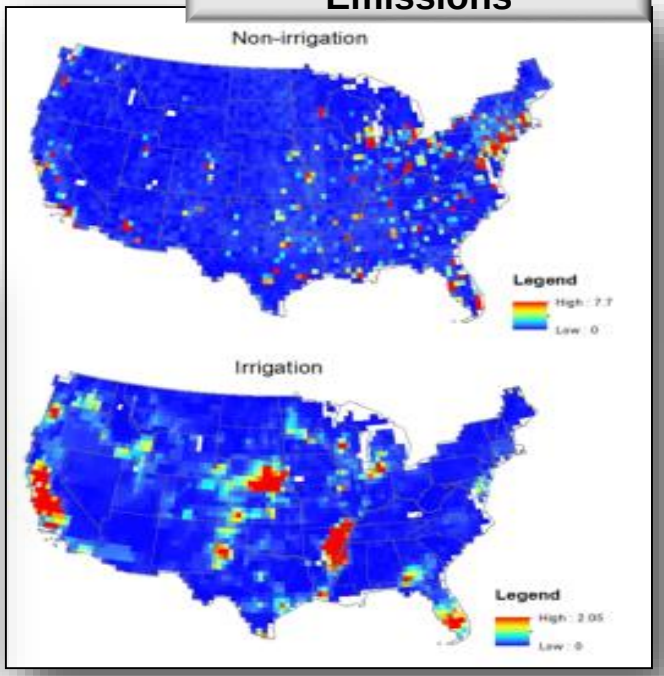
32 Energy Economy Regions



283 Land Regions

233 Water Basins

Grid-Level Water, Energy, Land, and Emissions



GCAM ENERGY, AGRICULTURE AND LAND USE

Building Energy Demand: Drivers

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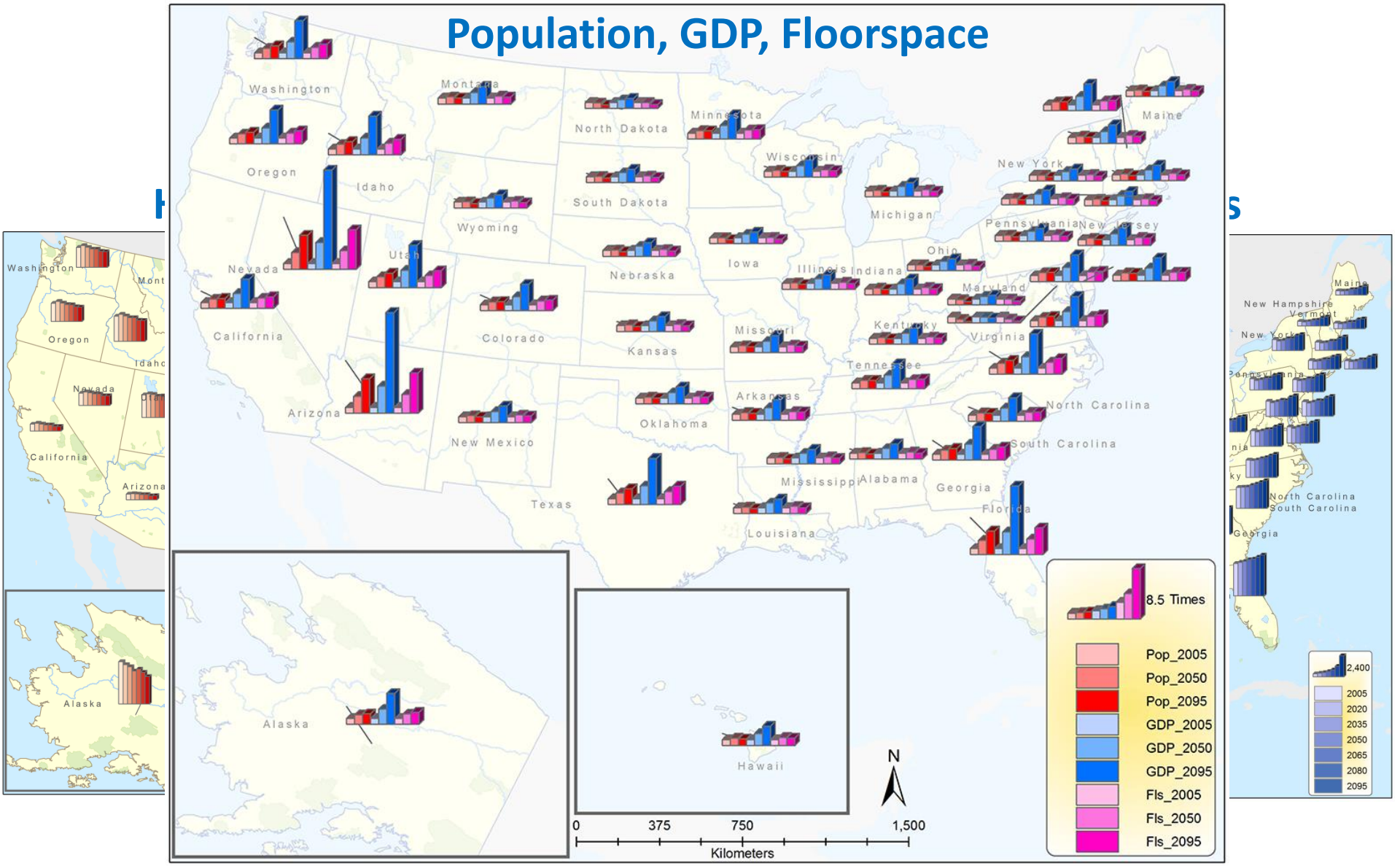

Regional and 'Local' Climate Change Feedbacks on Energy

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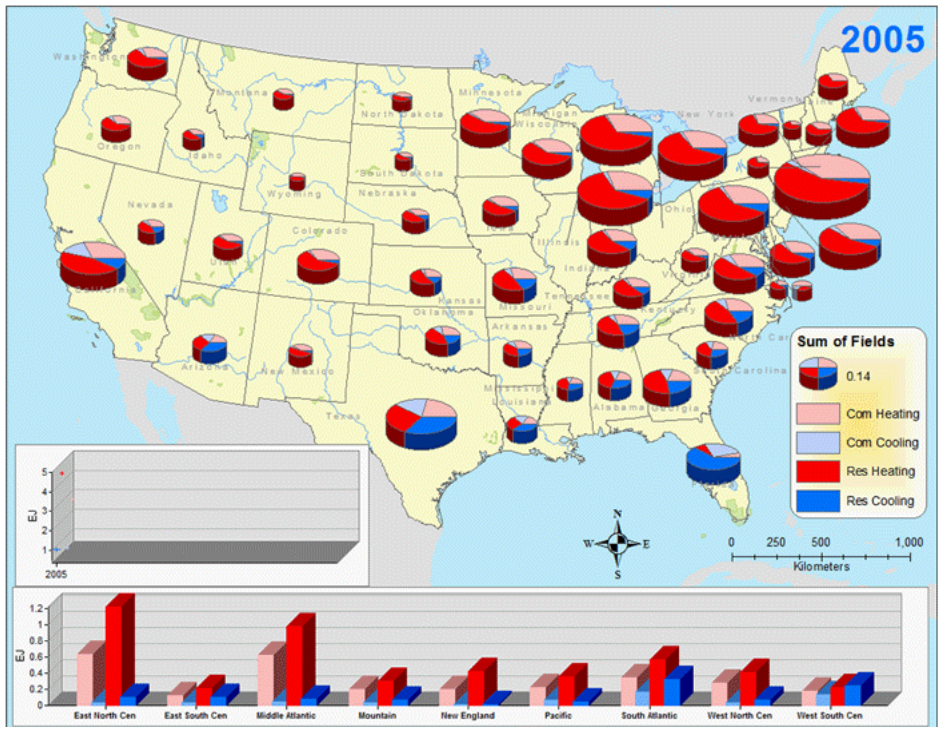
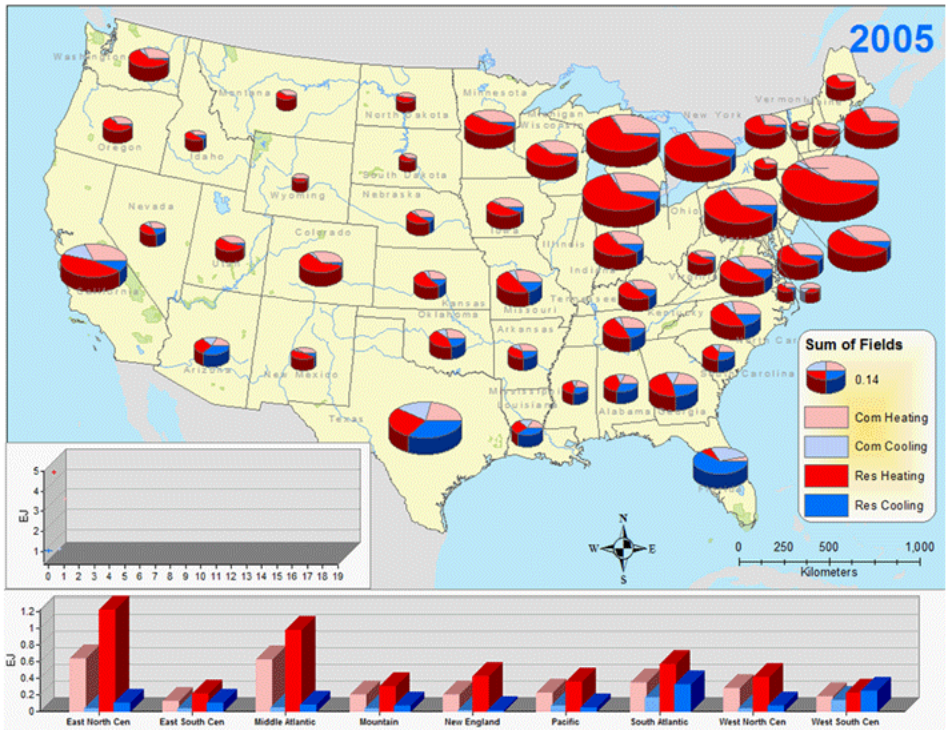
Climate Impacts on Building Energy Use

Fixed Climate



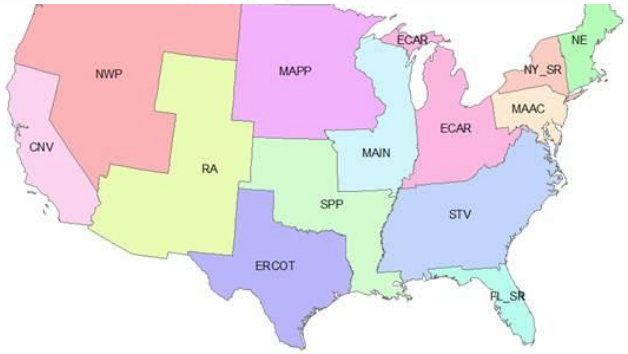
A2 Climate

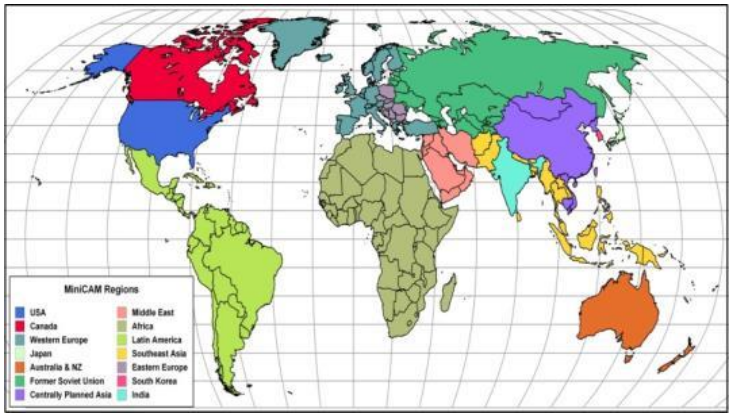


Source: Zhou Y, L Clarke, J Eom, G Kyle, P Patel, S Kim, J Dirks, E Jensen, Y Liu, J Rice, L Schmidt, T Seiple. 2013. "Modeling U.S. State Building Energy Use and Climate Change Impact." *Applied Energy* 113:1077-1088 .

GCAM-USA Electricity: Details

- Every state produces and consumes electricity according to the usual drivers (population, GDP, technology, etc.)
- There is a set of regional markets based on NEMS, and states can trade electricity within their markets
- Trade between markets can be fixed at base year levels or loosened up to roughly approximate the effects of increased transmission capacity, market changes, etc.
- GCAM still provides additional global constraints and context





GCAM-USA Electricity: Results

2050 Electricity supply mix in Gulf Coast states

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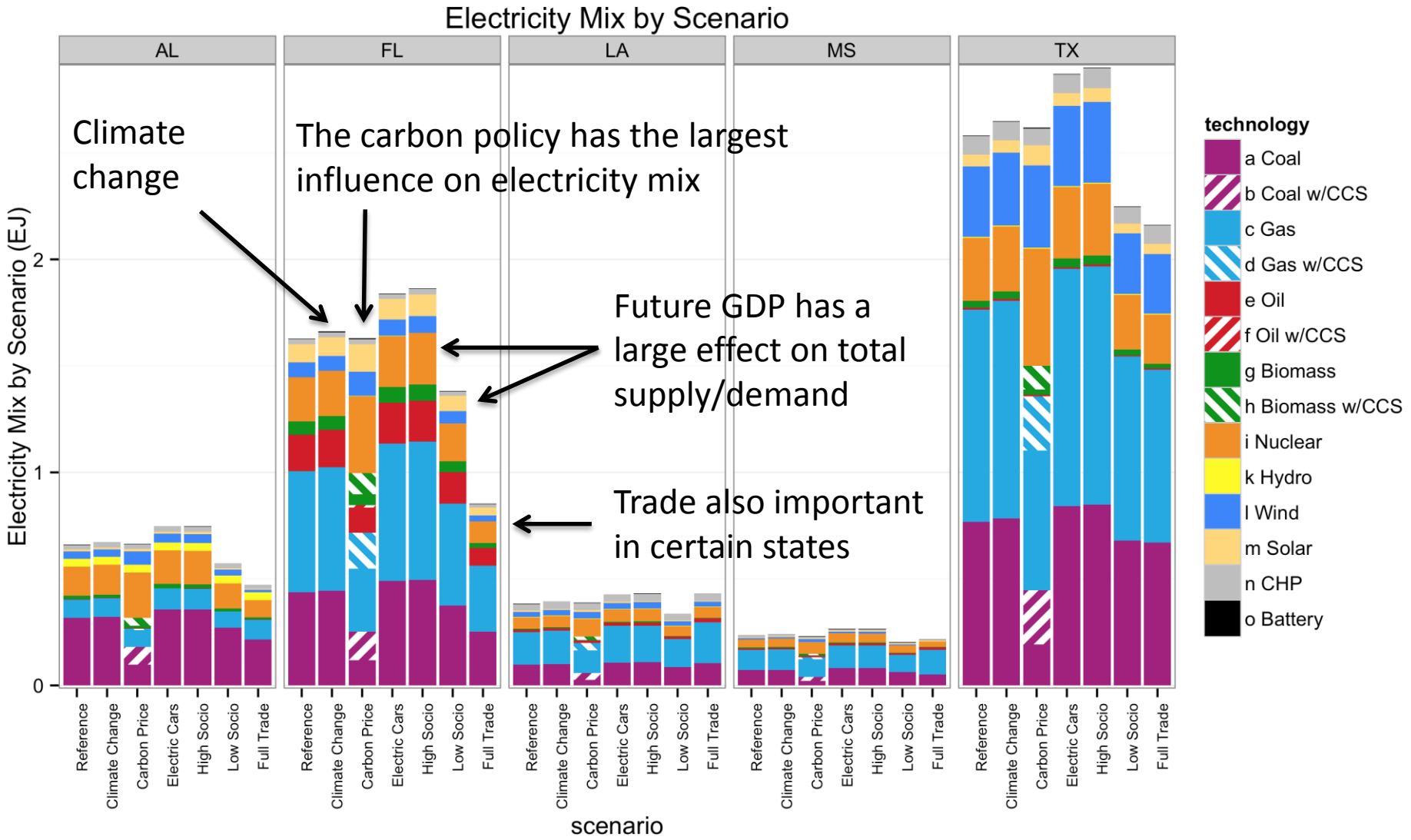

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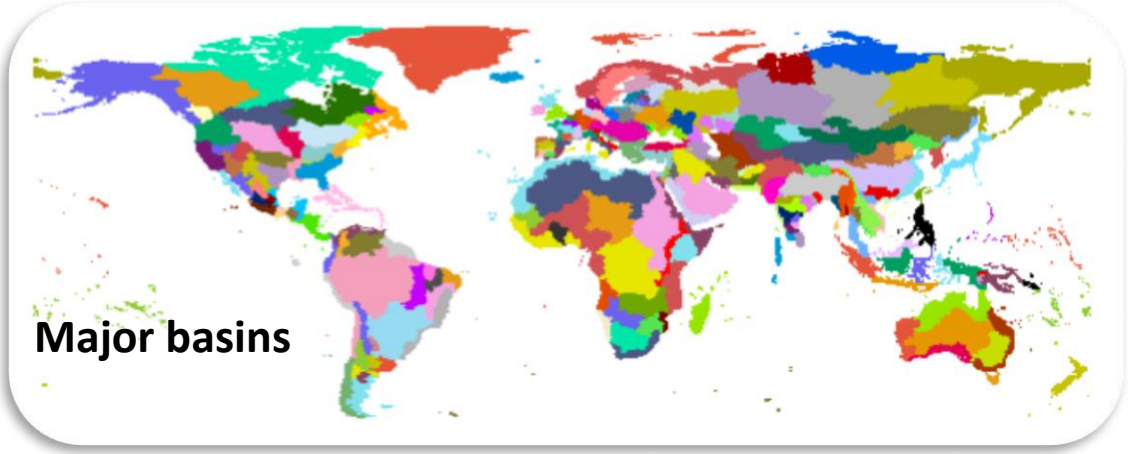
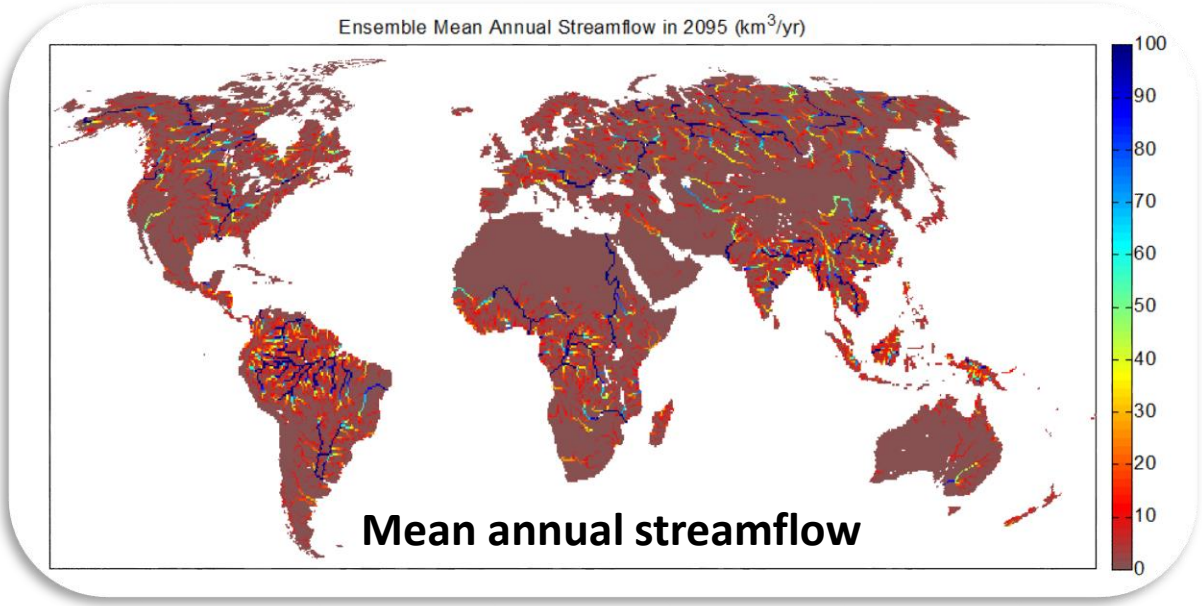
Hydrology using climate model outputs to assess stream-flow, river routing, and river management to assess energy system impacts

GCAM ENERGY, LAND AND WATER

The GCAM Global Hydrologic Model

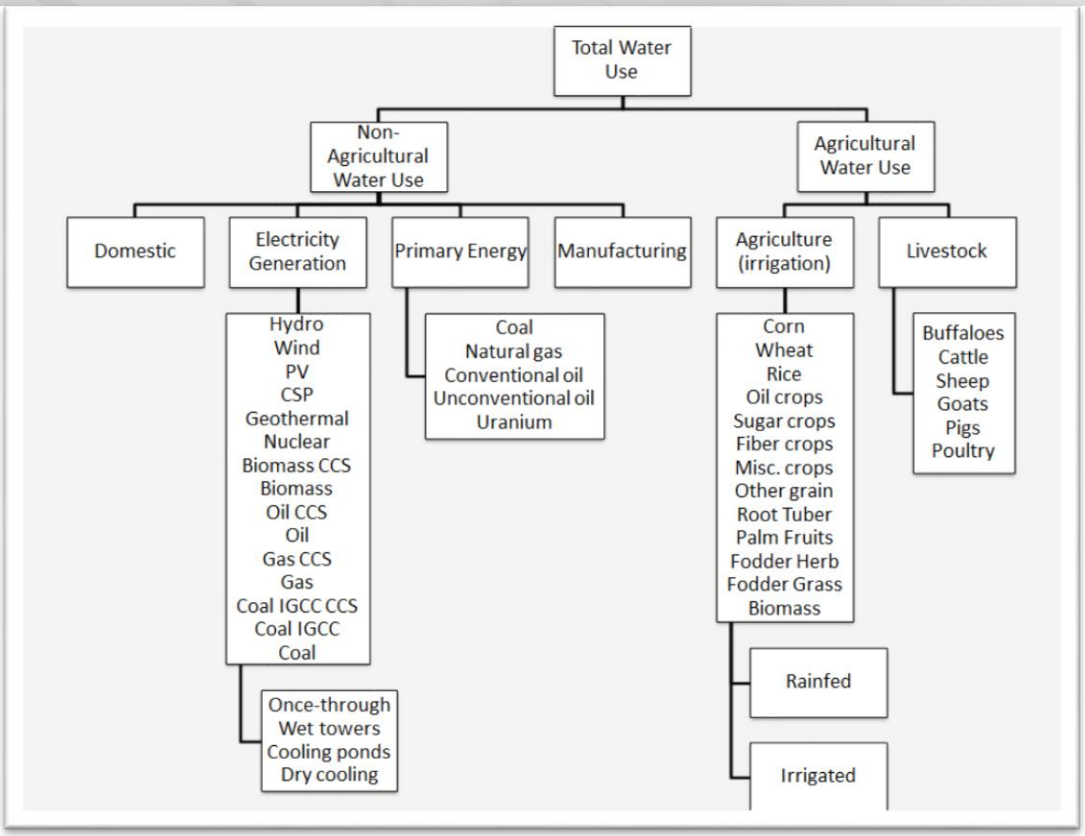


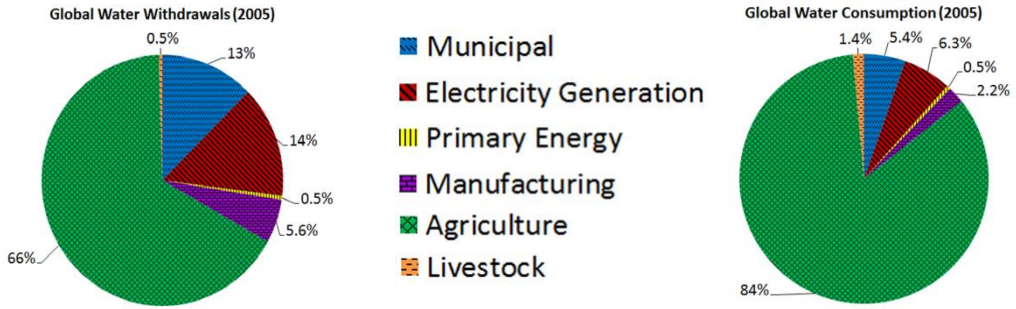


- GCAM has a macroscale global hydrologic model
- Modified River Transport Model scheme
- Simulates runoff and streamflow (1901-2100)
- Requires climate information from GCMs as inputs
- 233 basins globally
- 18 basins in the US consistent with the USGS WRRs
- Monthly temporal scale
- 0.5x0.5 degree spatial resolution

Toward understanding the implications of **climate change impacts** on **water** availability and on **energy and land** decisions in GCAM

How much water do humans demand for energy and food?





- Technologically detailed representation of water demand sectors
- Tracks water demands for several sectors, subsectors, and technologies
- Tracks water demands at various spatial scales (regions, state, agro-ecological zones)
- Tracks both annual withdrawal and consumptive water use
- Endogenously incorporated in GCAM

Sources: Hejazi et al. (2014), Technological Forecasting and Social Change, 81, 205-226, http://dx.doi.org/10.1016/j.techfore.2013.05.006.

Energy-Water Nexus: Projected Changes in Water Use for Electricity Generation

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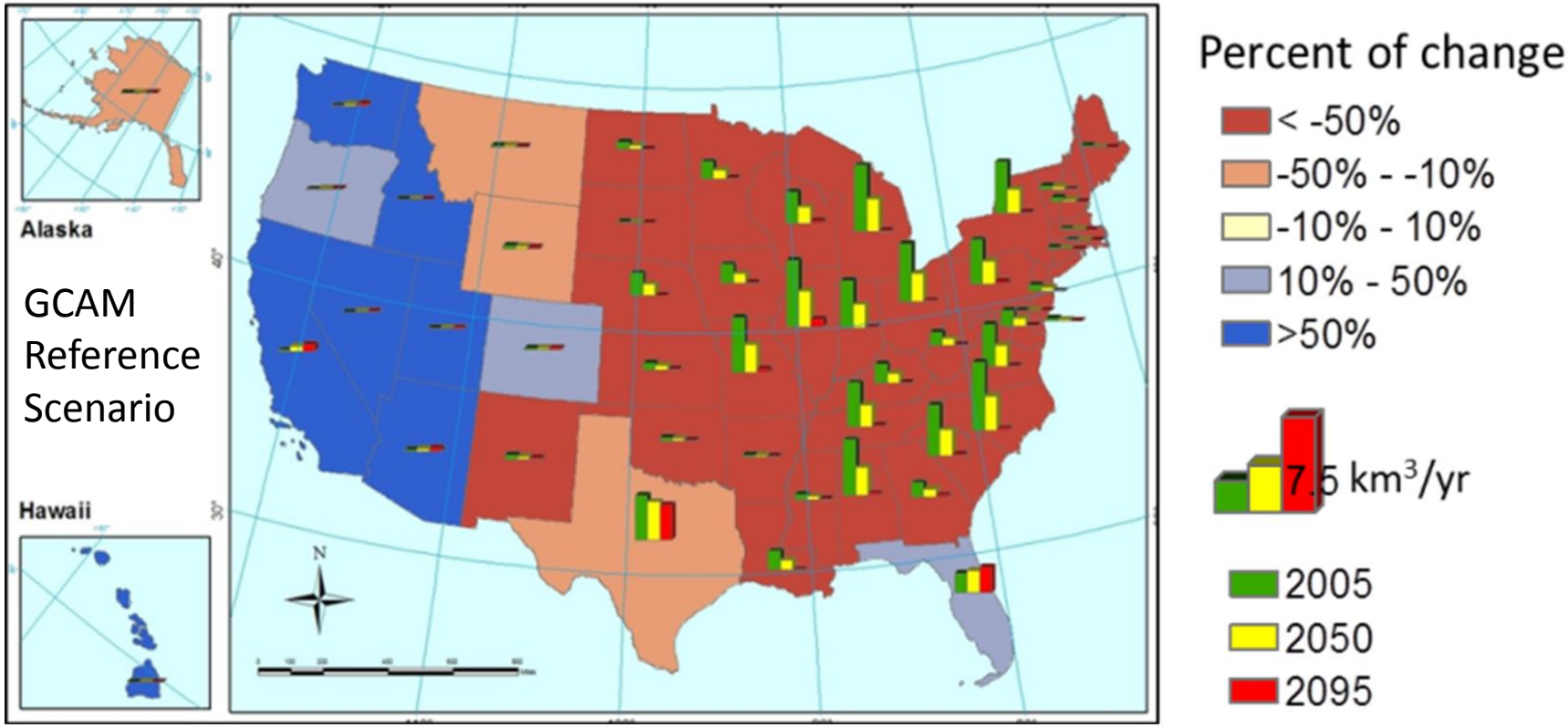
(Combines GCAM-USA 50-state electricity and water downscaling)

- Electricity water withdrawals will increase in the west and decrease in the east (factors: population movement, GDP, cooling techs, fuel mix, etc.)
- There is a trade-off between consumption and withdrawals (not shown)



Global water withdrawal and consumption in a reference scenario with increasing deployment of cooling towers in power generation

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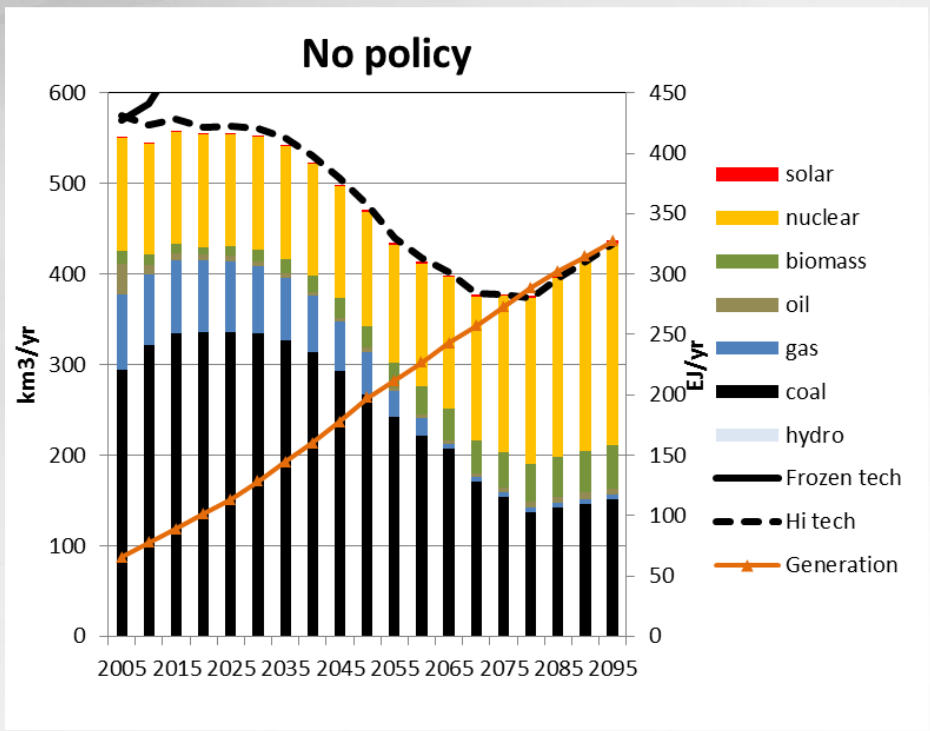
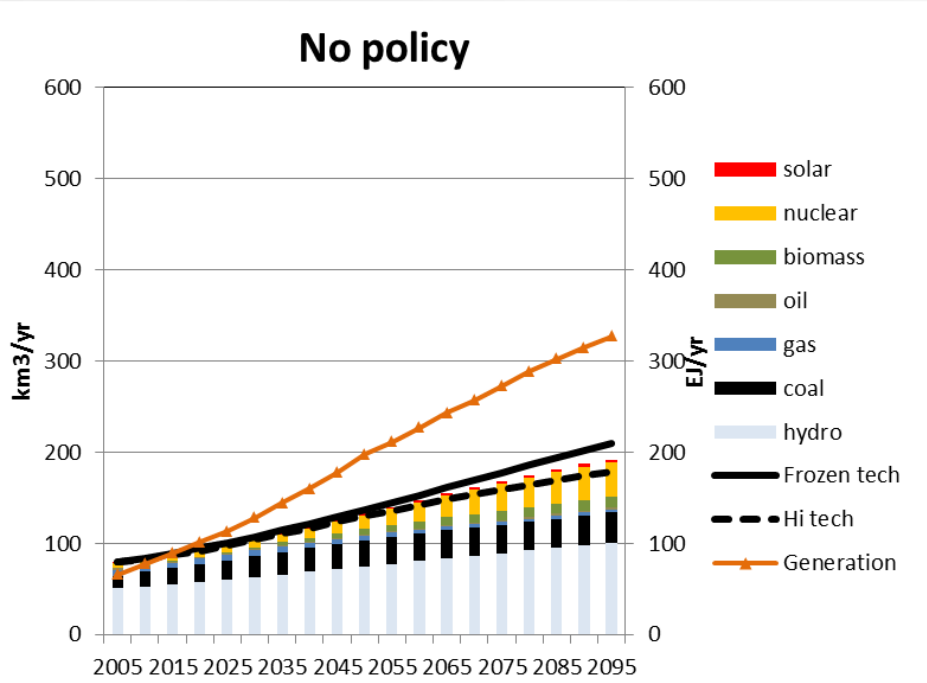


Withdrawal



Consumption

Page Kyle, Evan G.R. Davies, James J. Dooley, Steven J. Smith, Leon E. Clarke, **James A. Edmonds**, and Mohamad Hejazi. 2013. Influence of climate change mitigation technology on global demands of water for electricity generation. International Journal of Greenhouse Gas Control. Volume 13, March 2013, Pages 112–123. http://dx.doi.org/10.1016/j.ijggc.2012.12.006.

How do growing demands & changes in water supply from climate change affect water scarcity?

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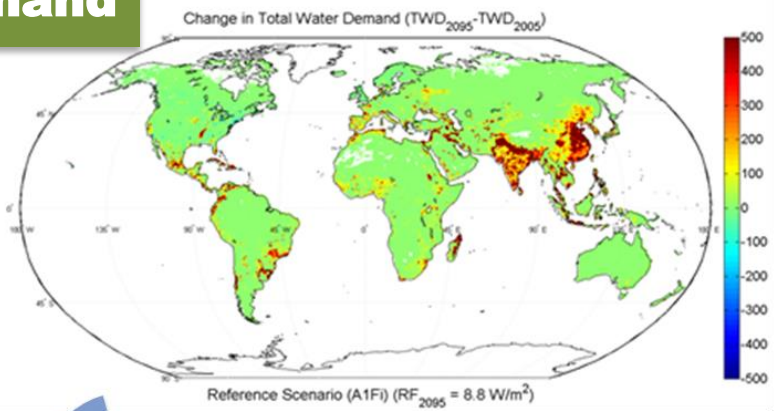
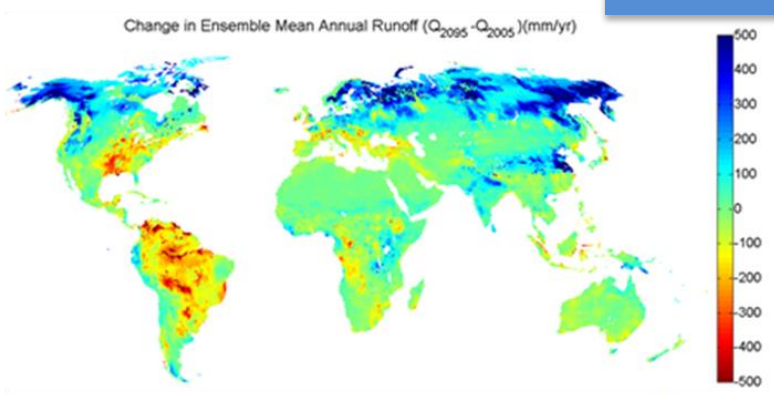
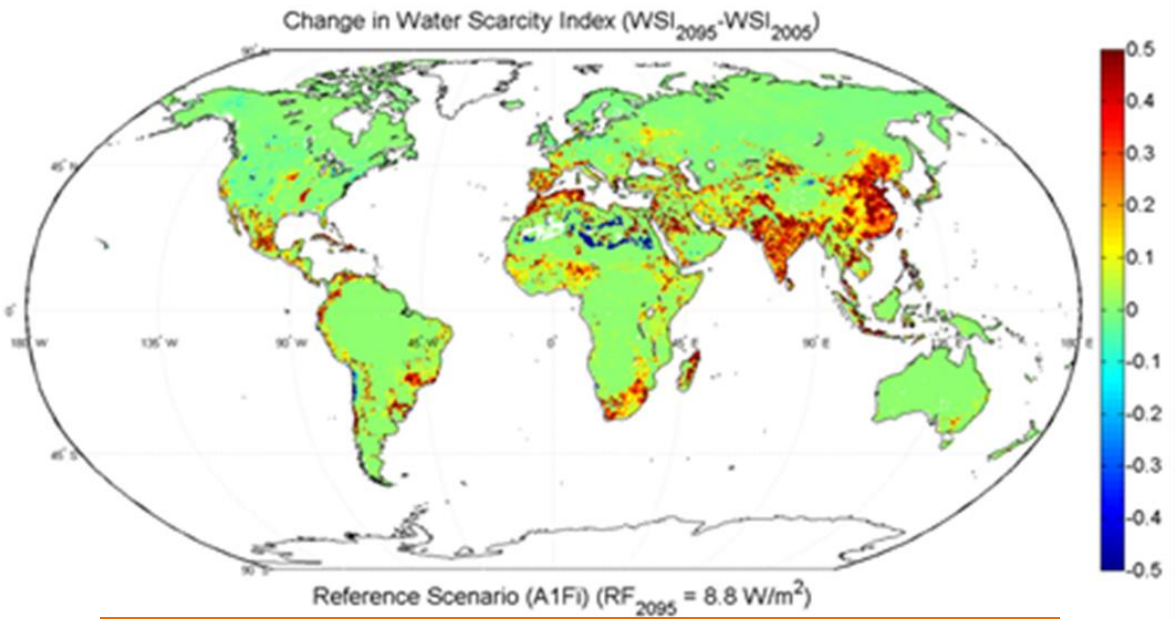
Δ Demand



Δ Runoff





Change in Scarcity

Source: Hejazi et al. (2013). Integrated assessment of global water scarcity over the 21st century: Global water supply and demand under extreme radiative forcing, Hydrology and Earth System Sciences Discussion, 10, 3327–3381, doi:10.5194/hessd-10-3327-2013.

Humans play a larger role in water scarcity in 93% of the basins (89% of total land)

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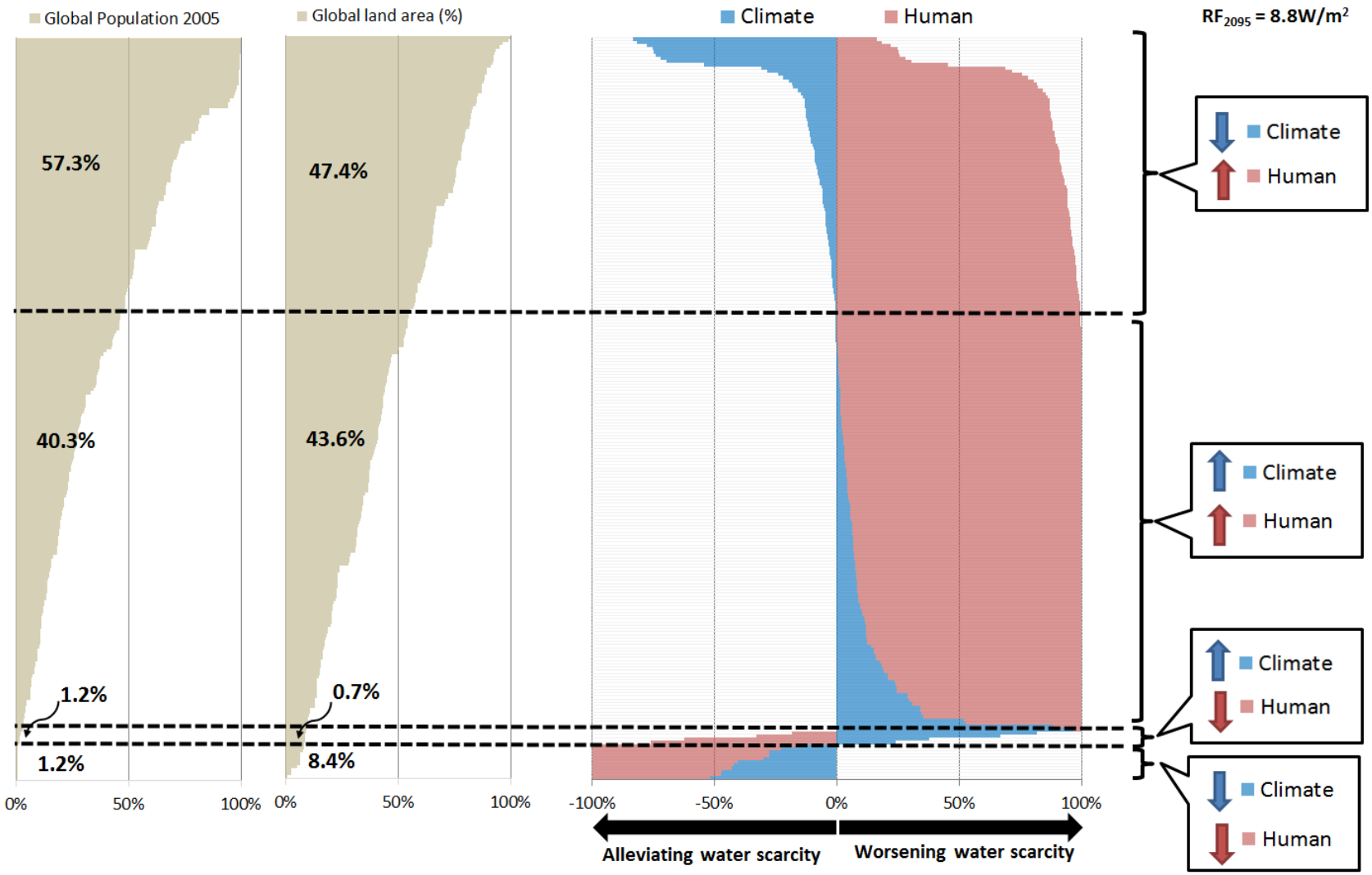
No policy (8.8 W/m^2 by year 2100)



Change in Scarcity

Climate change will affect hydropower generation (HadCM3)

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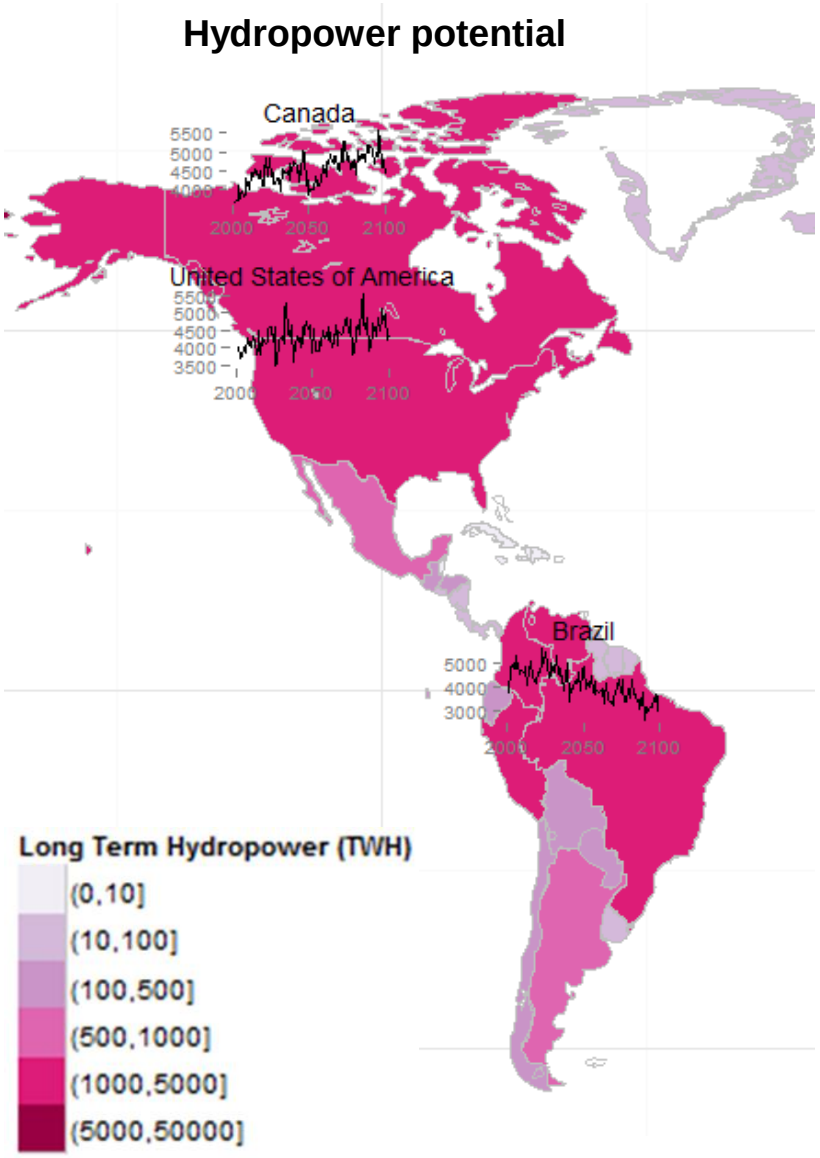

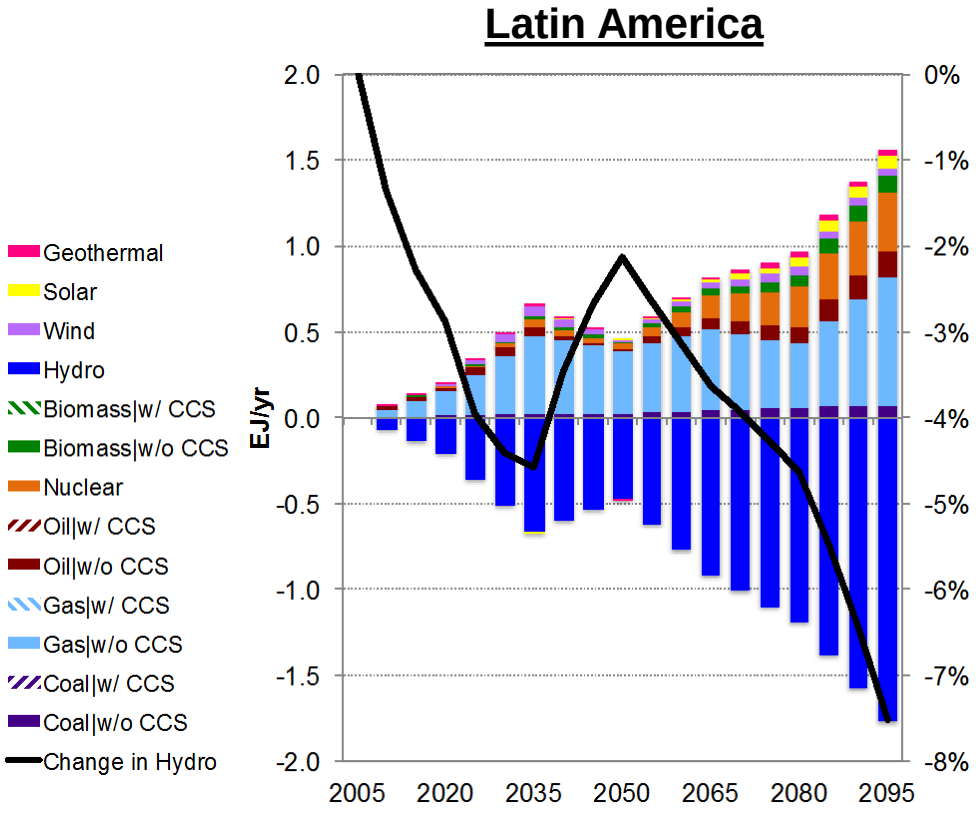

Positive values mean an increase in electricity generation when impacts are considered

Recent Development in GCAM: Fully-coupled ENERGY-WATER-LAND system within an IA model

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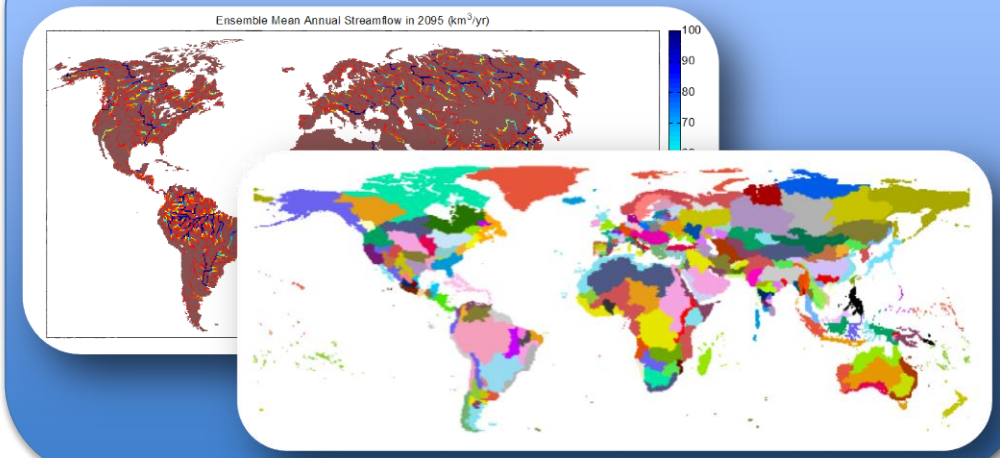
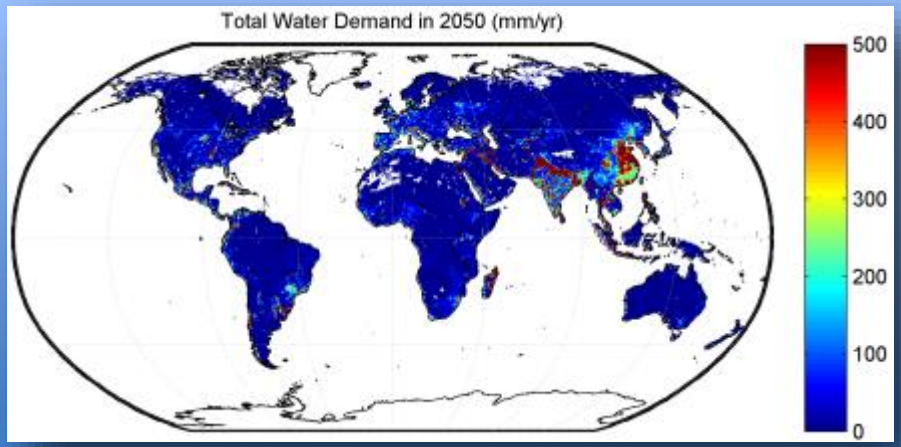
Water Supplies

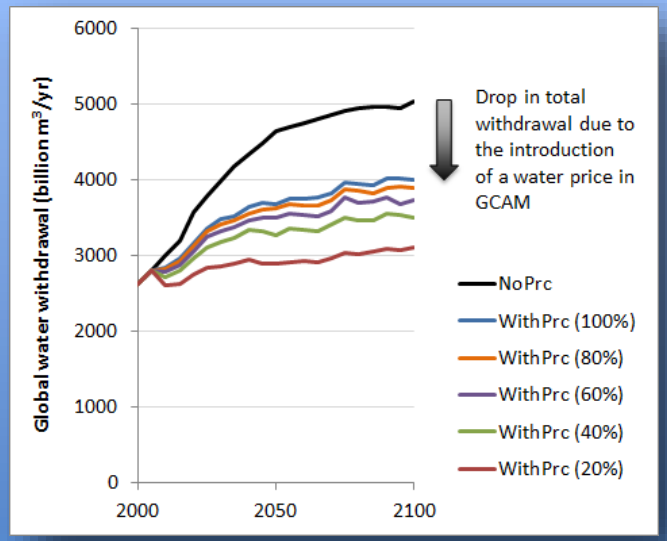


Water Demands



Water Use

Global Annual Water Withdrawals



Preliminary Results: Reconciling water demands and supplies alters water withdrawals and alters the distribution of food production.

FUTURE DIRECTIONS

Looking to the Future

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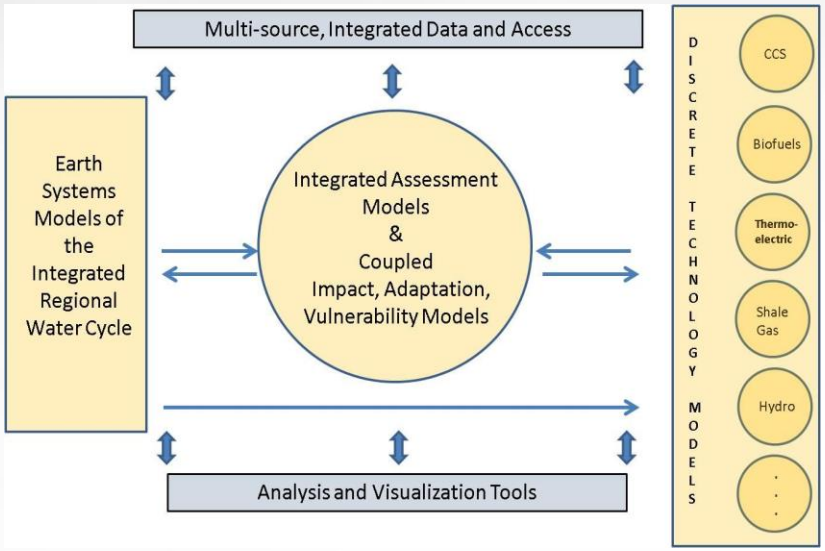
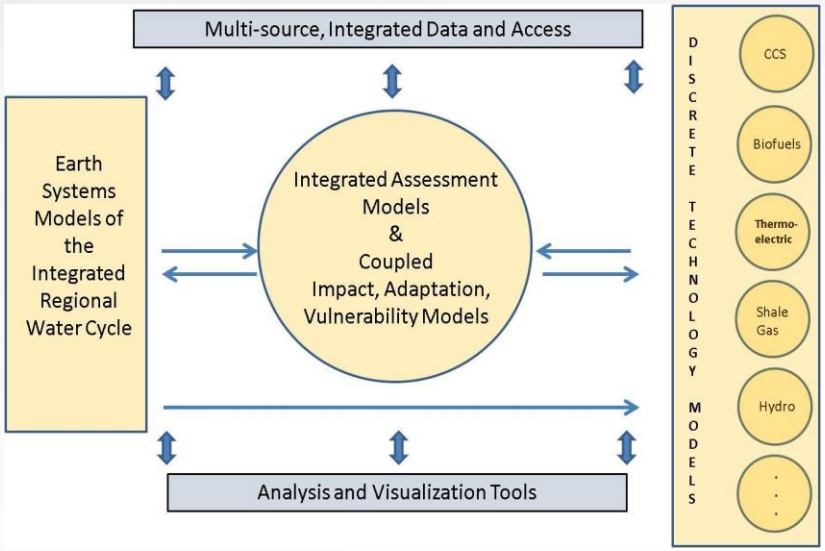
GCAM development will continue to be PROBLEM DRIVEN—E.g. climate impacts on the energy-water-land nexus.



Looking to the Future

GCAM development will continue to be PROBLEM DRIVEN—E.g. climate impacts on the energy-water-land nexus.

- **High-resolution input data**
  - Multiple sources
  - Reconciled data products
  - Multiple scales (appropriate to the problem at hand)
- **GCAM model modules**
  - Interoperable (appropriate to the problem at hand)
  - Utilization of GCAM's telescopic design to examine problems at a variety of resolutions—Space, Time, Sectors, Technologies
  - Connection to infrastructure models
  - Energy, water, land physical and economic system closure.



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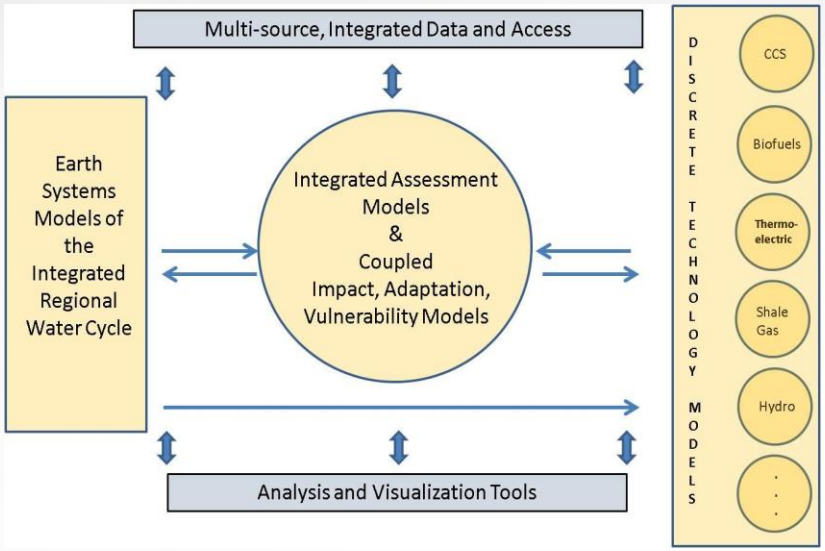

- ***The PNNL team also has a research theme that applies the results of GCAM to real-world applications, which creates a pathway for us to learn what matters to real-world decision makers and helps inform future research directions.***

Looking to the Future

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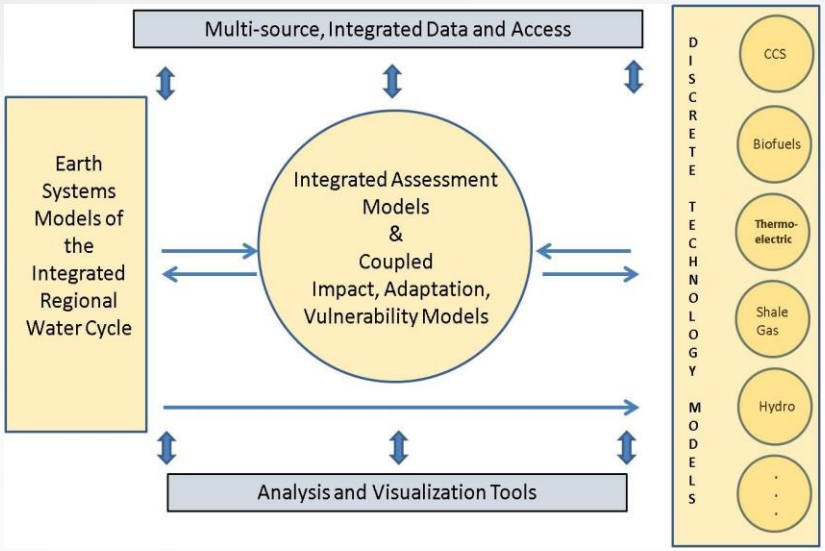

- ***GCAM's unique contribution remains INTEGRATION—the provision of insights from interactions between human and biogeophysical systems that would not otherwise be available from traditional independent disciplinary research alone.***

A note on Snowmass at 20

- Snowmass can change things pretty dramatically.

- The Integrated Assessment Modeling community owes an enormous debt to John Weyant.

What has Snowmass done for us lately?

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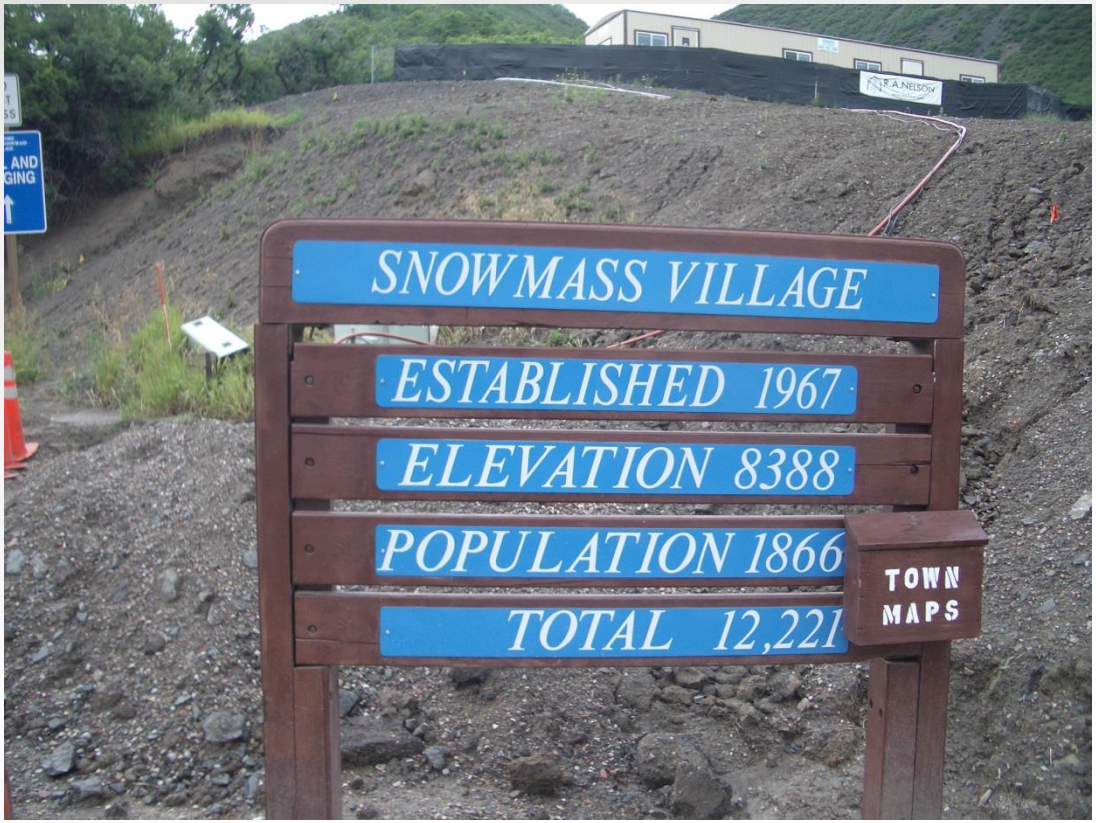
- In part its about the numbers.
- But, its much more about the connections
  - Across disciplines
  - Across the researchers



Thanks John

Backup Slides

The Global Change Assessment Model

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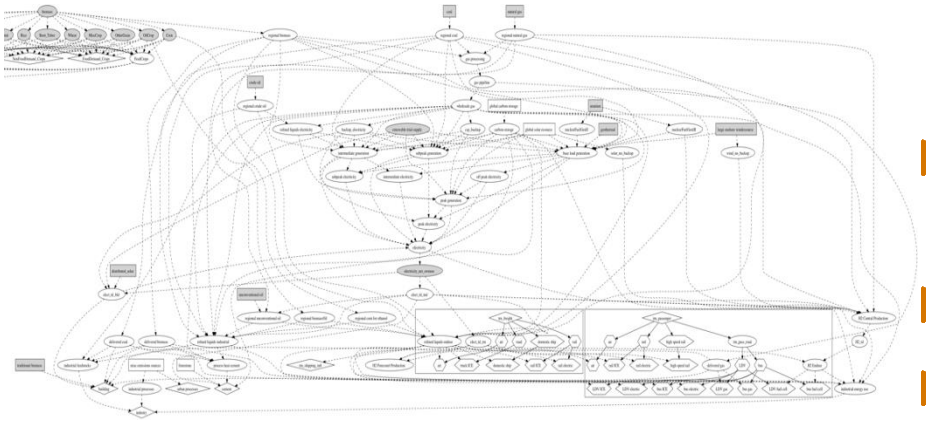
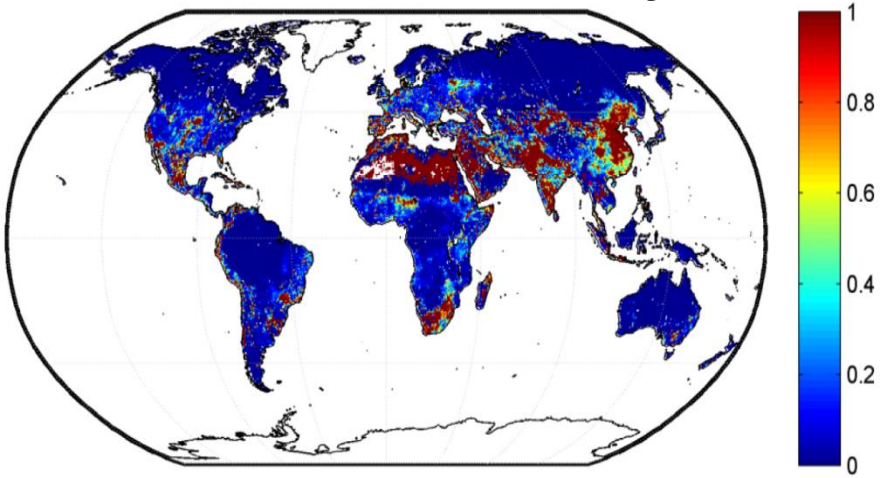
Regional Wiring Diagram



GCAM Water Scarcity



- GCAM is a **global integrated assessment model**, with regional and local resolutions
- GCAM links **Economic**, **Energy**, **Land-use**, **Water** and **Climate** systems
- Technology-rich model
- Emissions of 16 greenhouse gases and short-lived species: CO_2, CH_4, N_2O, halocarbons, carbonaceous aerosols, reactive gases, sulfur dioxide. At global, regional and 0.5° resolution.
- Land use, land use change, and land cover. At global, regional and 0.5° resolution.
- Runs through **2100** in **5-year time-steps.**

GCAM is a community model

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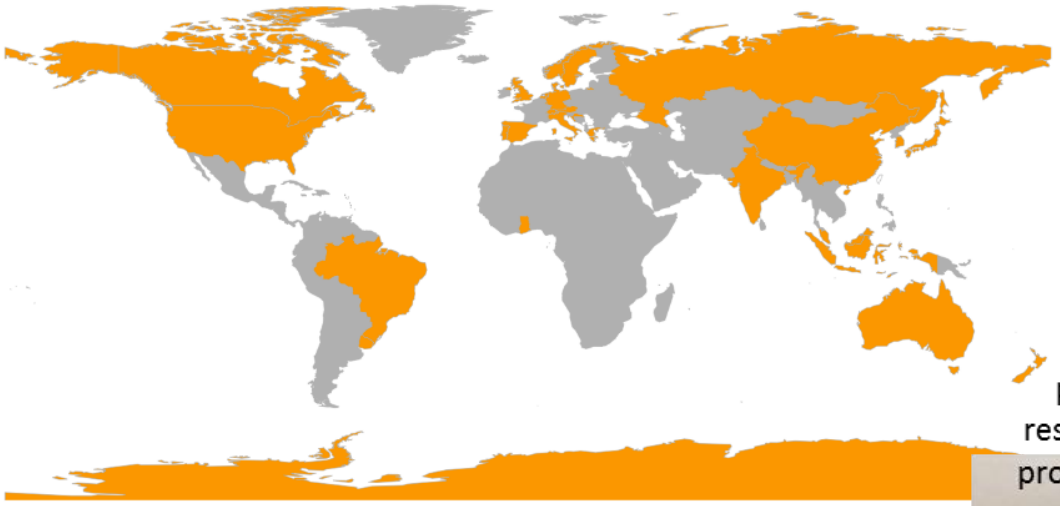
- GCAM has a large and growing community of users.
- GCAM annual meeting brings users together to collaborate and network.

GCAM Community Model Downloads

http://www.globalchange.umd.edu/models/gcam/download/



GCAM documentation: wiki.umd.edu/gcam/

418 people had received copies of GCAM (@258 institutions, in 58 countries, on 7 continents)

The availability of Evergreen, a high performance computing facility for IAM research, made available by the DOE IARP program, has helped facilitate research on GCAM's new class of problems.

GCAM also incorporates high resolution input data as appropriate to the problem at hand

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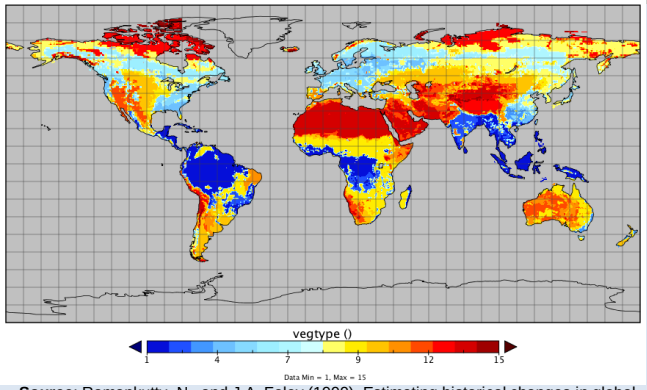
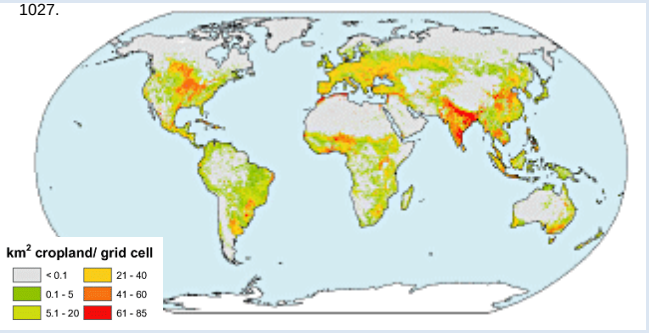
Potential Vegetation



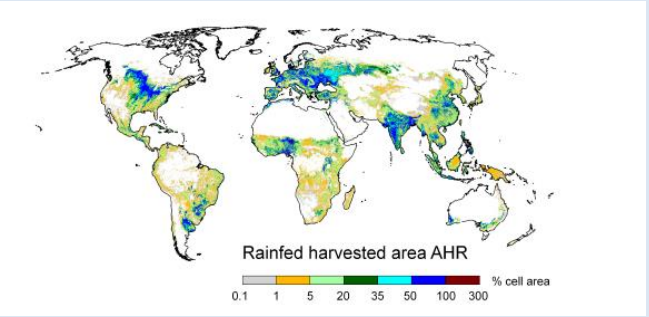
Source: Ramankutty, N., and J.A. Foley (1999). Estimating historical changes in global land cover: croplands from 1700 to 1992, Global Biogeochemical Cycles 13(4), 997-1027.

Cropland area

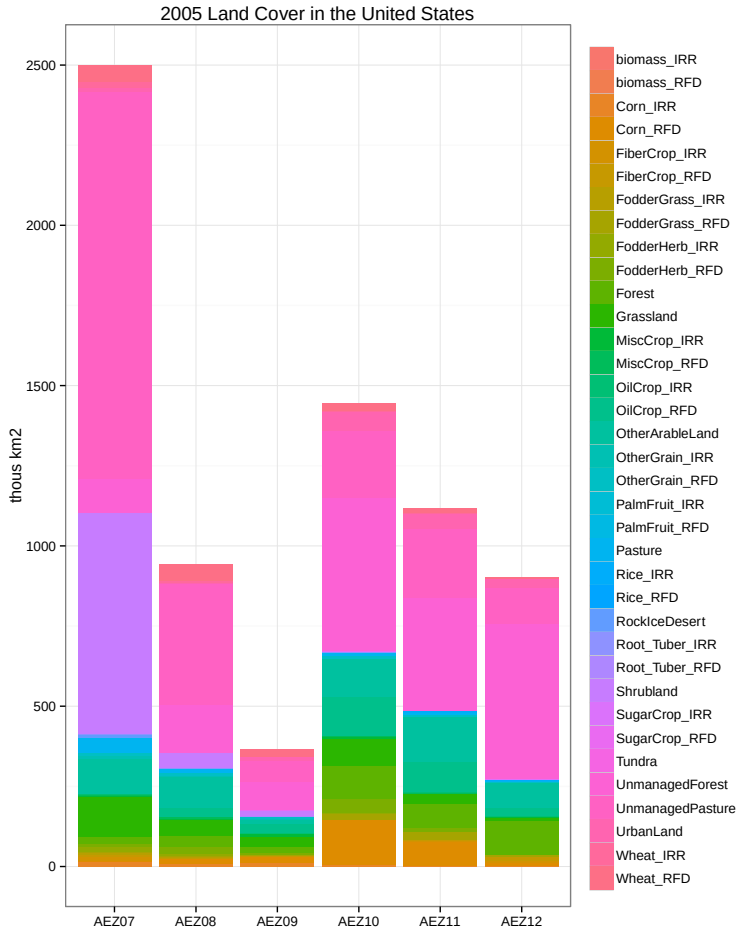


Source: Klein Goldewijk, K. , A. Beusen, M. de Vos and G. van Drecht (2011). The HYDE 3.1 spatially explicit database of human induced land use change over the past 12,000 years, Global Ecology and Biogeography20(1): 73-86.

Rainfed area



Source: Portmann, F. T., Siebert, S. & Döll, P. (2010): MIRCA2000 – Global monthly irrigated and rainfed crop areas around the year 2000: A new high-resolution data set for agricultural and hydrological modeling, Global Biogeochemical Cycles, 24, GB 1011, doi:10.1029/2008GB003435.

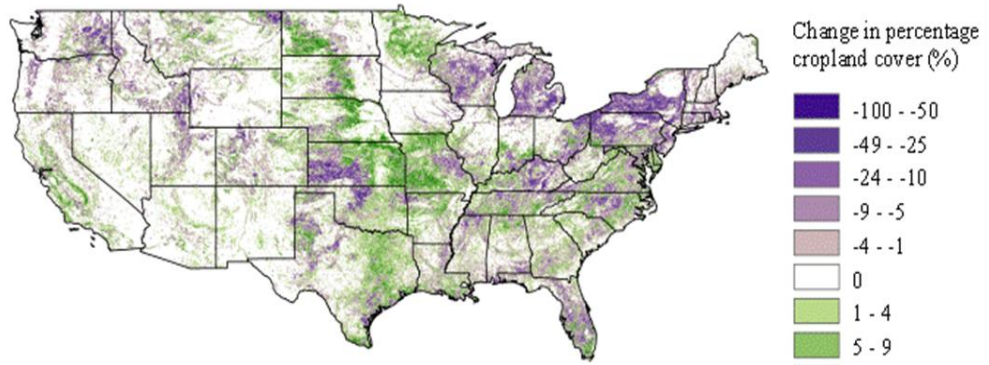


- We also produce reconciled data products in the process of incorporating data into GCAM.

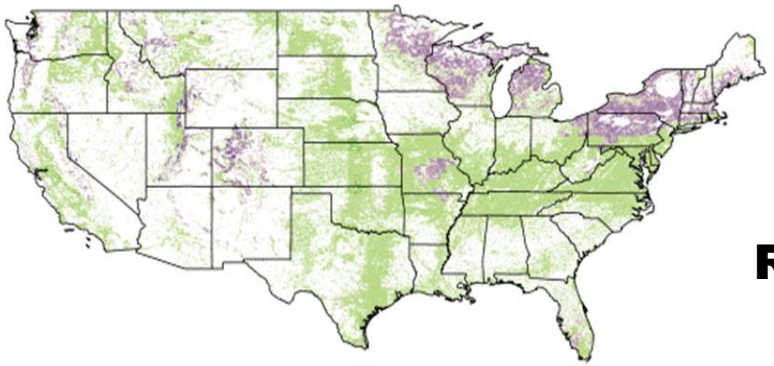
As we develop and incorporate new capability, we are evaluating its performance.

- Correlation between crop PFT land cover in the native 2010 MODIS **land cover** and the 2010 land GCAM RCP 4.5 was **r^2=0.98**.
- Correlation between the **cropland difference maps** representing only those grid cells that changed, was **r^2=0.83**.

Cropland Change MODIS 2005-MODIS 2010



Cropland Change MODIS 2005-GCAM 2010



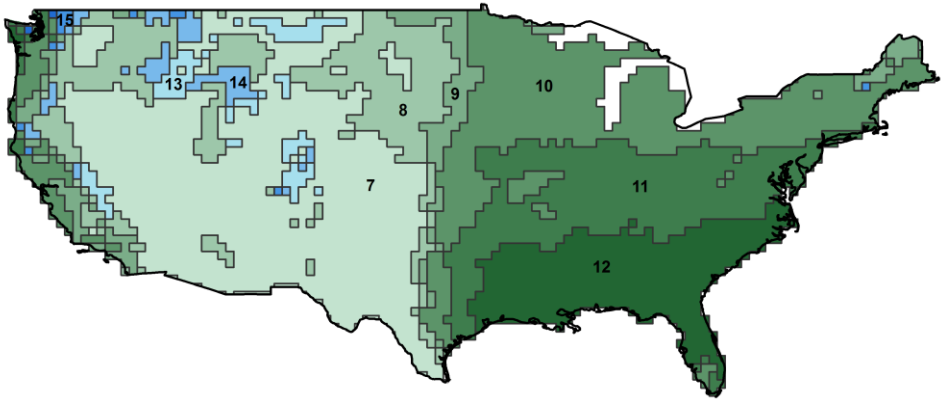
R^2 = 0.83

Source: Tristram O. West, Yannick Le Page, Maoyi Huang, Julie Wolf, and Allison M. Thomson. 2014. Downscaling Global Land Cover Projections from an Integrated Assessment Model for Use in Regional Analyses: Results and Evaluation for the US from 2005 to 2095. Accepted for Publication in *Environmental Research Letters*.

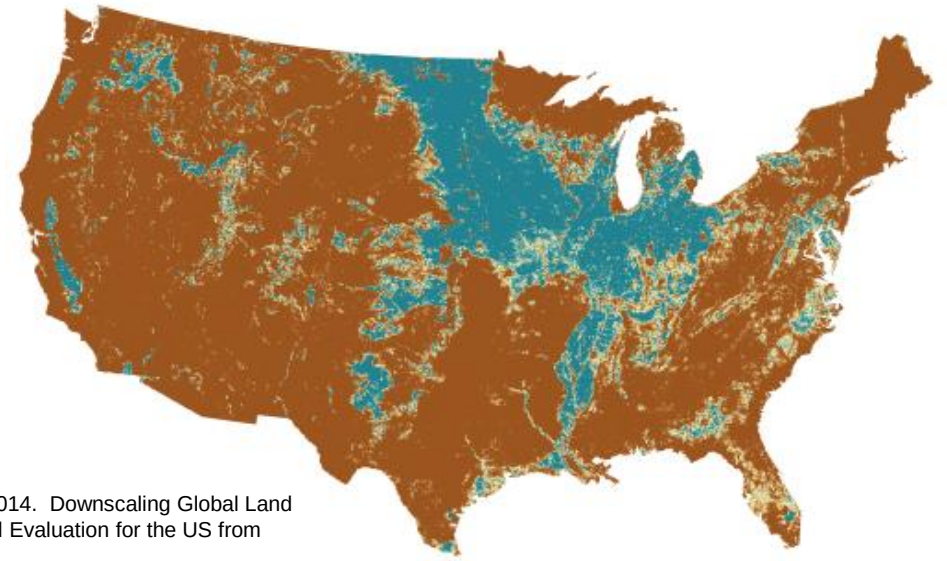
GCAM land cover decisions occur at 283 region resolution, but results are available at 0.05° resolution

- Economic decisions about land are made at a 283 region resolution globally (9 regions in the USA).
- However, land cover data is output at 0.05° x 0.05° resolution.
- Transition from economic regions to spatial scale considers factors like proximity to existing agricultural areas and conversion types.
- We are expanding this modeling to include land suitability and protected lands.

9 AgLU Economic Regions in the USA



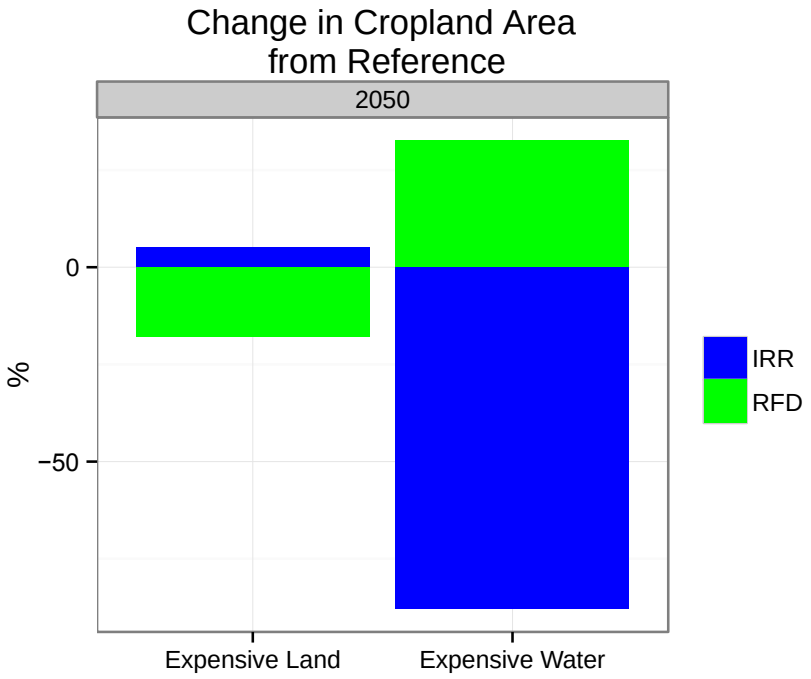
Cropland area in 2005 at a 0.05° Resolution

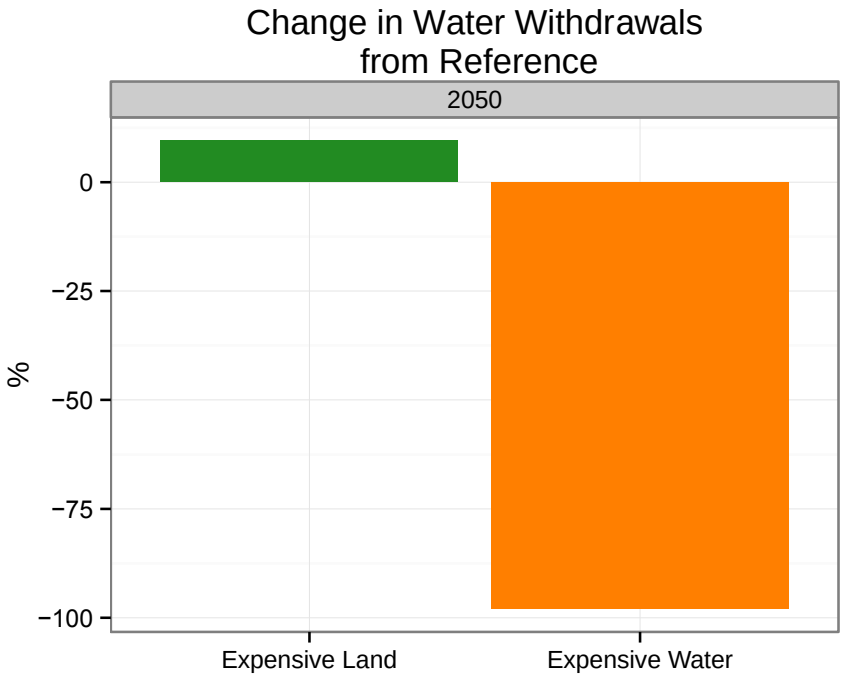


Source: Tristram O. West, Yannick Le Page, Maoyi Huang, Julie Wolf, and Allison M. Thomson. 2014. Downscaling Global Land Cover Projections from an Integrated Assessment Model for Use in Regional Analyses: Results and Evaluation for the US from 2005 to 2095. Accepted for Publication in *Environmental Research Letters*.

We are assessing interactions between land and water, expanding GCAM to include irrigation.

- Allocation between irrigated & rainfed depends on economics.
- Profit rate for each will depend on yield, cost of production, and carbon price (if applicable)
  - Yields are higher for irrigated crops.
  - Costs are higher for irrigated crops.
  - Carbon implications are lower for irrigated crops.





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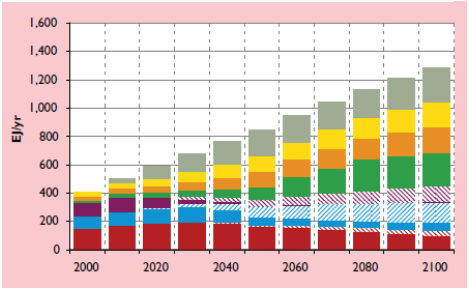
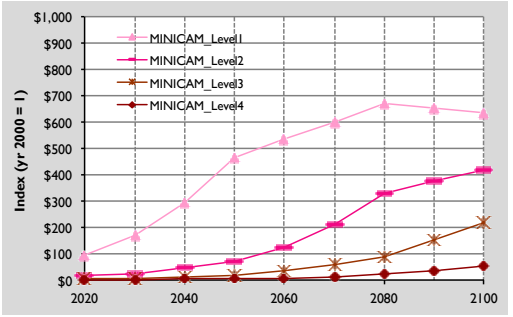
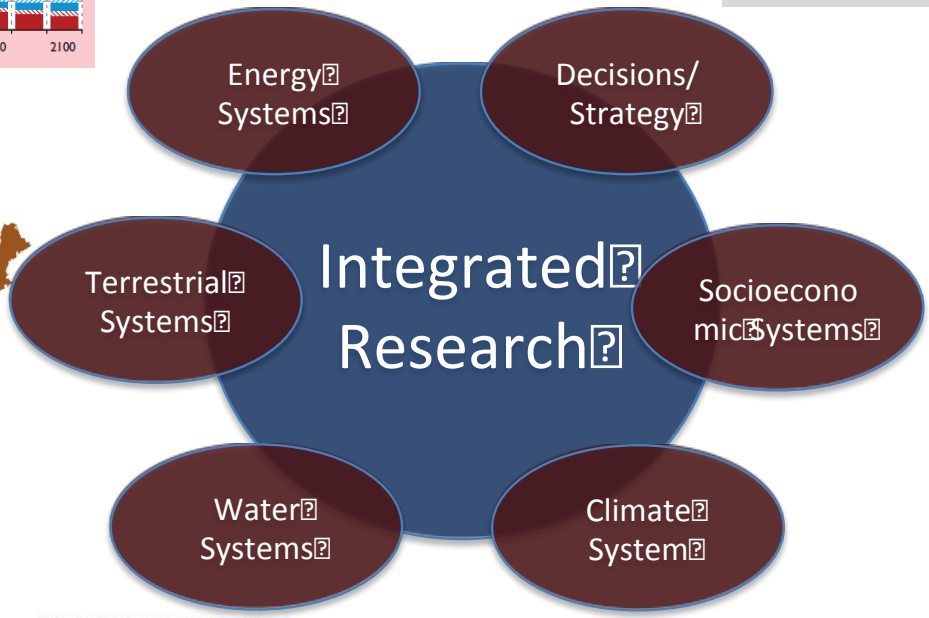
Changes in Energy Supply



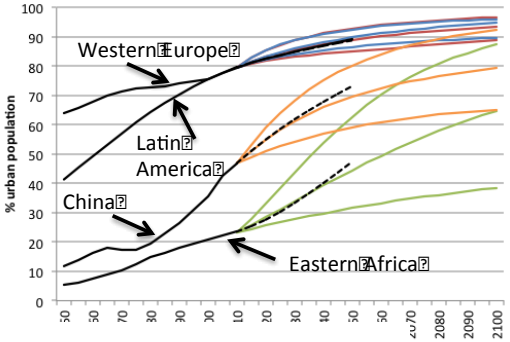
Carbon Prices



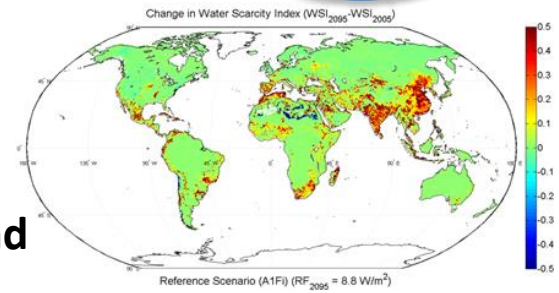
Land Surface Dynamics



Urbanization and Development



Measures of Water Supply/Demand



GHG Concentrations and Radiative Forcing