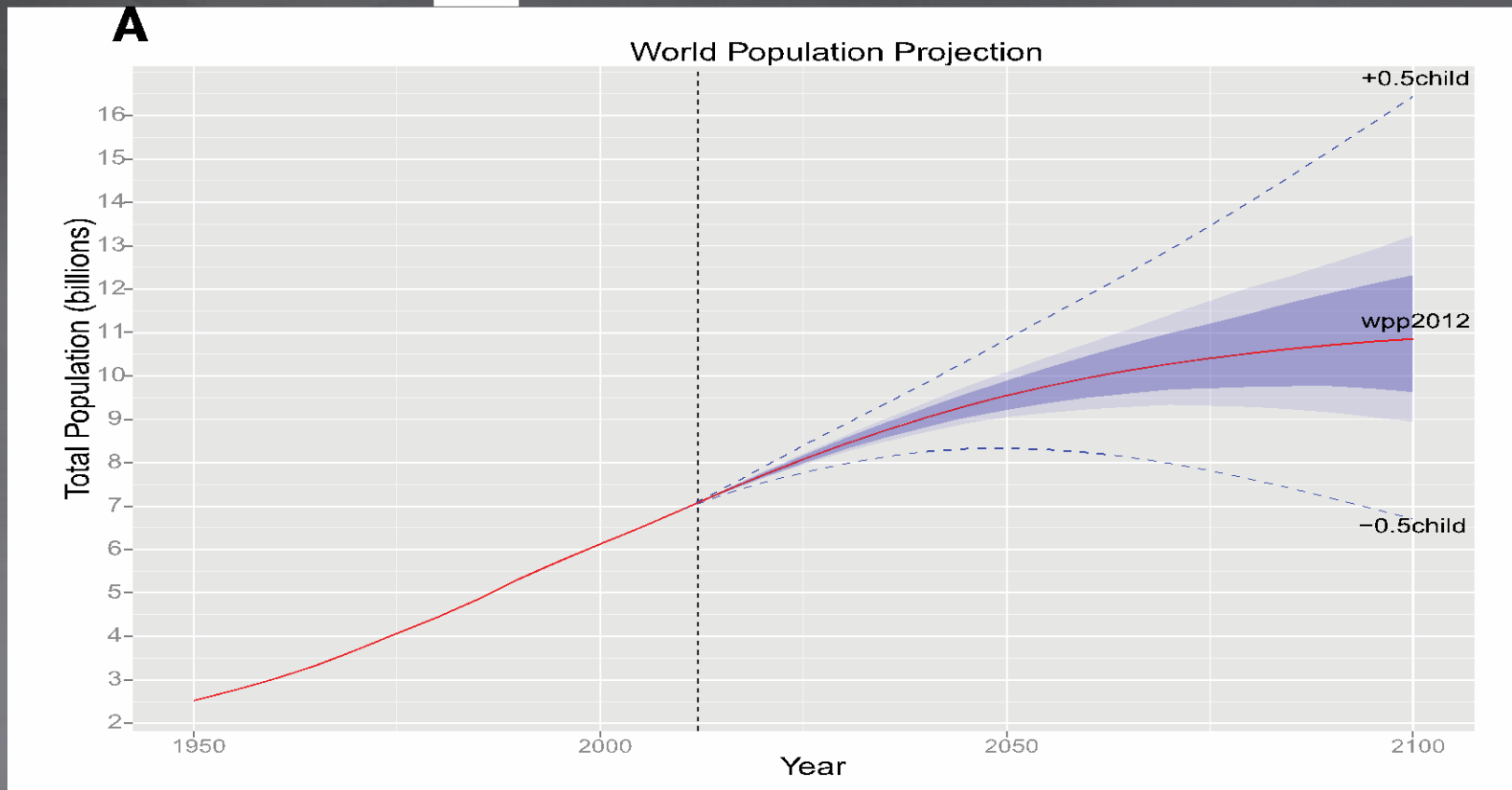


# Energy, Policy, and Ecosystems Services on a +11 Billion Person Planet: What's Ahead?

MARC IMHOFF

Joint Global Change Research Institute  
ACES 2014

# A More Crowded World: Approx. 11 Billion Likely by 2100



**From: World Population Stabilization Unlikely This Century**

P. Gerland et al., 2014. *Science* (10 October 2014): Vol. 346 no. 6206 pp. 234-237

# Energy, Water, Land on a +11-billion Person Planet...

Earth

Daytime Polar View (North)

MODIS Composite





# Urbanization - as a process - impacts ecosystems directly and indirectly.

Earth

Nighttime Polar View (North)

DMSP/OLS Composite

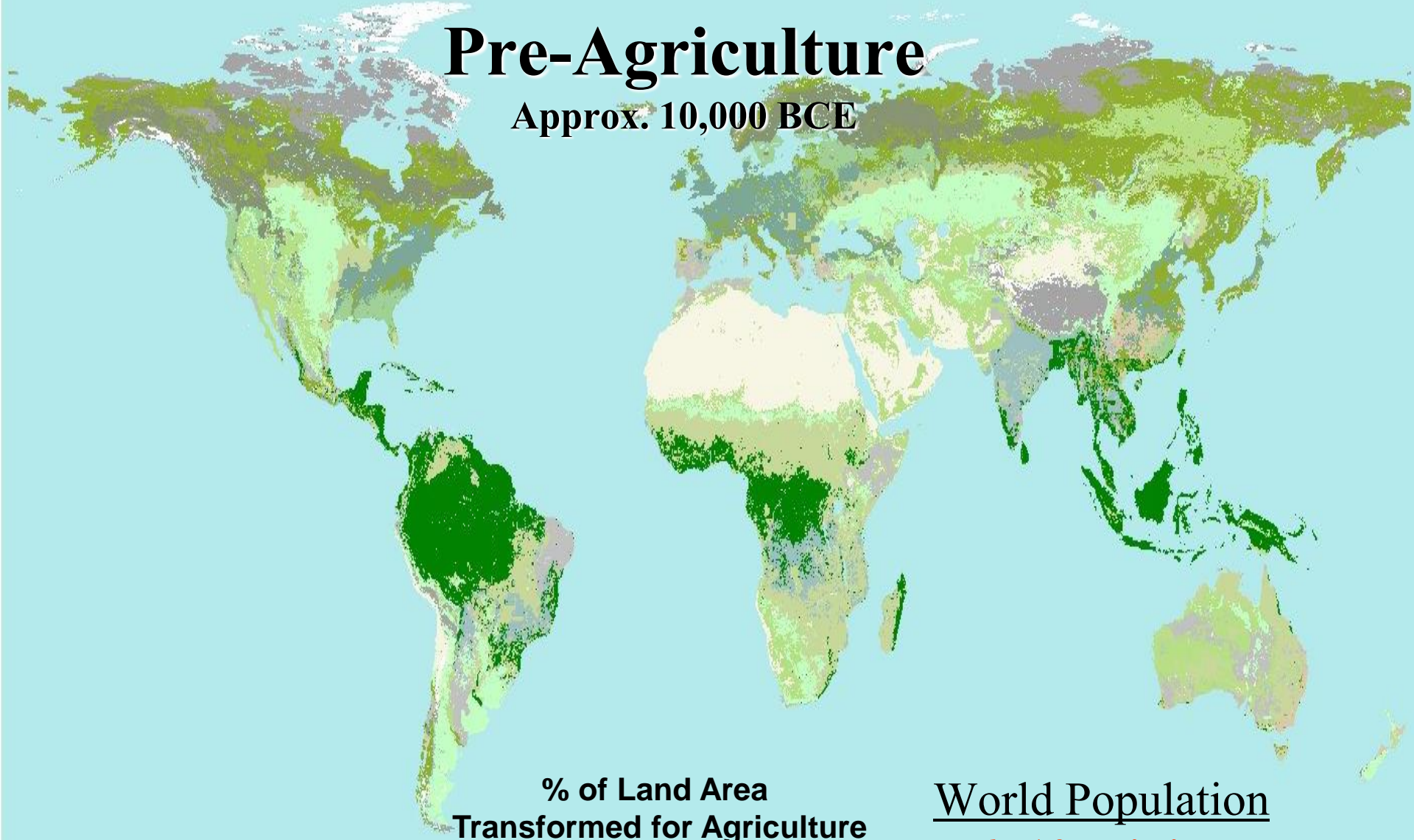


How do we address the complex interactions between the human and natural Earth systems in such a way that we can better determine our own destinies?



# Global Land Cover Pre-Agriculture

Approx. 10,000 BCE

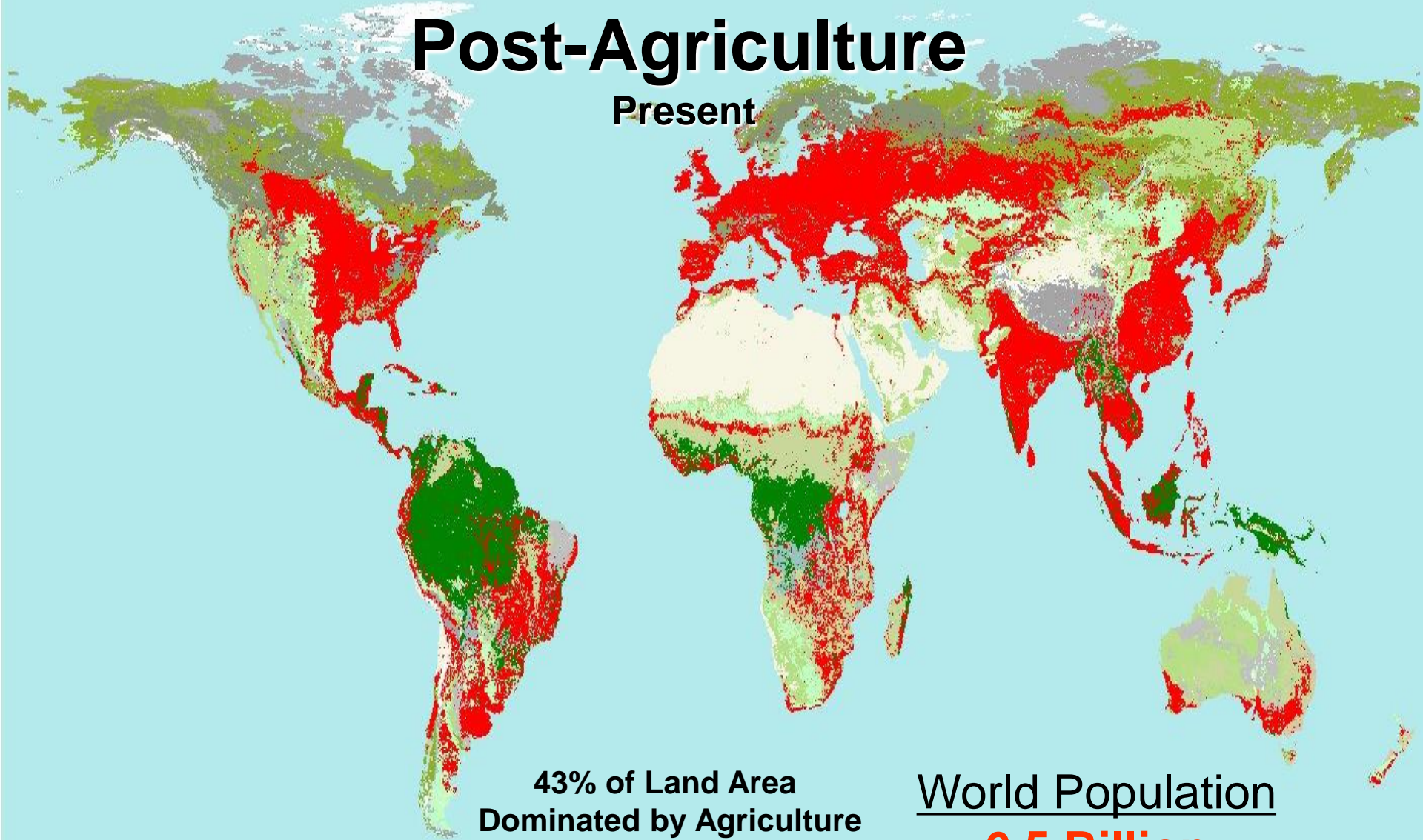


% of Land Area  
Transformed for Agriculture  
(Negligible)

World Population  
**6 -10 Million**

# Global Land Cover Post-Agriculture

Present



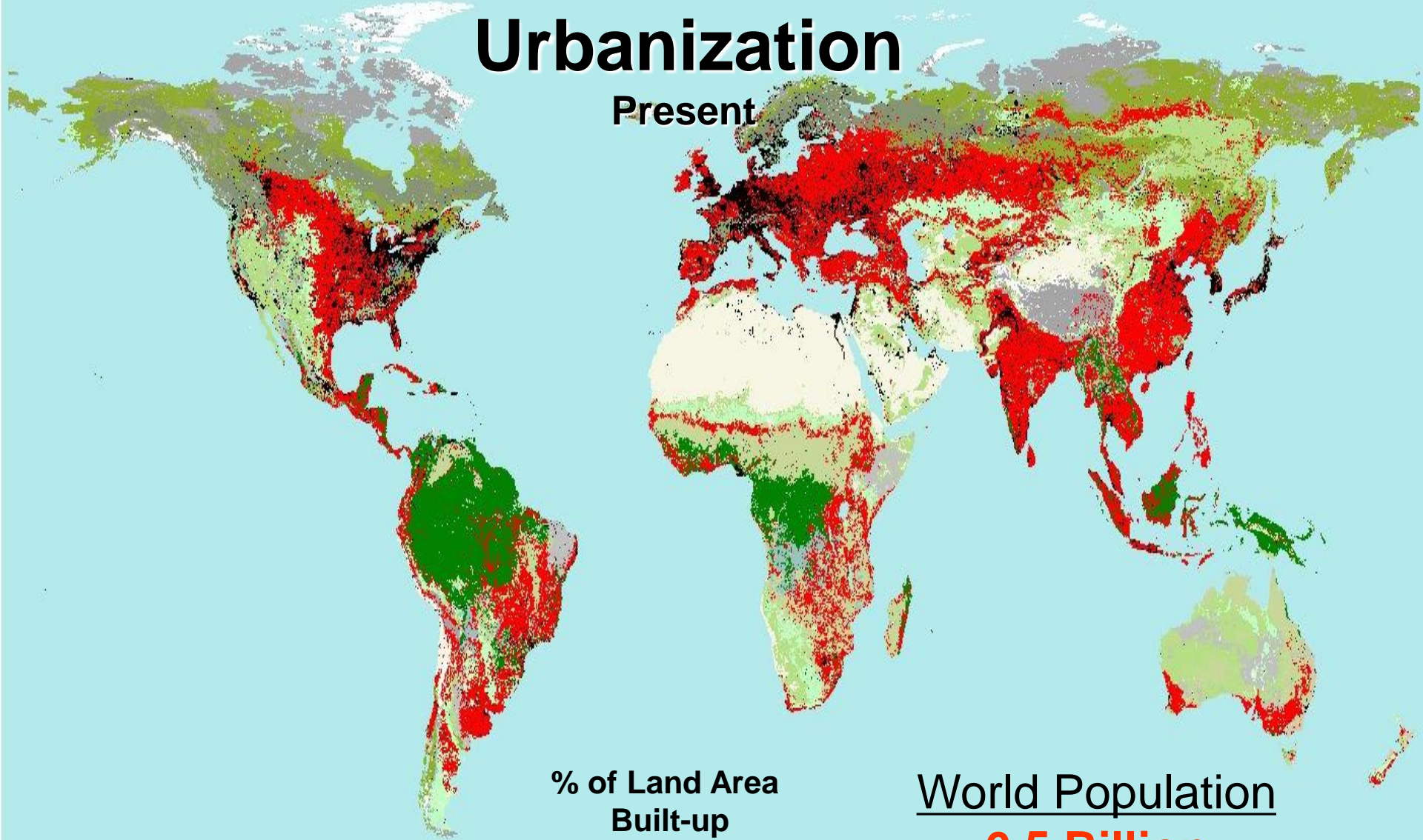
43% of Land Area  
Dominated by Agriculture

World Population  
**6.5 Billion**



# Global Land Cover Urbanization

Present



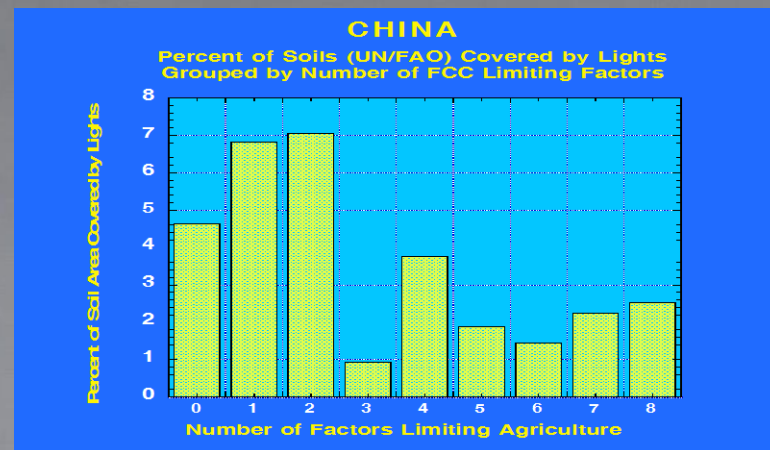
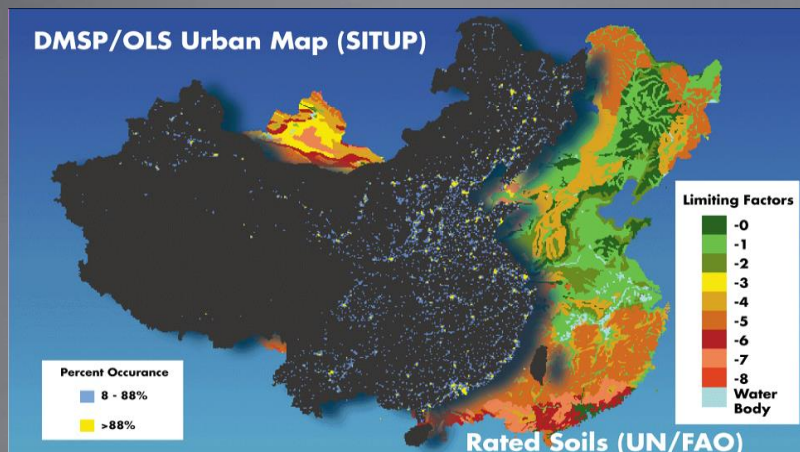
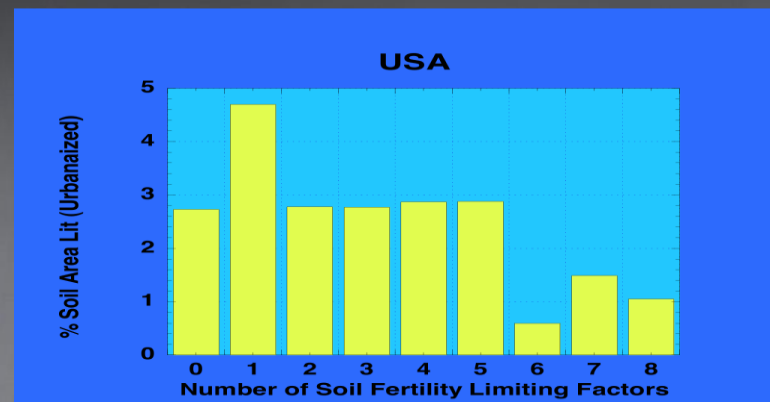
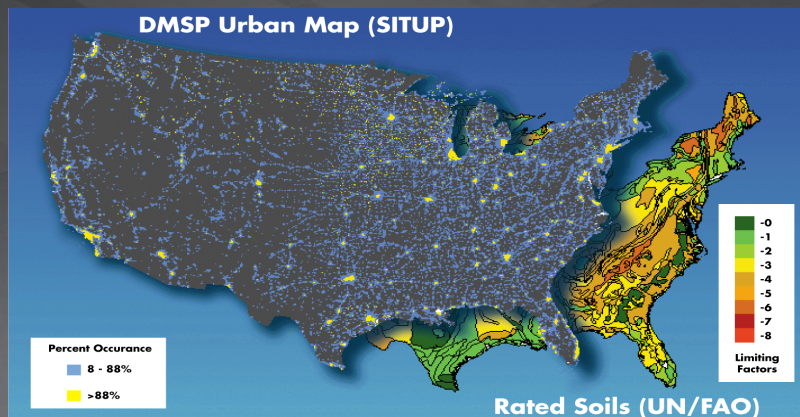
% of Land Area  
Built-up  
3 - 6%

World Population  
**6.5 Billion**



# Food Energy and Competition for Land: Urban Occupation of Fertile Soils (circa 1995)

GIS overlay of processed Nighttime city lights data on soil productivity maps



# ***China to Flatten 700 Mountains to Build a City | TIME.com***



**Pacific Northwest**  
NATIONAL LABORATORY

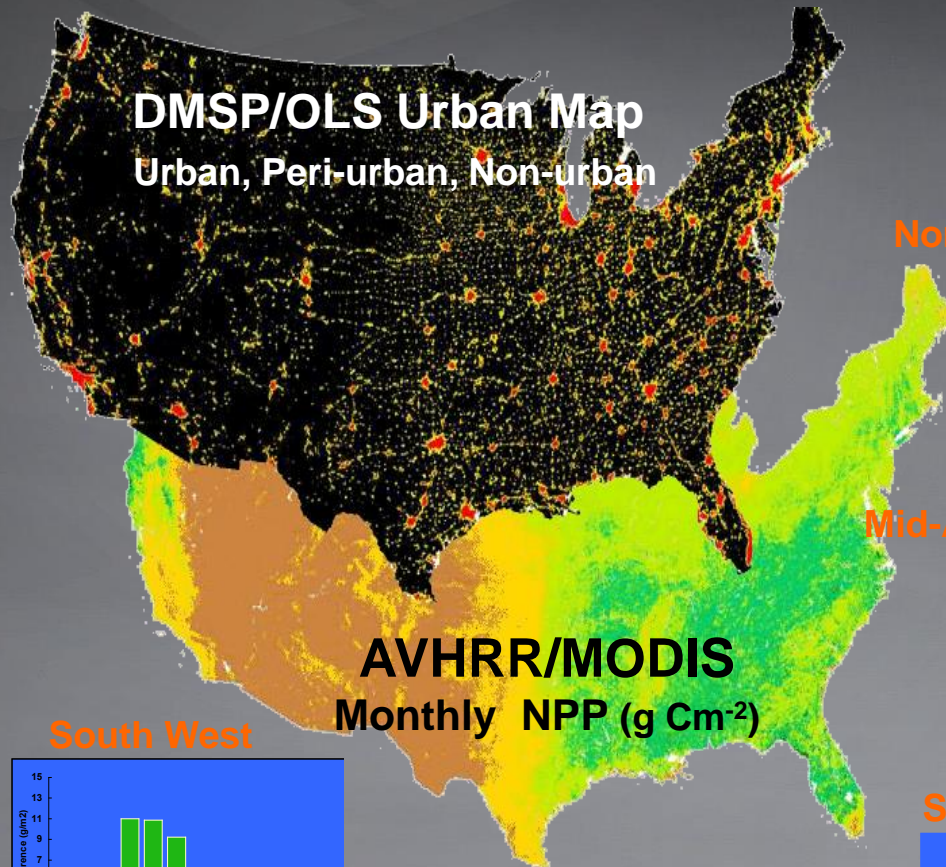
*Proudly Operated by Battelle Since 1965*





# Consequences of Urbanization on NPP

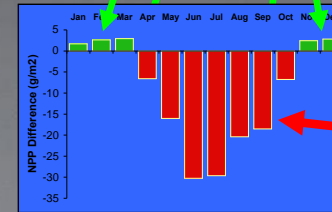
## Satellite Observations



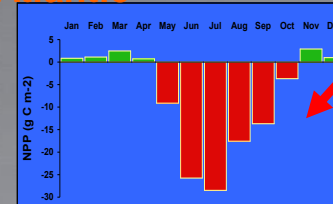
## NPP and Local Climate:

Urban Heating Extends  
Length of growing season  
locally in cold climates.

### North East

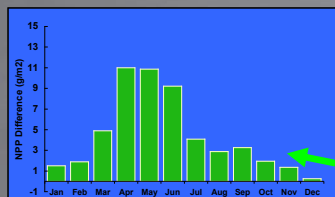


### Mid-Atlantic



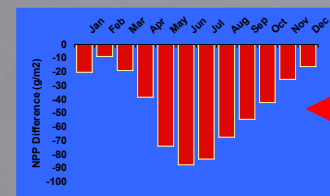
Winter NPP  
gain negated  
in peak  
season by  
reduced  
vegetation  
and heat  
stress.

### South West



In semi-arid regions cities  
enhance NPP relative to  
surrounding areas

### South East



Seasonal Offset  
diminishes in  
tropics





# Consequences of Urbanization on NPP-Carbon in the U.S.

## ***Urbanization and NPP***

- NPP decreased 41.5 M tons C / year.
- Roughly equivalent to the increase created by 300 years of agricultural development.

**How can this happen when urban areas occupy only 3% of the land surface and agriculture occupies 29%?**

## ***Location, Location, Location.***

***Urbanization is taking place on the most fertile lands***

Reduction of NPP may have biological significance:

## **NPP Lost or Gained (annual) Due to Urbanization**

Going from a pre-urban to a post urban world

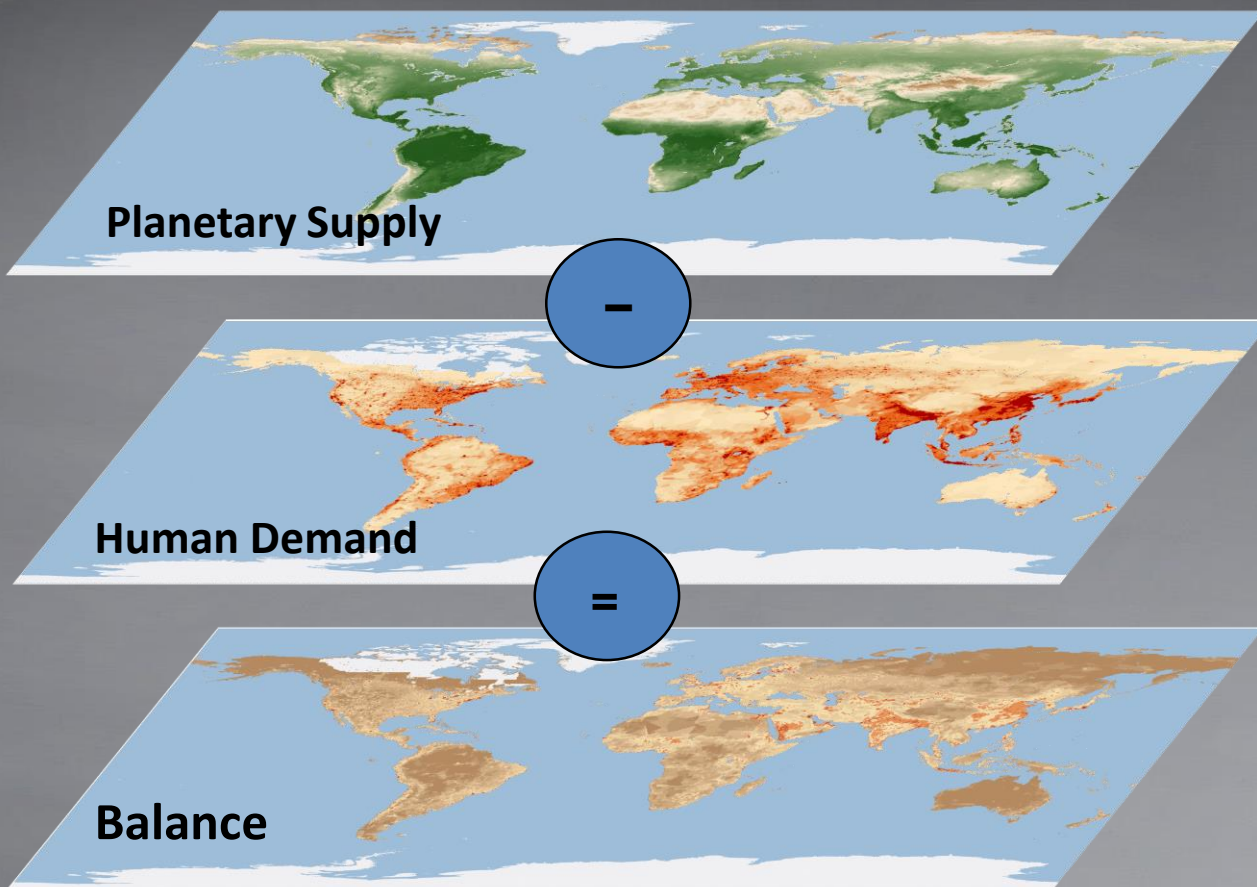
**Total Reduction  
41.5 Mt C**

**From Ag Lands  
25.5 Mt C**



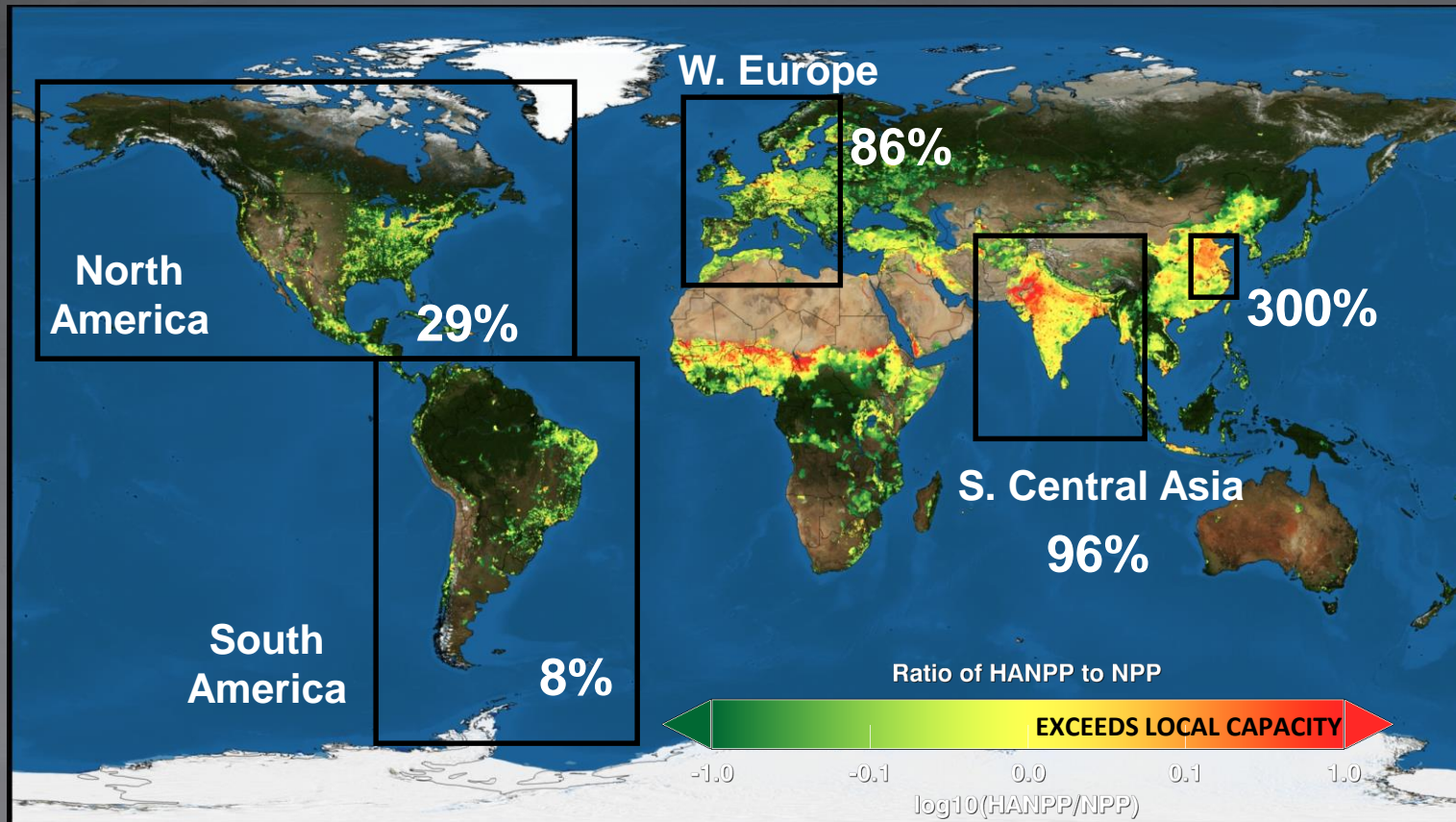
# Human Consumption of NPP: Can the Earth Keep Up?

## NPP Carbon Balance



# Geography of Food Energy: Human Appropriation of NPP (HANPP) as % of Terrestrial Supply

Some regions exceed their local capacity by many times.  
Food security dependent on trade.



M. L. Imhoff et al., Nature 429, 870, 2004  
M. L. Imhoff et. al., JGR, VOL. 111, 2006

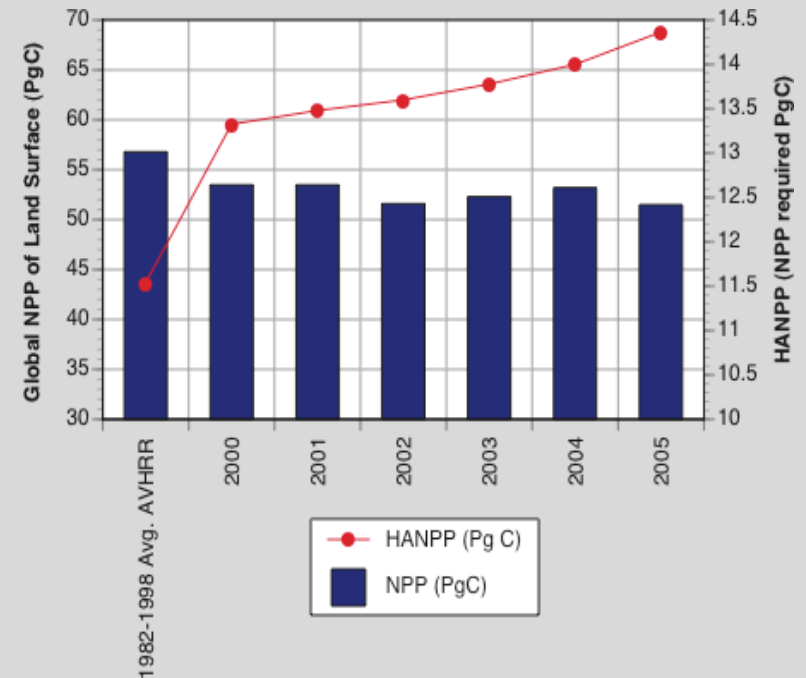
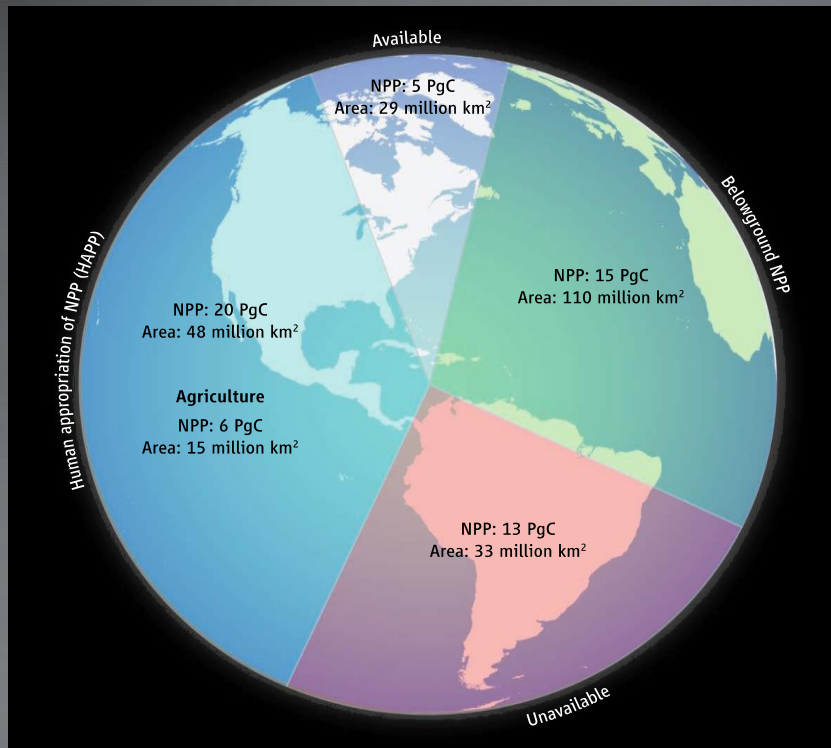




# Will human consumption of primary plant production soon reach its limits?

Terrestrial net primary (plant) production provides a measurable boundary for human consumption of Earth's biological resources.

Satellite observations of planetary NPP  
“Supply” shows no trend but human  
“Demand” is rising



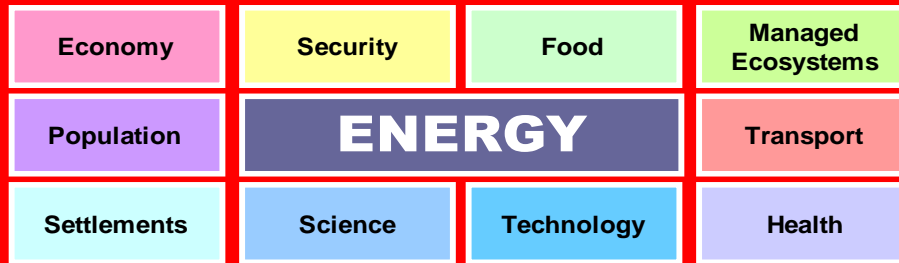
# What Are the Real Limits and Sensitivities of the System?

- ▶ Snapshot based analyses of HANPP or other resources are not adequate to understand the limits and associated trades available to overcome them.
- ▶ **A systems based approach that can account for the interactions of the Earth and Human systems is needed.**
  - Products must be “dynamic” and capable of both hindcasting for uncertainty analyses as well as have prognostic capability for testing potential outcomes of choices (sensitivity).
  - ***Critical for policy evaluation!***

# Integrated Assessment:

Energy, Water, Land, Demographics, Economics, Technology, Policy, Climate - fully coupled in a single model

## Human Systems



## Natural Earth Systems



## PNNL's Global Change Assessment Model (GCAM)

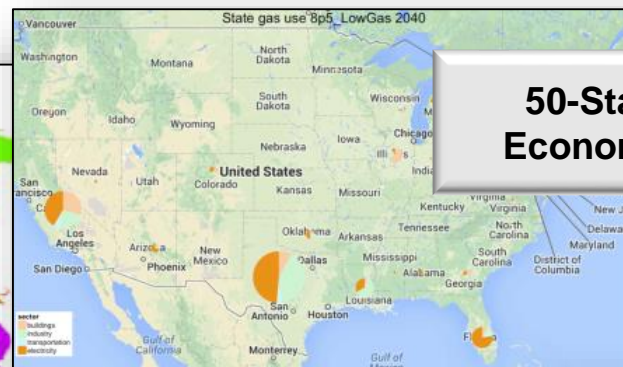
- ▶ GCAM is a **global integrated assessment model**
- ▶ GCAM links **Economic**, **Energy**, **Land-use**, **Water** and **Climate** systems
- ▶ Technology-rich model
- ▶ Emissions of 16 greenhouse gases and short-lived species: CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>O, halocarbons, carbonaceous aerosols, reactive gases, sulfur dioxide.
- ▶ Runs through **2095** in **5-year time-steps** – **soon 1 year time steps**
- ▶ GCAM has participated in virtually every major climate/energy/economics assessment over the last 20 years
- ▶ Globally, there are roughly six IA teams with RCP-class IA models
- ▶ GCAM is a community model
- ▶ Documentation available at: [wiki.umd.edu/gcam](http://wiki.umd.edu/gcam)



# GCAM's Adaptive Spatial Resolution

**32 Energy  
Economy  
Regions**

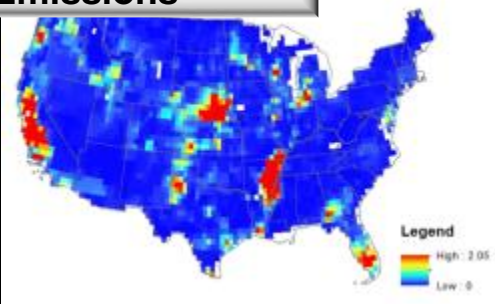
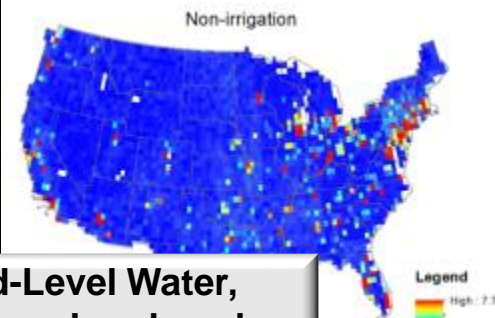
**50-State Energy  
Economy Regions**



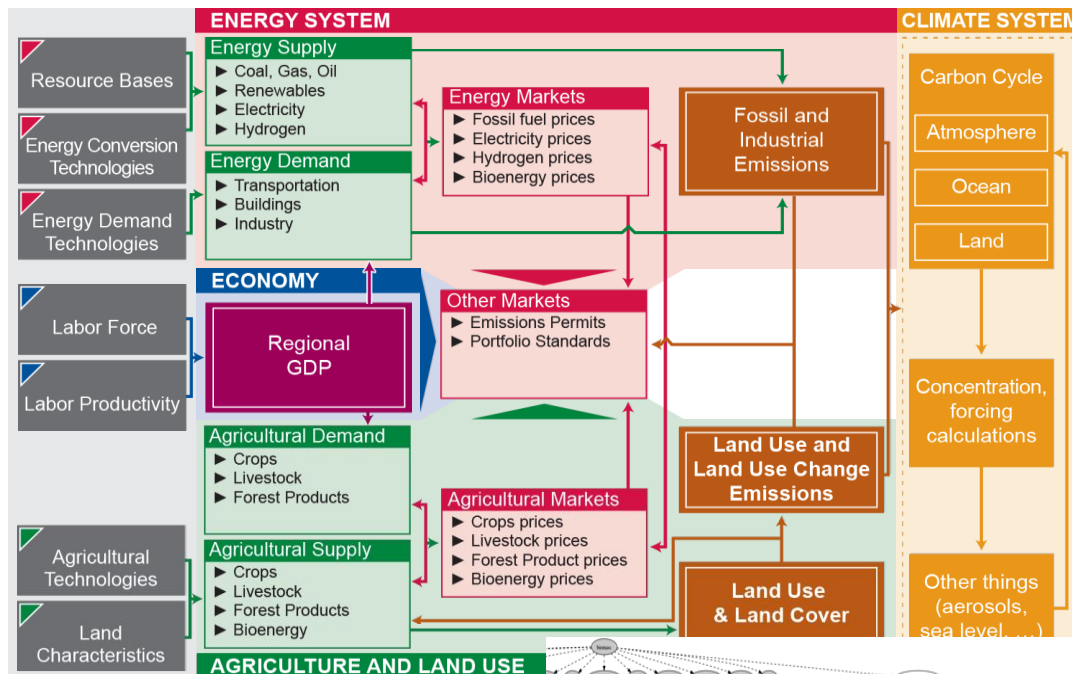
**283 Land  
Regions**

**Grid-Level Water,  
Energy, Land, and  
Emissions**

**233 Water  
Basins**

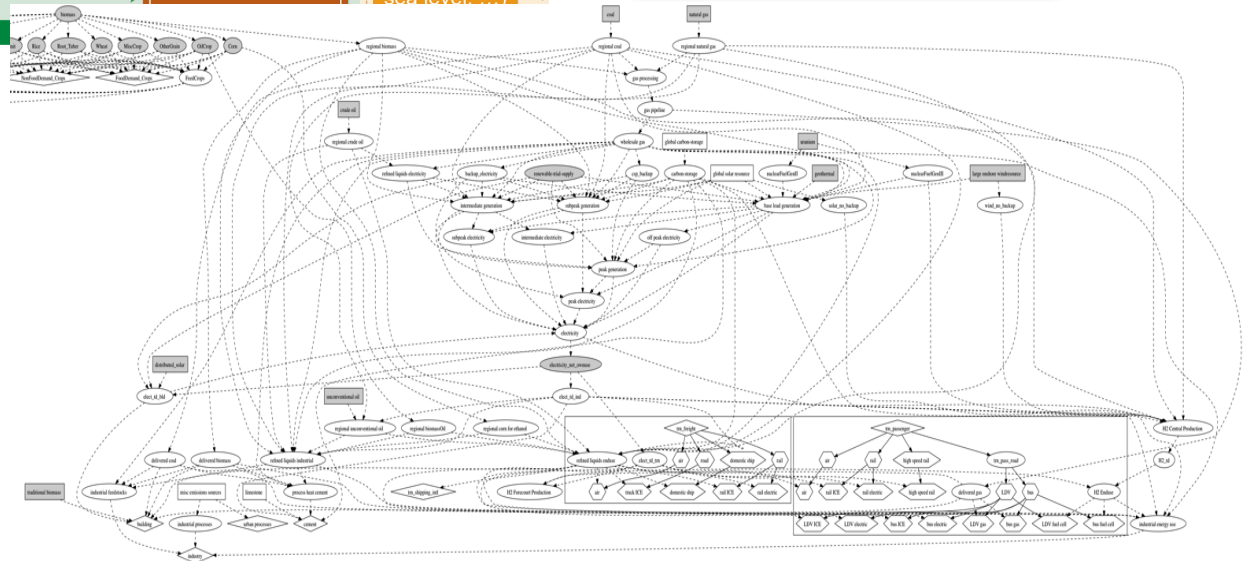


# GCAM Structure and Function



Integrated Assessment means complex relationships are retained. Global drivers and regional outcomes.

These systems can get very complicated very quickly.

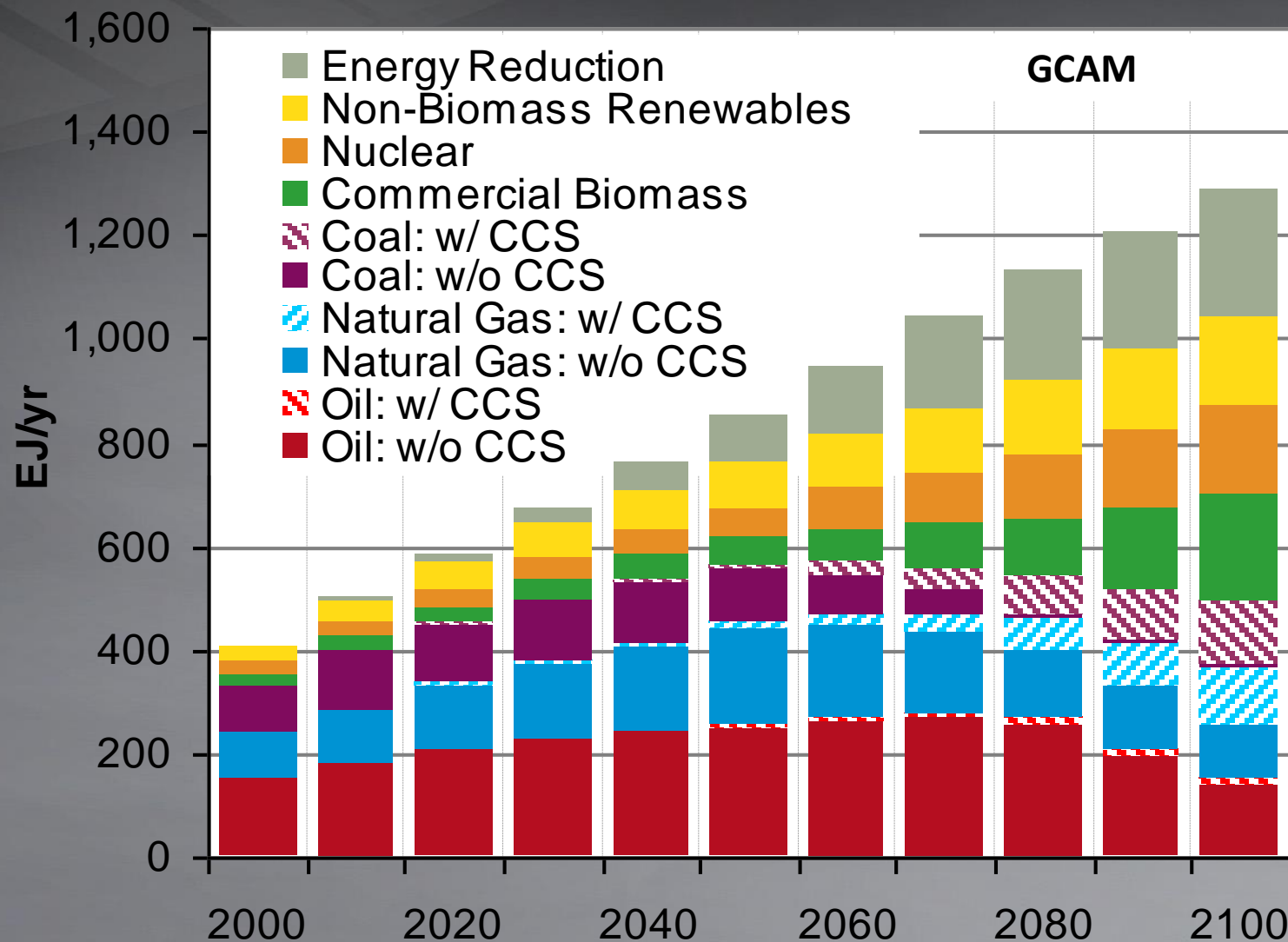


# GCAM allows for fully integrated inquiry and “What if” Scenarios

- ▶ How will growth and changes in the global demand for energy, water, and agricultural goods affect each other and impact stability?
- ▶ What are the factors that drive these changes?
  - **Energy sources, Technology** (generation, conversion, transmission), **Socio-economics** (economics, demographics, and migration), **Policies** (national and multinational), **Water scarcity, Food production and prices, Climate** and **extreme weather**.
- ▶ How do these drivers interact (+ or - feedbacks)?
- ▶ **Who “wins”? Who “loses” if....?**
  - **Simple questions. Complex answers!**



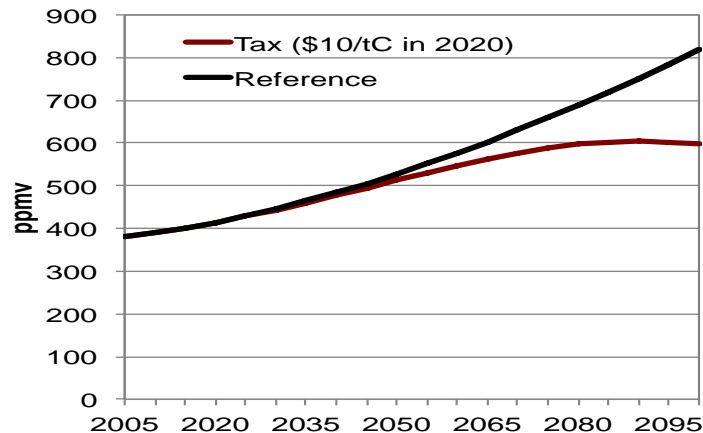
# Global Energy Portfolio (Primary Energy) to Meet a 550 ppmv CO<sub>2</sub> target by 2100



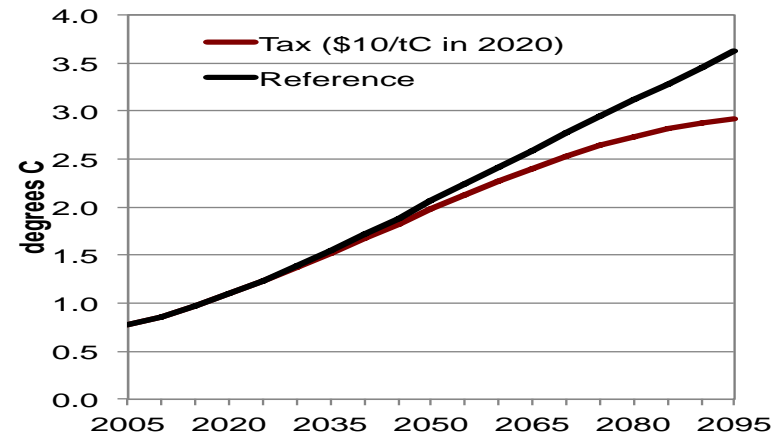
From *CCSP Product 2.1a: Scenarios of Emissions and Greenhouse Gas Concentrations*

# How do climate change policies affect fossil fuel and agriculture prices?

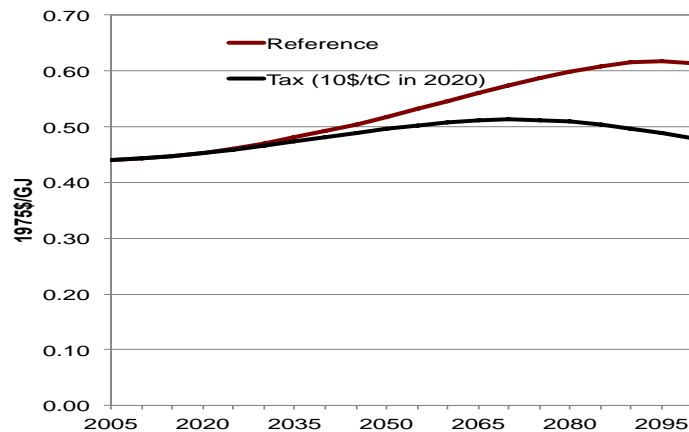
## CO<sub>2</sub> Concentration



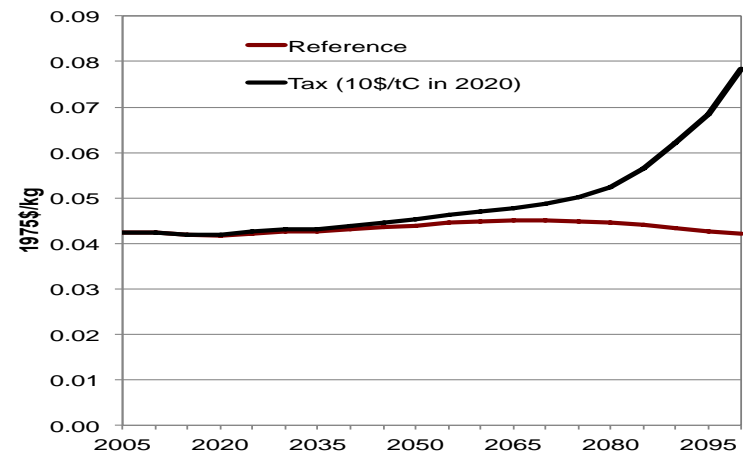
## Global Mean Temperature Rise



## Coal Price



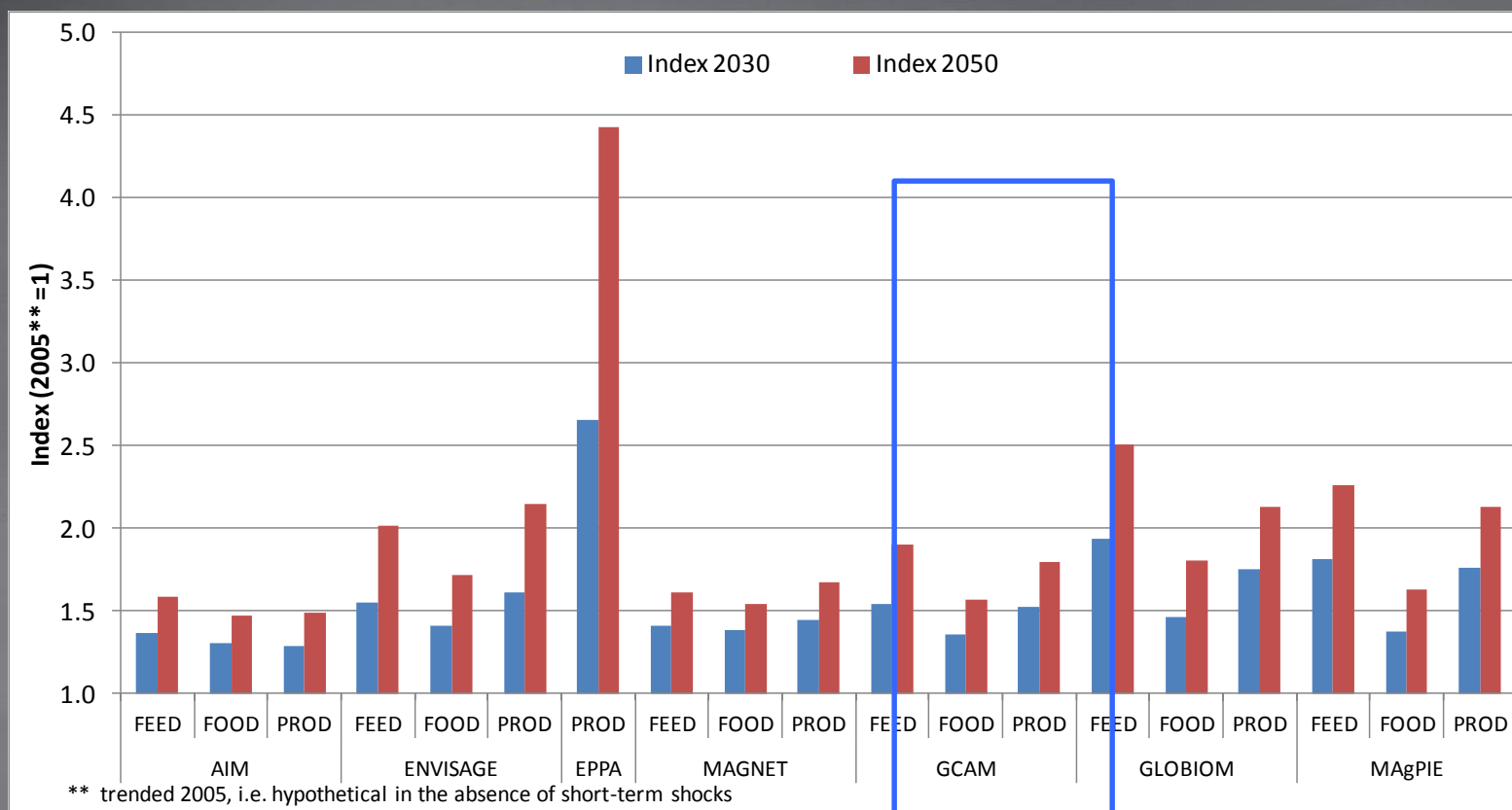
## Wheat Price



# How Much Food Will We Need?

- ▶ Global agricultural economic modeling for AgMIP
- ▶ Model comparison among leading models
- ▶ Harmonized reference case and both climate impacts and bioenergy scenarios

## Results projected to 2030 and 2050

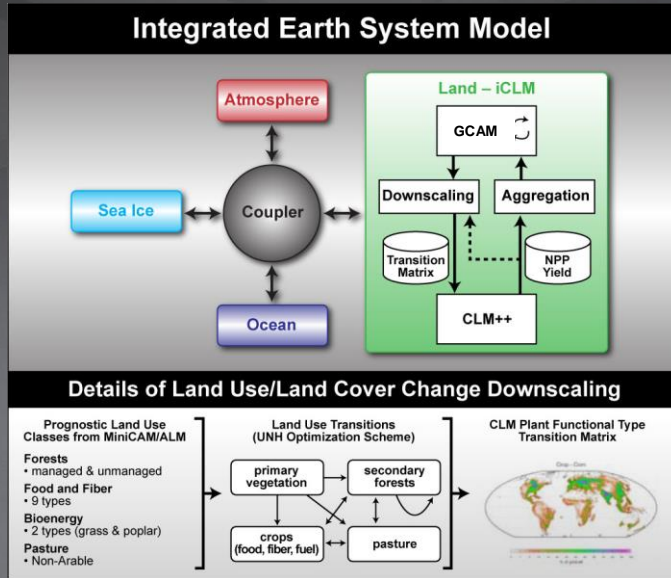


Future world agricultural production (feed and food) needed compared to 2005

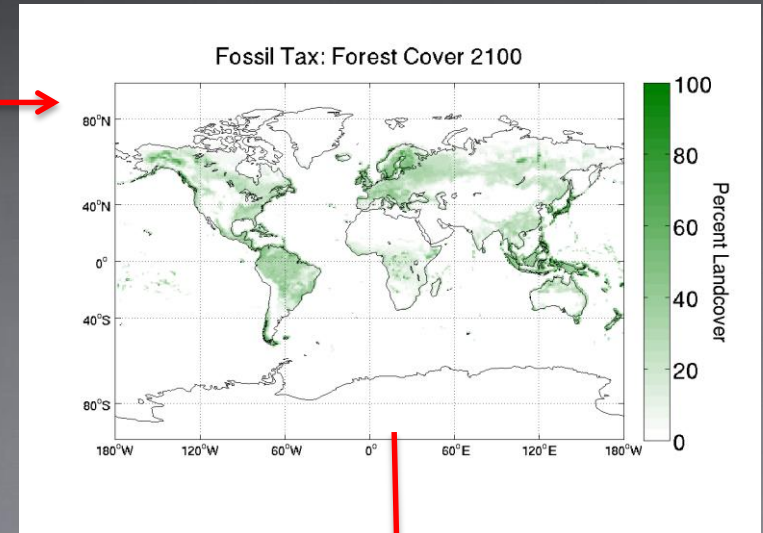


# Energy policy can have surprising feedbacks with land cover and climate forcing!

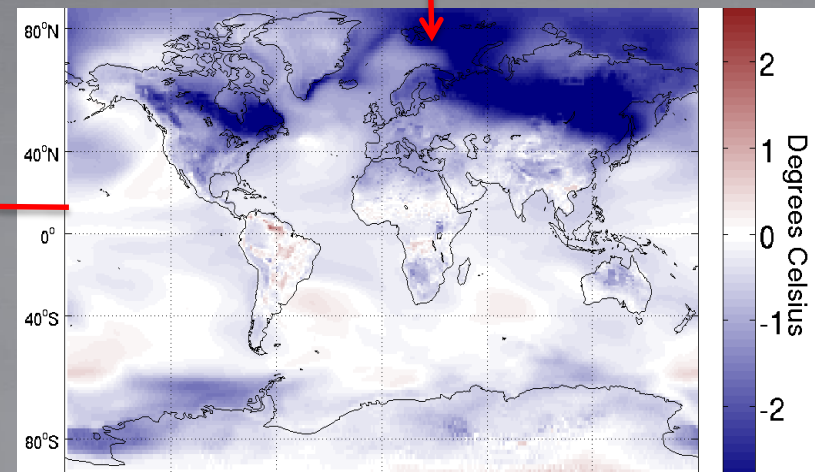
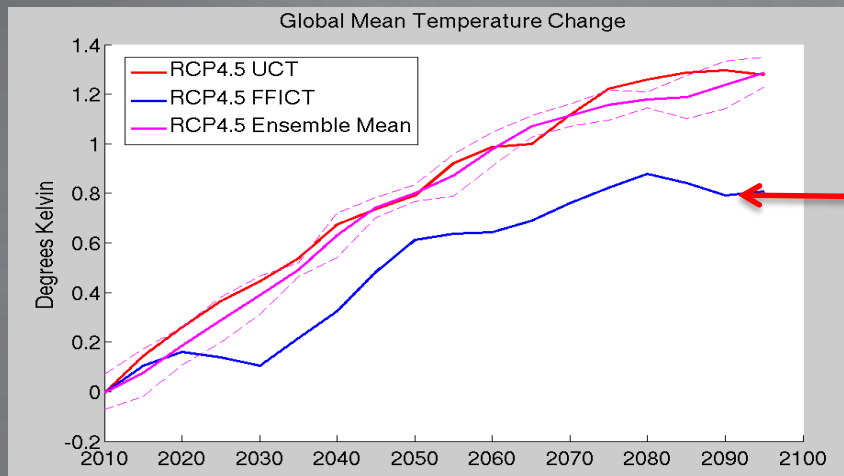
**Taxation policy favoring biofuels raises food prices, decreases coal prices, accelerates deforestation, and slows down climate warming due to raised surface albedo.**



Fossil Fuel  
Only Carbon  
Tax resulted  
in nearly 50%  
deforestation



**Higher albedo = cooling!**



# Water Impacts: Current Results

Many parts of the world will face more scarcity in the future, largely driven by changes in demand

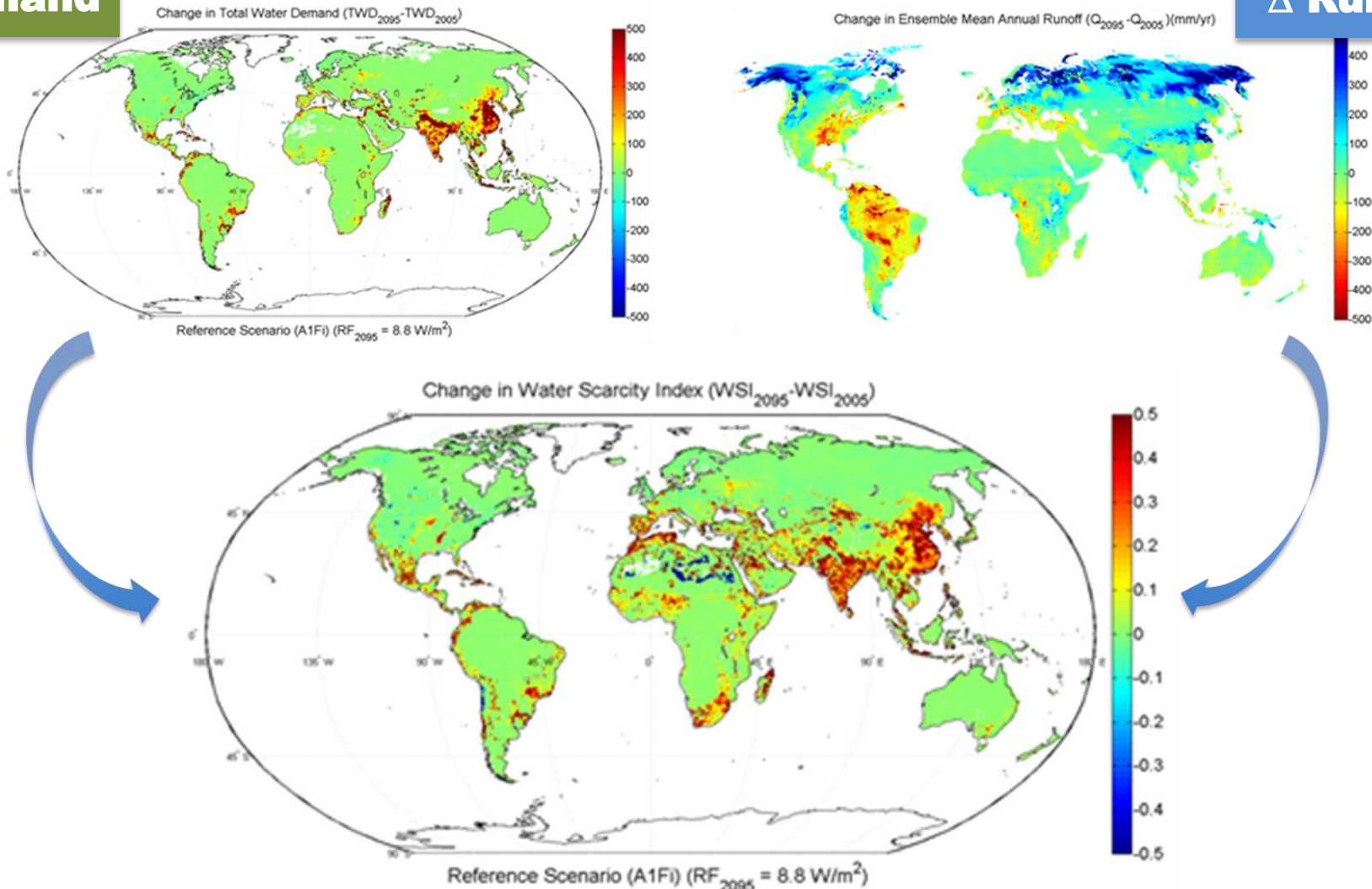


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## Δ Demand

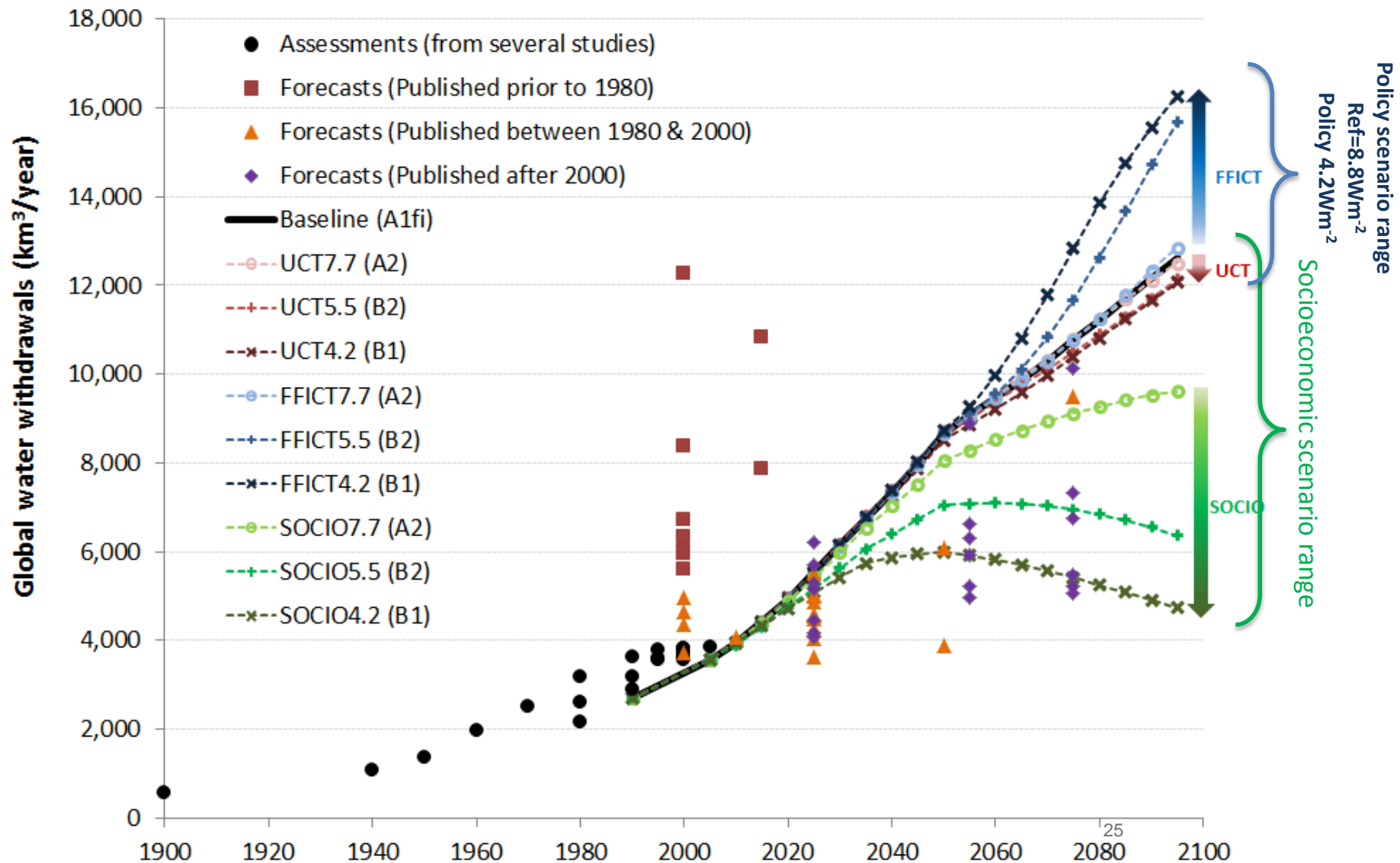
## Δ Runoff



## Change in Scarcity

Source: Hejazi et al. (2014). 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.

# Future water demands depend heavily on socioeconomic developments

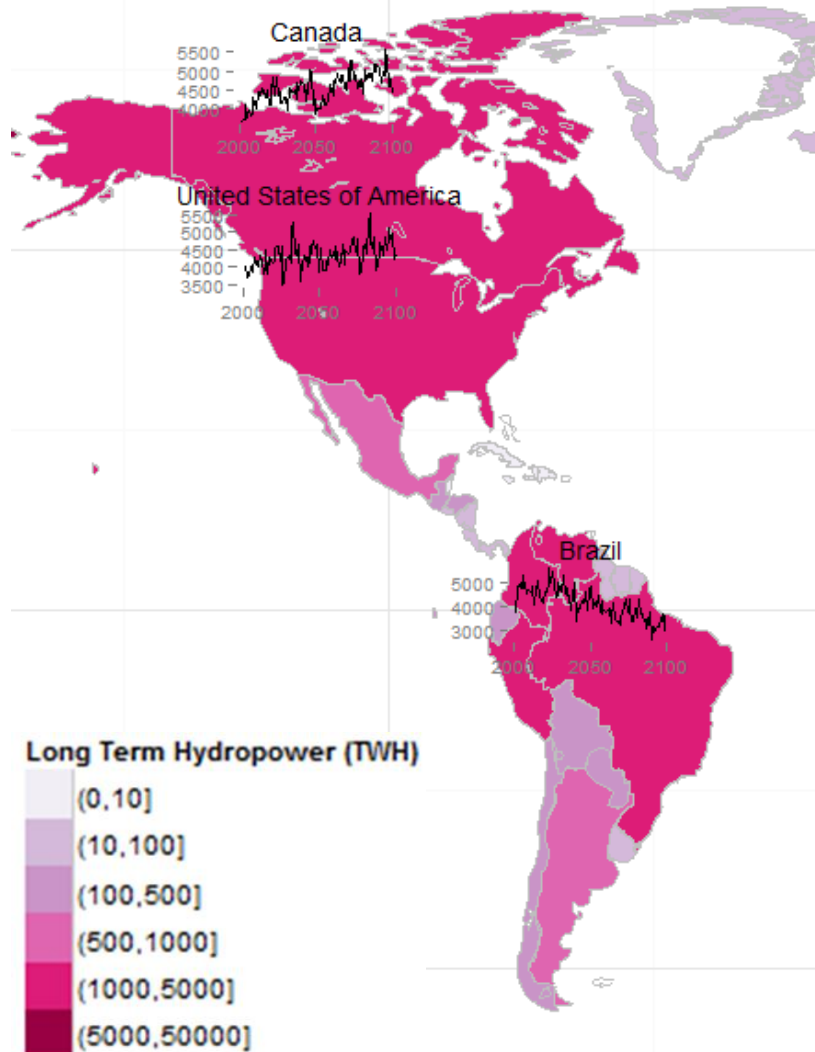




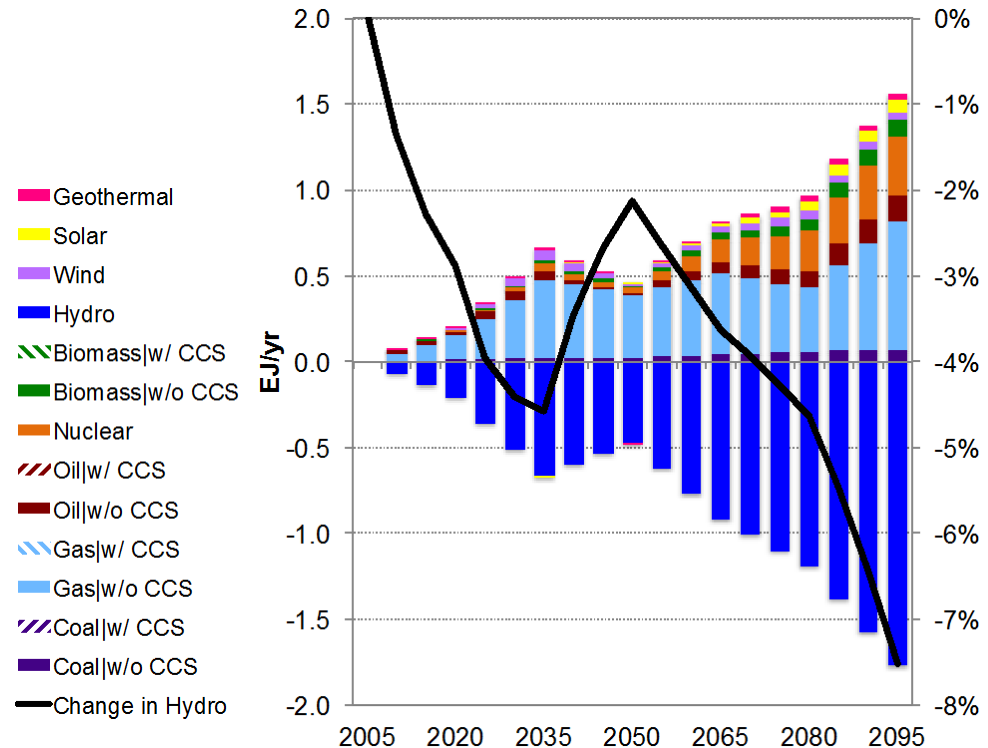
# Water Impacts: Key Research Directions

Climate change will affect hydropower generation, which in turn affects other electricity generation

## Hydropower potential (HadGEM)



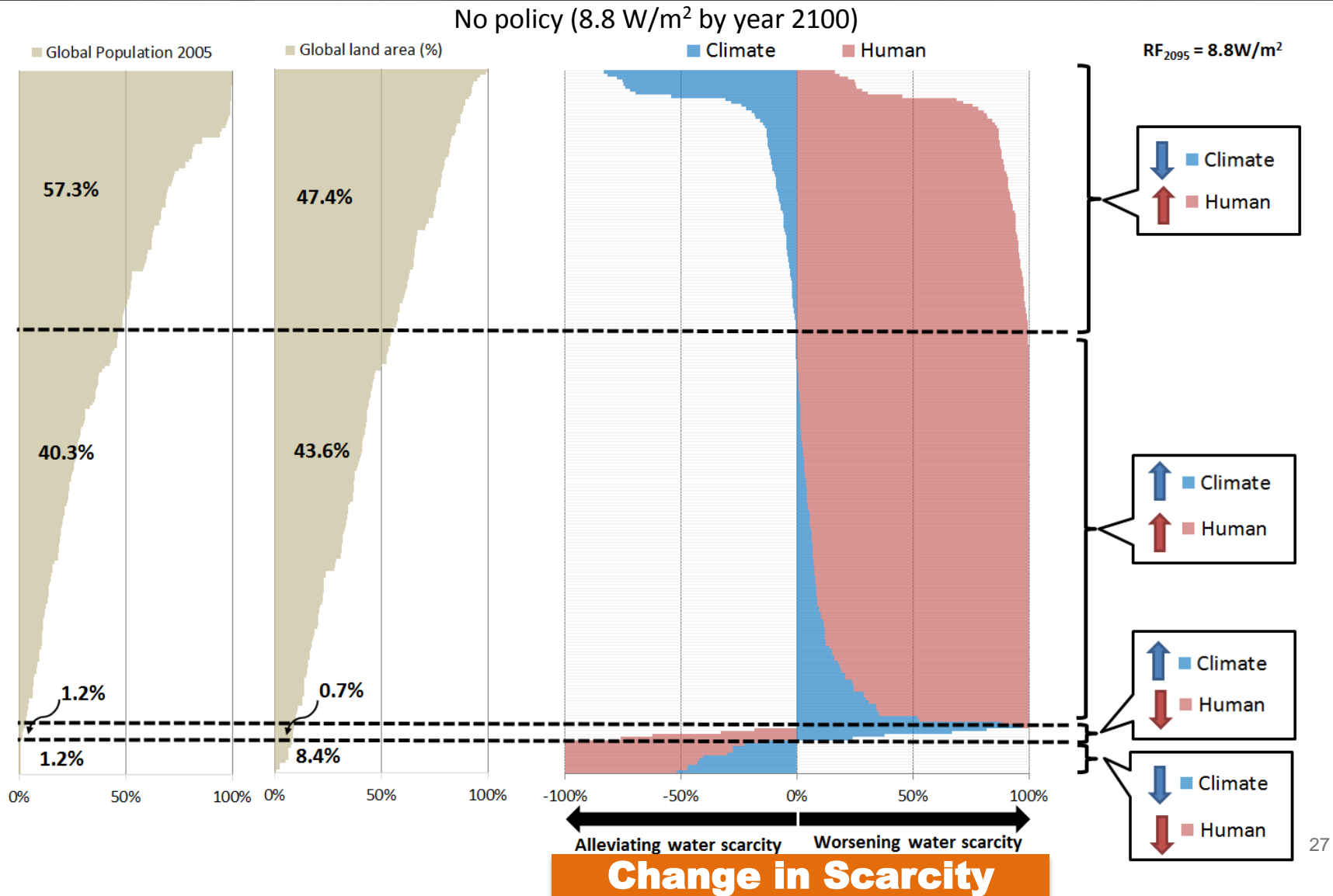
## Latin America



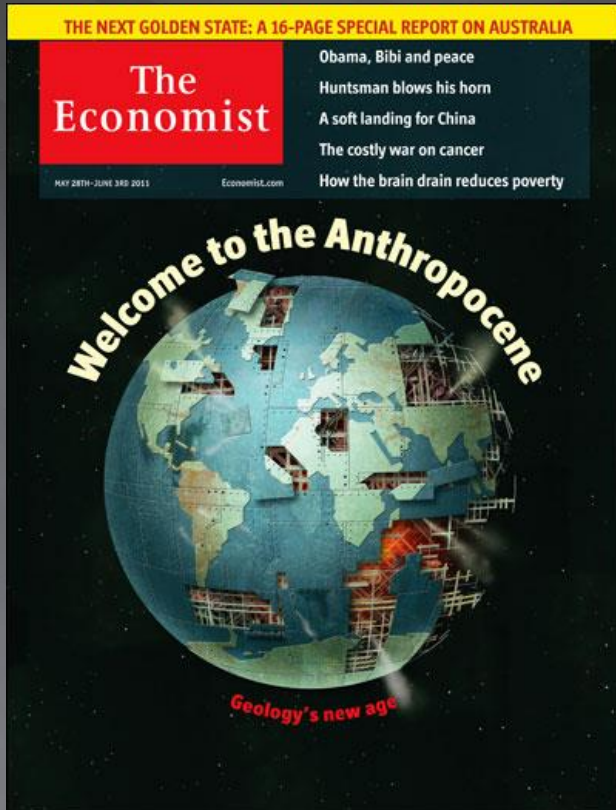
Positive values mean an increase in electricity generation when impacts are considered

# Water Impacts: Current Results

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

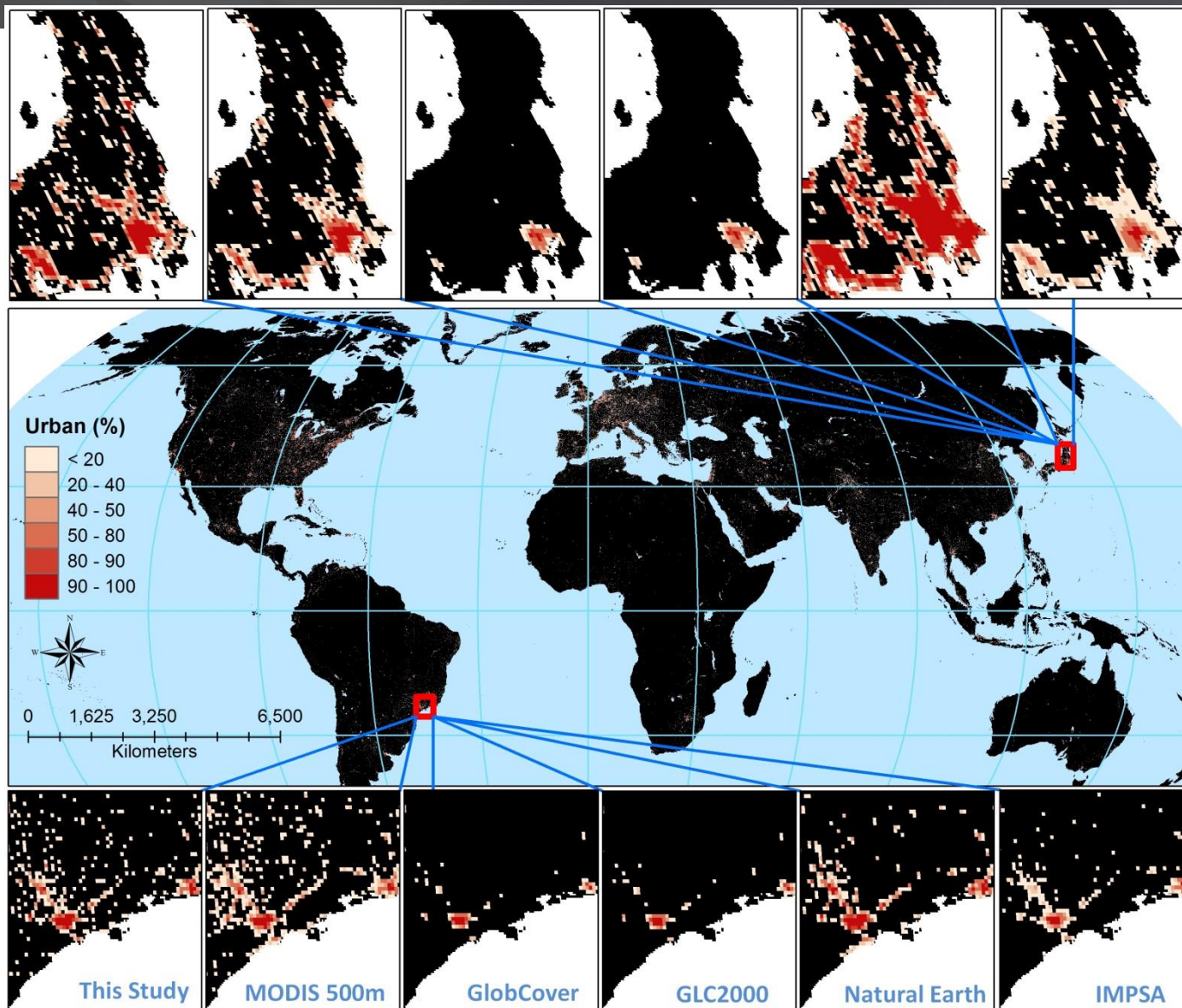


# Urbanization in the Anthropocene: What's Ahead for Food Security, Energy, and Climate?





# Spatial extension (global urban mapping)



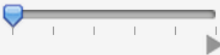
# An online modeling and visualization system

Province

Beijing ▼

urban in year

1,992 2,012



☐ Overlay County

Run Regional Modeling

Run

Run Spatial Modeling

Run

Run Projection

Run

History Patterns

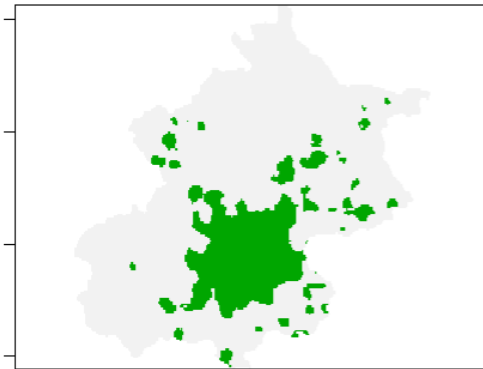
Urbanization Modeling (R.)

Urbanization Modeling (S. validation)

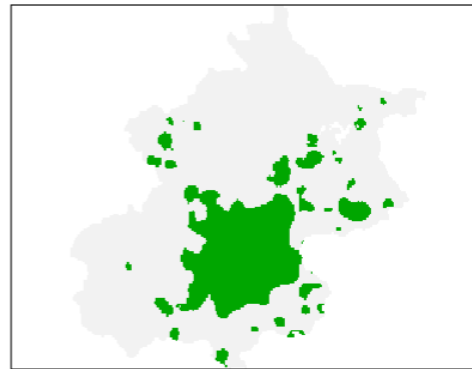
Urbanization Modeling (S. evaluation)

Urbanization Projection (S.)

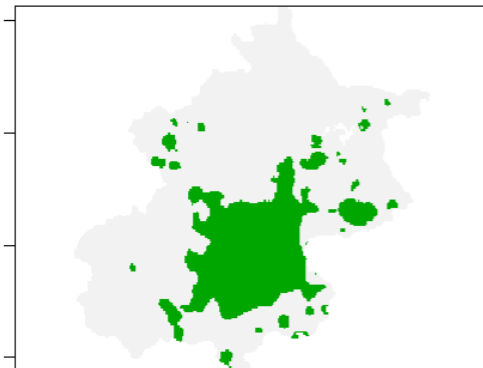
2012



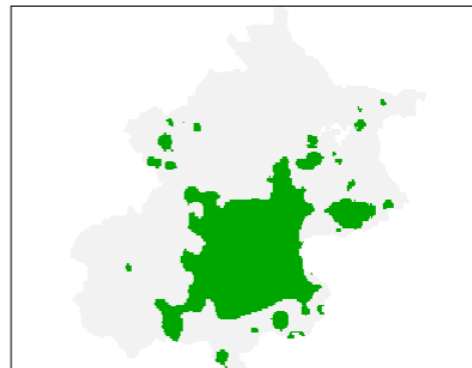
2015



2020



2025

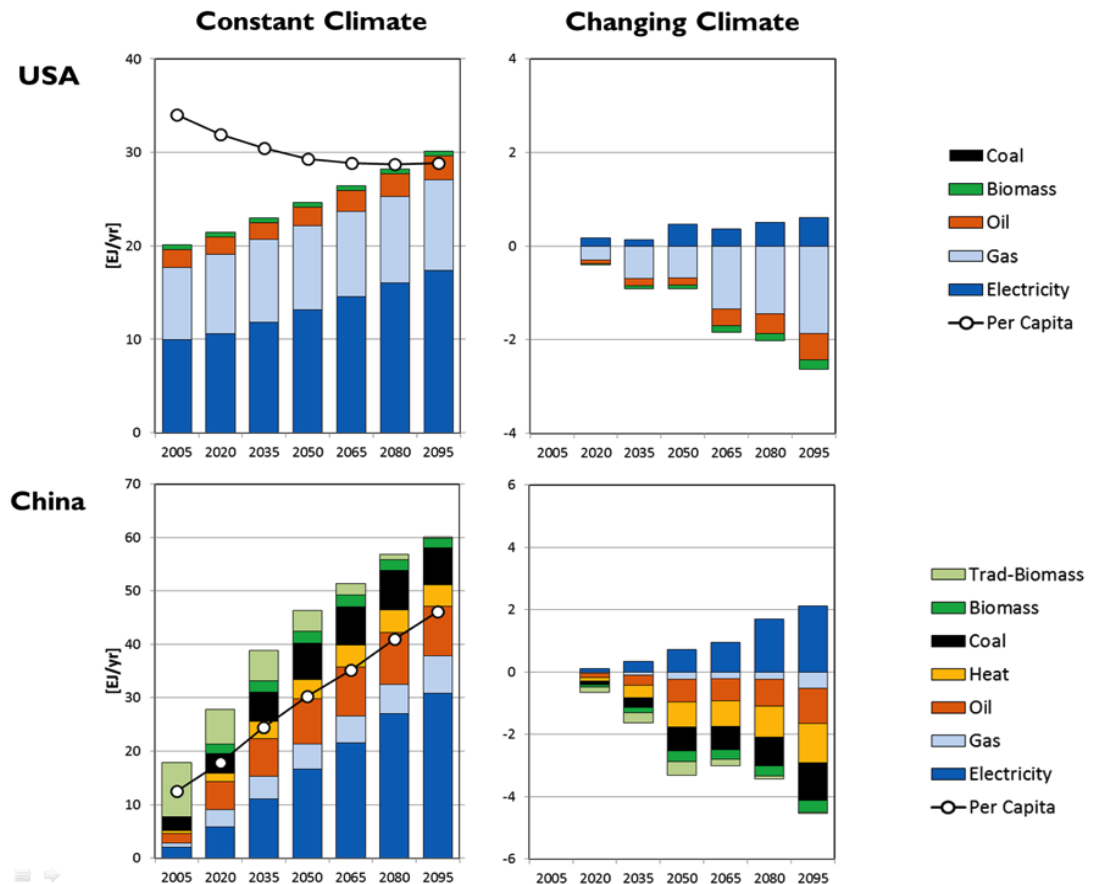


<http://terpconnect.umd.edu/~yuyuzhou/urbanization.html>

# How Will Climate Change Affect Energy Demand for Urban Areas?

## Building energy demand out to 2095 in the U.S. and China

Climate change reduces overall energy use for some areas but shifts pressure onto cooling in the building sector resulting in an added demand for electricity in megacities.



(Source Zhou, 2013)

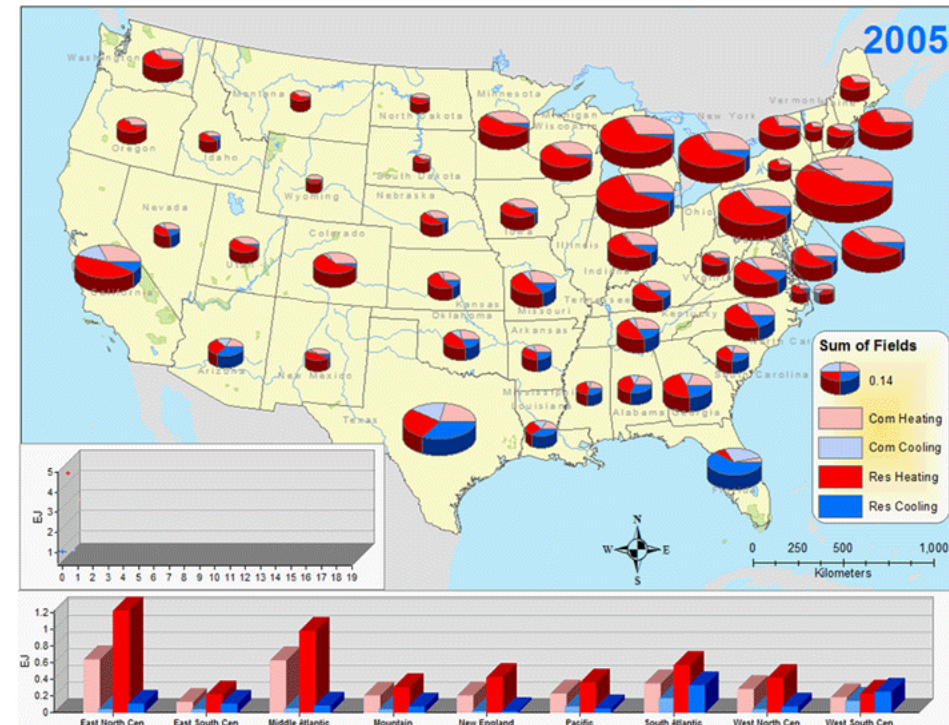
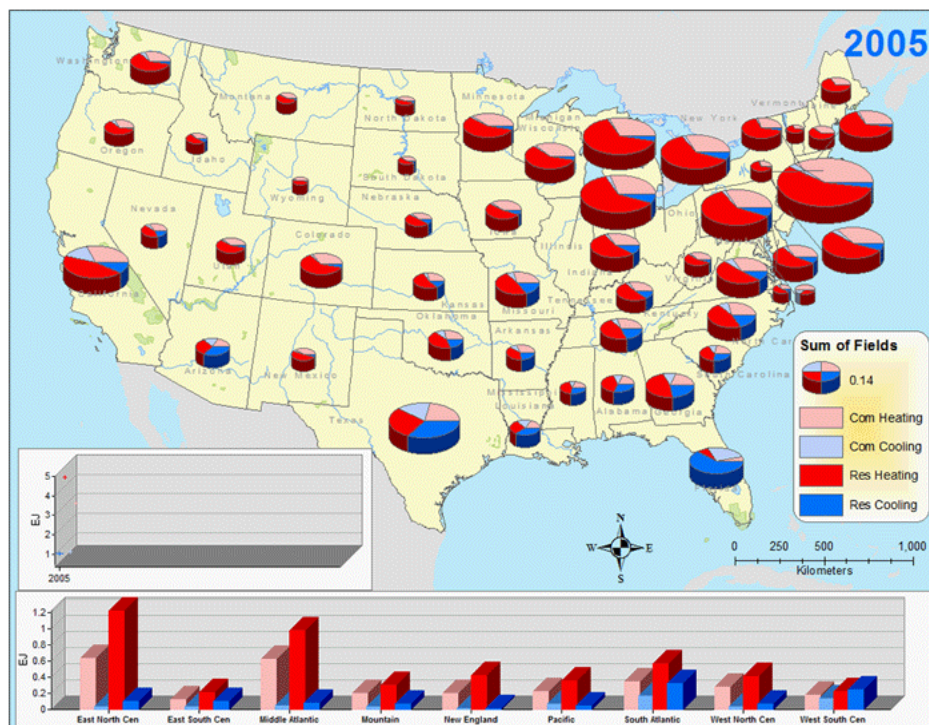


# Regional Downscaling of GCAM: Provides Insights about Regional and 'Local' Impacts of Global Forcings

## Climate Impacts on Building Energy Use

Fixed Climate

A2 Climate



# Summary

- ▶ Fully understanding the interaction of ecosystem services, climate, and human action requires integrated approaches at various spatial and temporal scales.
- ▶ Integrated assessment models need to be supported by high quality data and process understanding that are vetted and consistent across the user communities.
- ▶ The interoperability of IAMs with other models can be enabled by developing spatially explicit representations of important “shared” elements such as specific land cover/land use types or infrastructural features (e.g., location and extent as well as infrastructure type, location, and density, and population and demographics) that link to IAV models and tools.
  - Urbanization as a multifaceted entity is one such example
- ▶ IAM’s have demonstrated that policy matters if consistently and widely applied and that results can be surprising.

# Acknowledgment

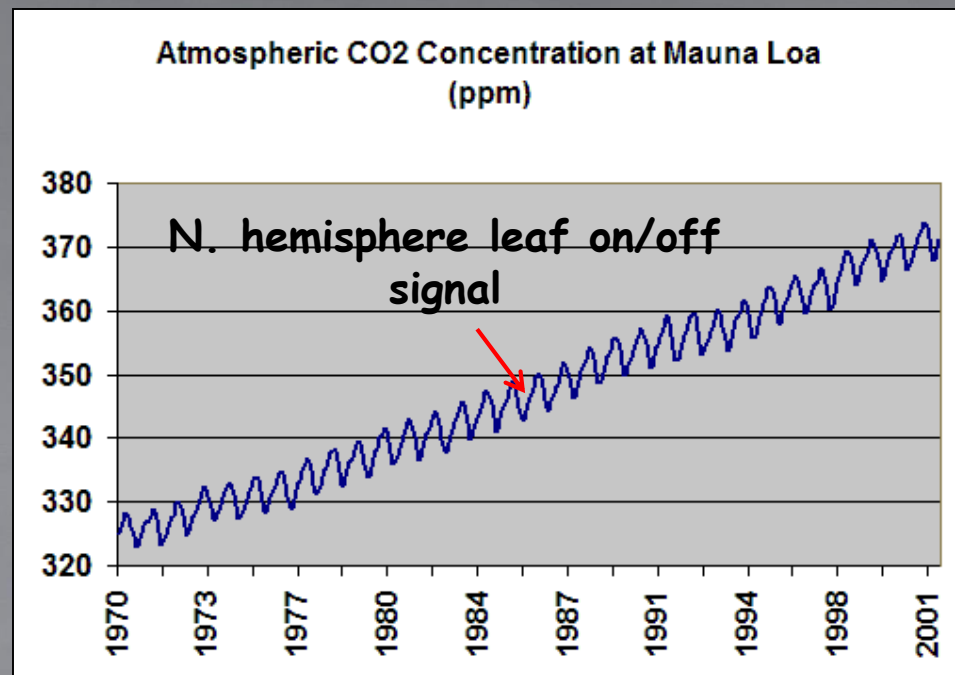
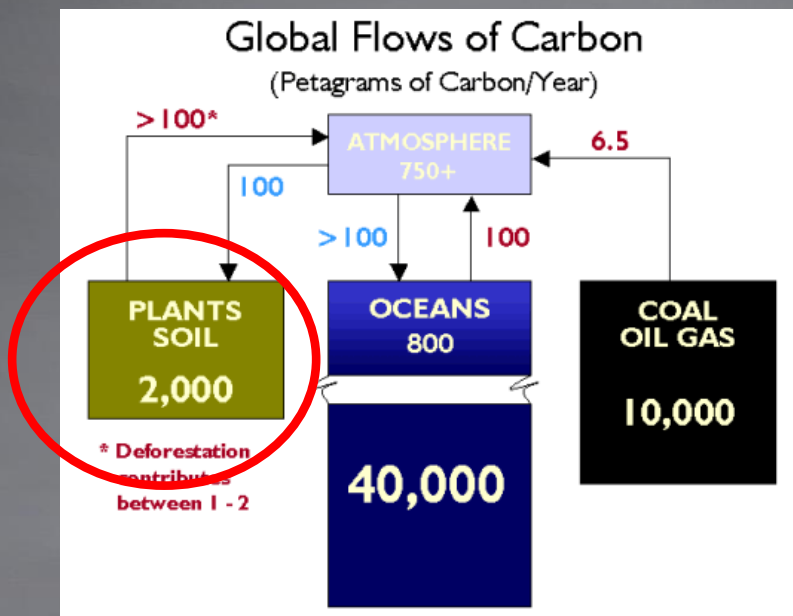
- ▶ Satellite observation-based research funded by NASA's Science and Engineering Directorate
- ▶ DOE Integrated Assessment Research Program through the iHESD SFA and RIAM projects
- ▶ PNNL Platform for Regional Integrated Modeling and Analysis (PRIMA) Initiative



# The Carbon Cycle

Primary Production is critical part of the carbon cycle for human existence

*Vegetation and its phenology has immediate impact on atmospheric CO<sub>2</sub>*



# Earth's "Bio-Engine"

## Net Primary Production (NPP)

**NPP is the amount plant material produced on Earth.**

It is the primary fuel for Earth's food web.  
Represents all available food and fiber.

**NPP can be measured in terms of Carbon**

(photosynthesis - CO<sub>2</sub> exchange between atmosphere and biosphere  
(global climate change)).

**Land use strongly impacts NPP**

Humans require almost 20% of Earth's NPP capacity on land

**NPP is the "Common Currency" for Climate Change, Ecological,  
& Economic Assessment.**



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# **Example of end-to-end interaction in GCAM**

**“What if a global policy favoring biofuels was implemented and ran out to 2100?”**



