Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

Modeling Climate Impacts in GCAM: Where are We Now and Where are We Headed?

KATE CALVIN

Joint Global Change Research Institute

JGCRI Integrated Assessment Technical Workshop

October 21, 2014

Roadmap for this talk

- Some ways to differentiate impacts studies
- Examples of current and completed research:
  - Energy
  - Water
  - Land
- Elements of a continuing research strategy

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Ways to Differentiate Impacts Studies

Ways to Differentiate Impact Studies

- How does climate influence human systems (e.g., via energy, water, or land)?
- What is the temporal character of the impacts?
- At what regional scale are we considering the impacts?
- How is climate represented?
- Are human and natural system represented all within the IA model or using multiple models?

2. What is the temporal character of the impacts?

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Research focused on *climate variability*

- Brown-outs during heat waves due to insufficient electricity capacity
- Reduced agricultural production due to extreme temperature events or droughts
- Price spikes

Research focused on climate trends

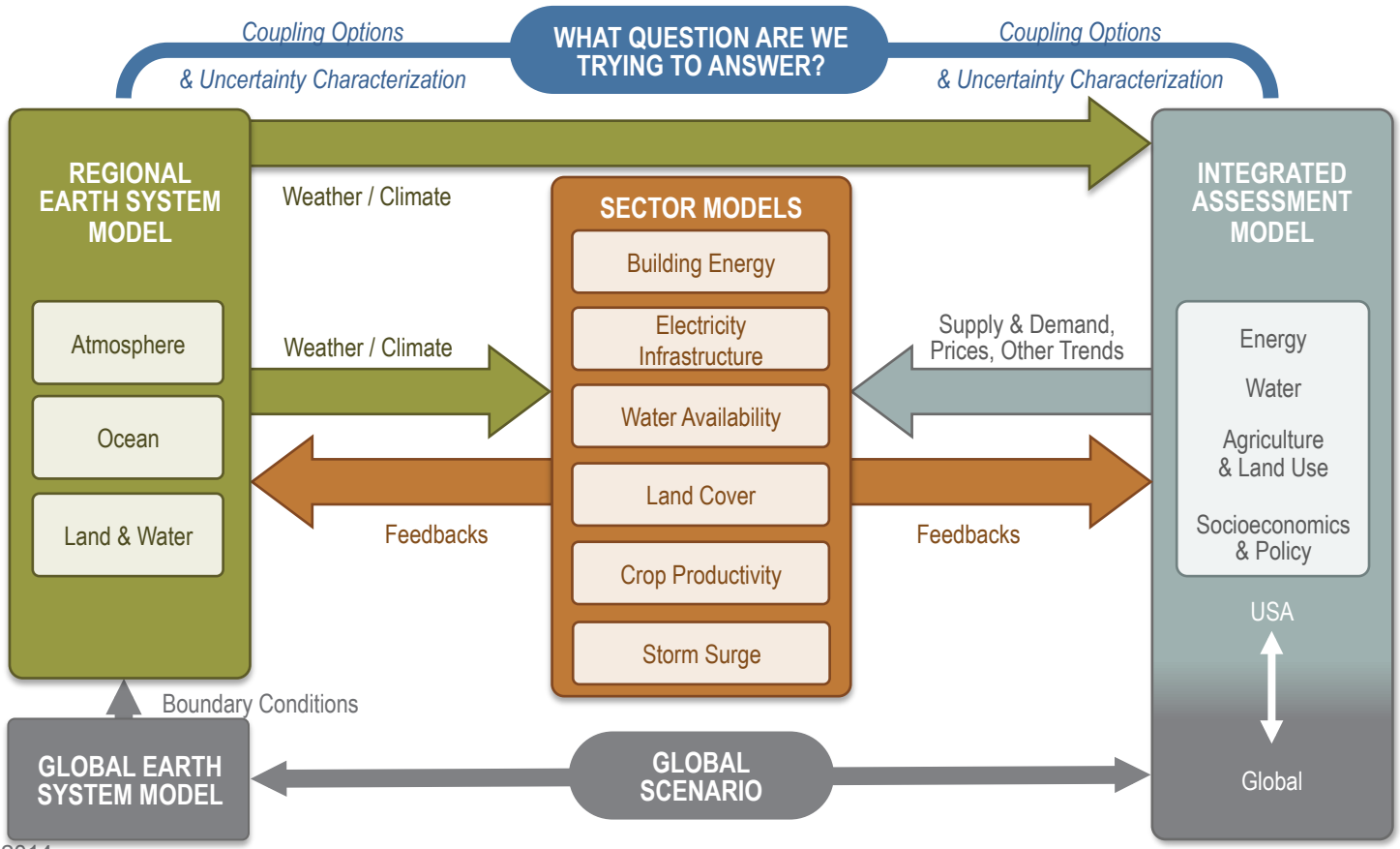
- Increased in average air conditioning
- Shifting of the electricity generation mix in response to changing renewable resource potential
- Adjustment of planting dates and which crops to grow where
- Changes in irrigation, fertilization, and other management practices
- Changes in thermal cooling technology

Sub-Annual Time Scales | Annual Time Scales | Decadal Time Scales | Multi-Decade Time Scales

5. Are human and natural system represented all within the IA model or using multiple models?

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Example: PNNL's PRIMA Initiative



Ways We have Differentiated Impact Studies for the Examples in this Talk

- How does climate influence human systems (e.g., via energy, water, or land)?
  - Energy, water, land
- What is the temporal character of the impacts?
  - Decadal to multi-decadal
- At what regional scale are we considering the impacts?
  - Energy: State to regional
  - Water: Grid-level
  - Land: Regional to global
- How is climate represented?
  - Loose coupling of models, all using CMIP data
- Are human and natural system represented all within the IA model or using multiple models?
  - All within the IA system

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

Energy

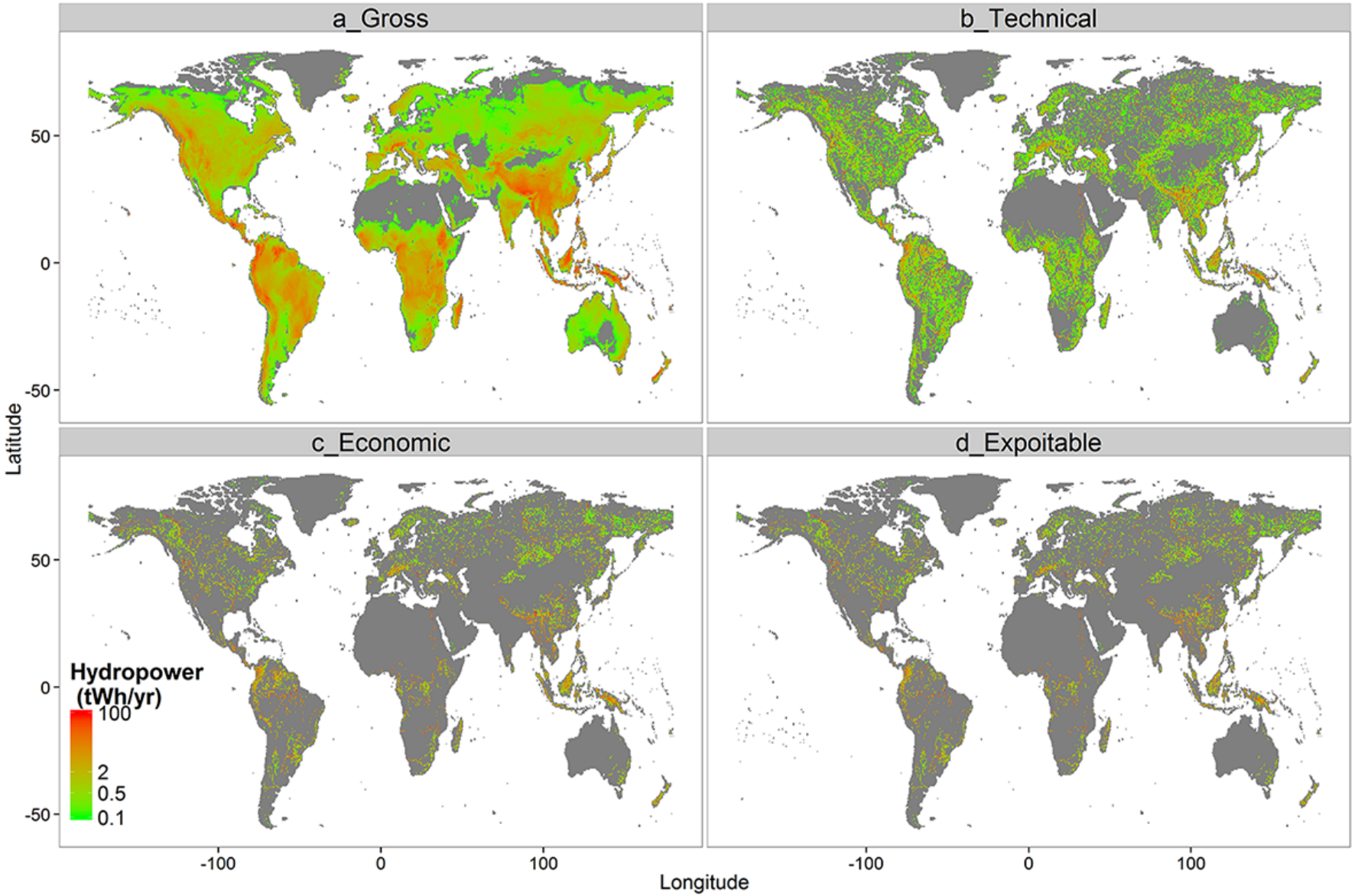
Energy Impacts: Overview

Impact Sector	Climate Variable	Implications
Hydropower	Stream flow	Electricity generation, grid reliability
Bioenergy	Temperature, precipitation, CO_2 concentration, ozone, pests, etc.	Energy production (electricity, liquids, etc.)
Demand for heating and air conditioning	Temperature	Energy use, grid reliability
Wind energy	Wind speed	Electricity generation, grid reliability
Solar energy	Clouds	Electricity generation, grid reliability
Thermal power cooling	Temperature, precipitation	Electricity generation, water use

Considering Hydropower Impacts

(*See Yuyu Zhou's talk yesterday)*

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

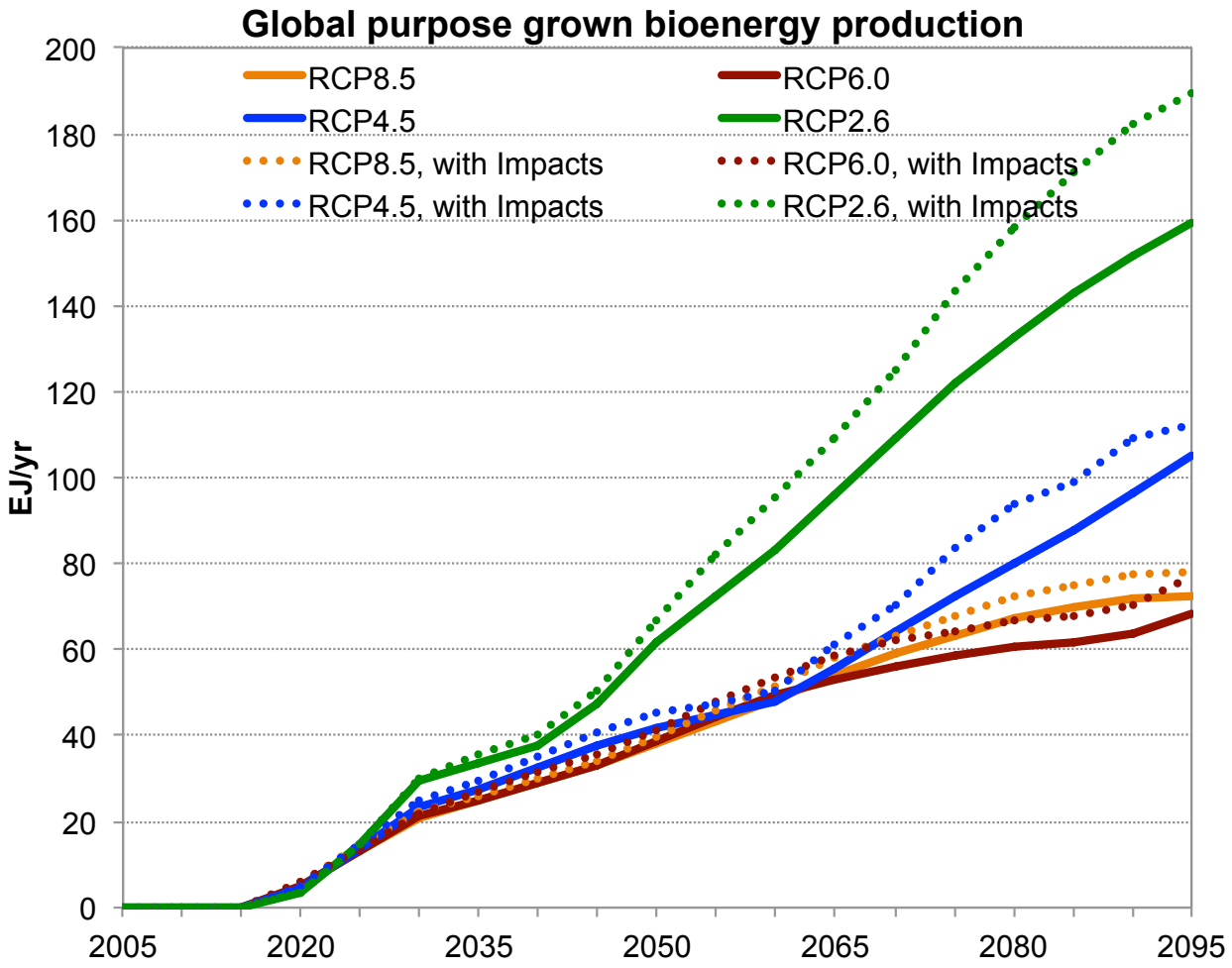


Impacts on Bioenergy Production

(See slides later in this talk)

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965



Source: Kyle, P., C. Mueller, K. Calvin and A. M. Thomson (2014). "Meeting the Radiative Forcing Targets of the Representative Concentration Pathways in a World with Agricultural Climate Impacts." Earths Future 2(2): 83-98.

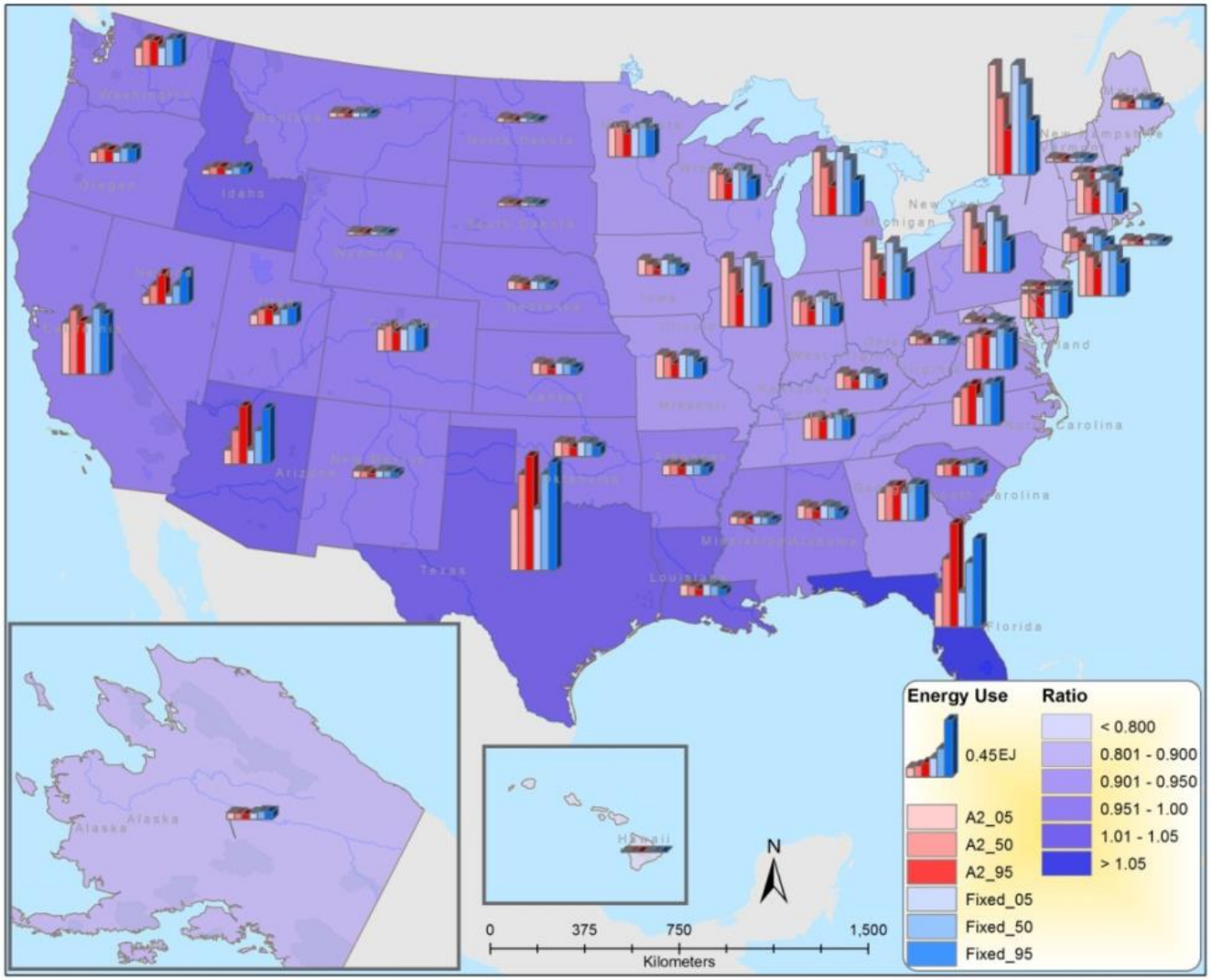
Building Energy Impacts: Current Results

Increases in summer cooling demand are more than offset by reduced winter heating

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Projected building energy use in 2005, 2050, and 2095 driven by CASCaDE A2 statically downscaled climate scenario (red bars) versus fixed 2005 climate (blue bars).

Purple shading denotes ratio of cumulative 21st century building energy use for A2 scenario versus no climate forcing (i.e., versus a scenario that only includes changes in population, building floor space, building technologies, GDP, and other socioeconomic trends)

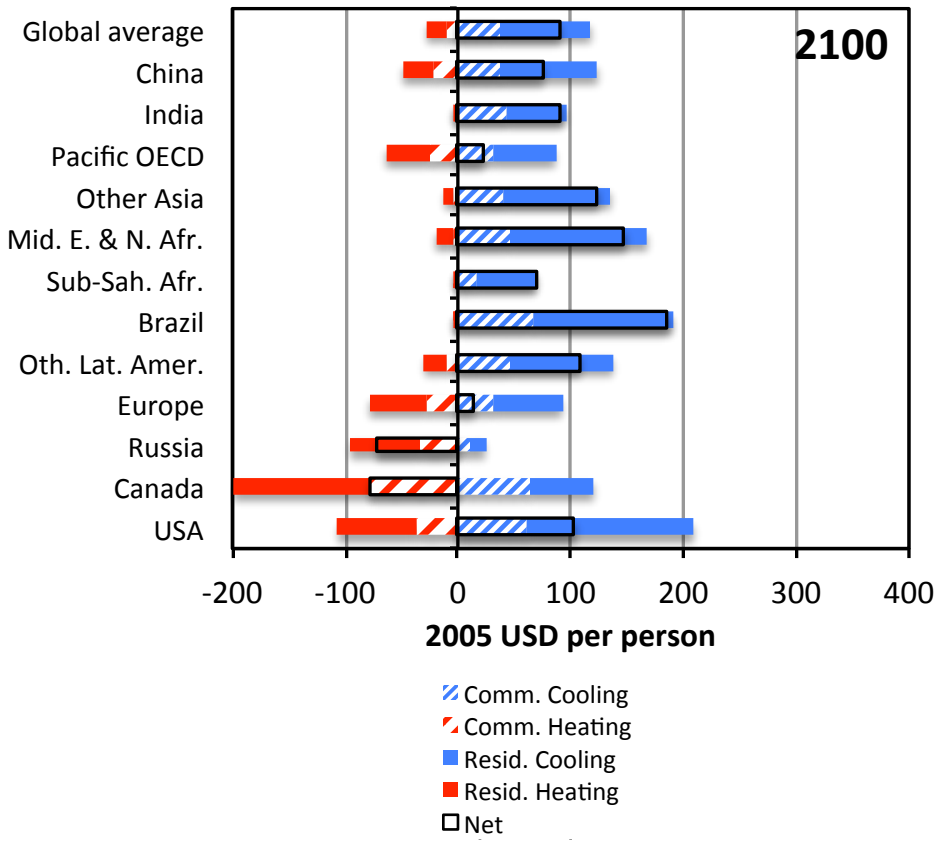


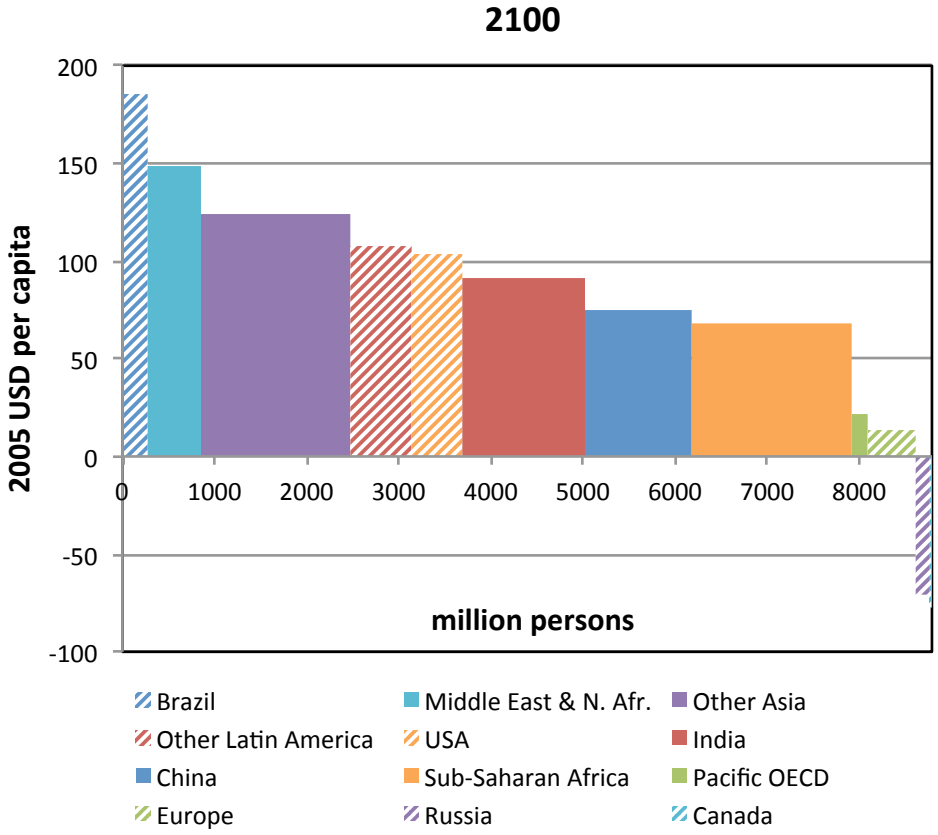
Building Energy Impacts: Current Results

Increases in cooling expenditure exceed declines heating expenditure in most regions

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Change in energy expenditures for heating & cooling





Climate data from CCSM A2 scenario

Summary of Energy Impacts

- We're getting a handle on long-term energy demand effects in buildings and general increases in runoff for hydropower.
- We are not yet really capturing the human response to annual and intra-annual variability in the full IA model.
  - Model coupling remains an important strategic approach to capture these dynamics
- There have been some studies on wind and solar, but these resources push on the ability of the climate models to create meaningful projections for the change in these variables.
- There have been a couple of studies on the effects on thermal power plants, but these are complicated by the challenges in modeling cooling water supplies and policies, along with the relationships between power plants (i.e., several operating on the same river).

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

Water

Water Impacts: Overview

Impact Sector	Climate Variable	Implications
Water supply	Precipitation, temperature, land cover	Hydropower, irrigation, domestic consumption
Crop water demand	Temperature	Irrigation demand, water availability
Thermal power water demand	Temperature	Electricity generation, water availability

Coming from One Direction: Annual Water Demands

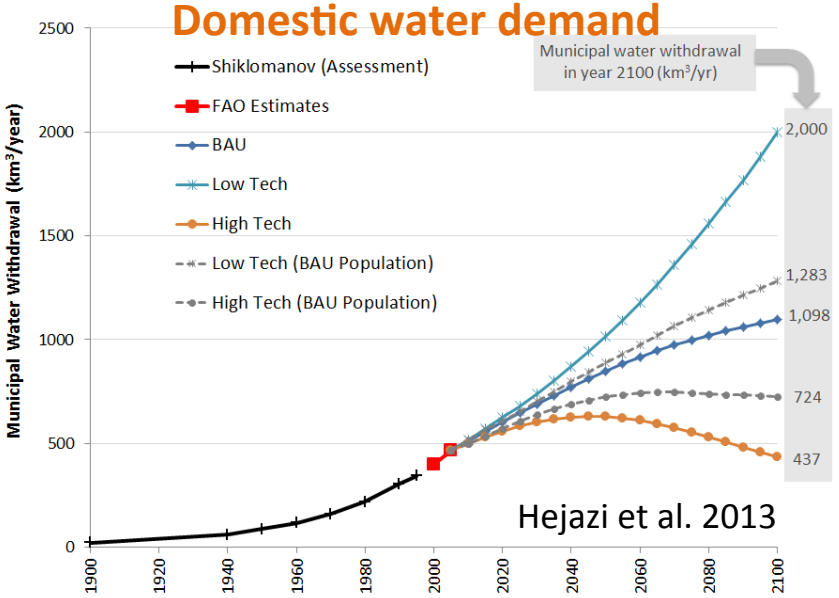
(See Mohamad Hejazi's Talk from Yesterday)

Pacific Northwest NATIONAL LABORATORY

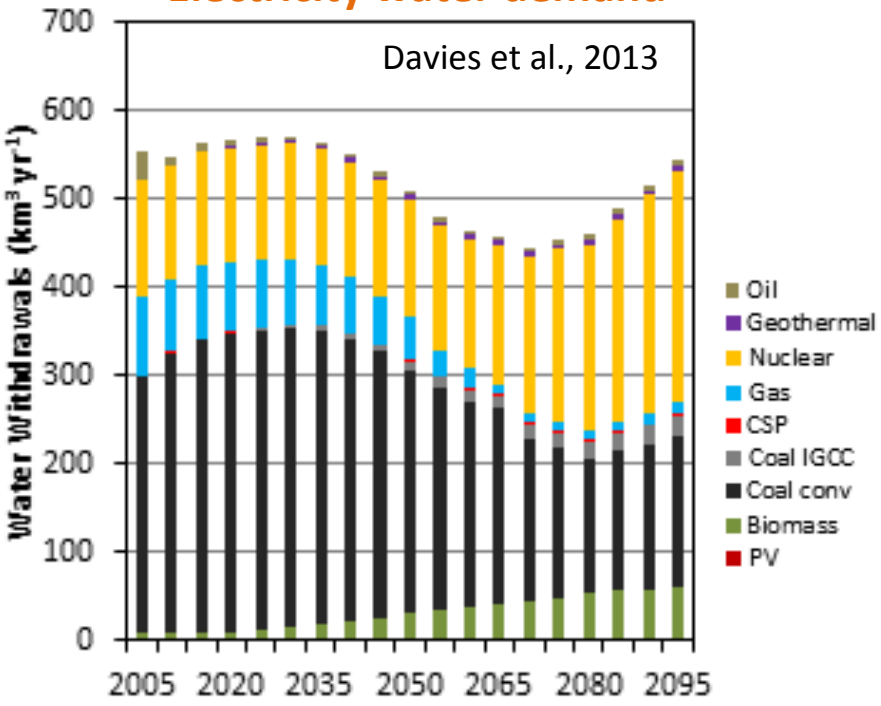
Proudly Operated by Battelle Since 1965

GCAM tracks water demands for several sectors, subsectors, and technologies, and at various spatial scales (regions, state, agro-ecological zones)

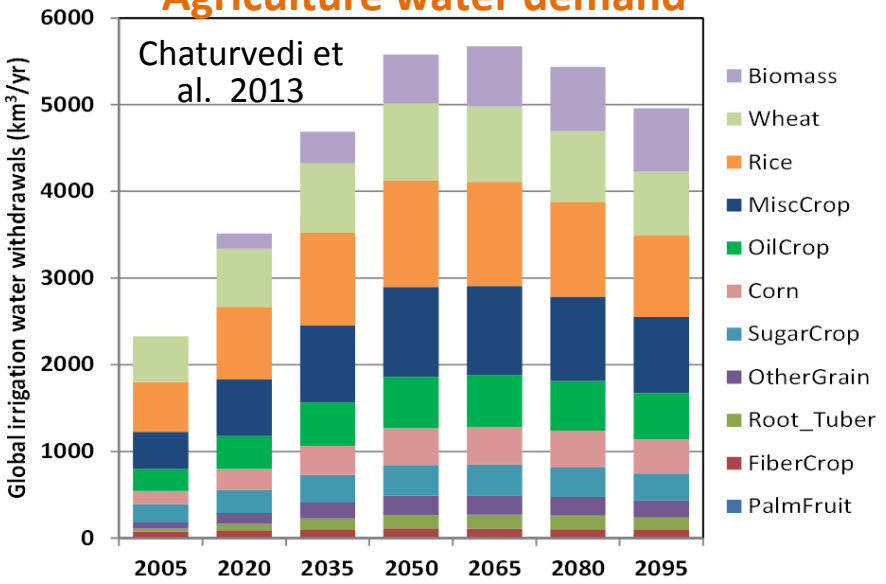
Domestic water demand



Electricity water demand



Agriculture water demand



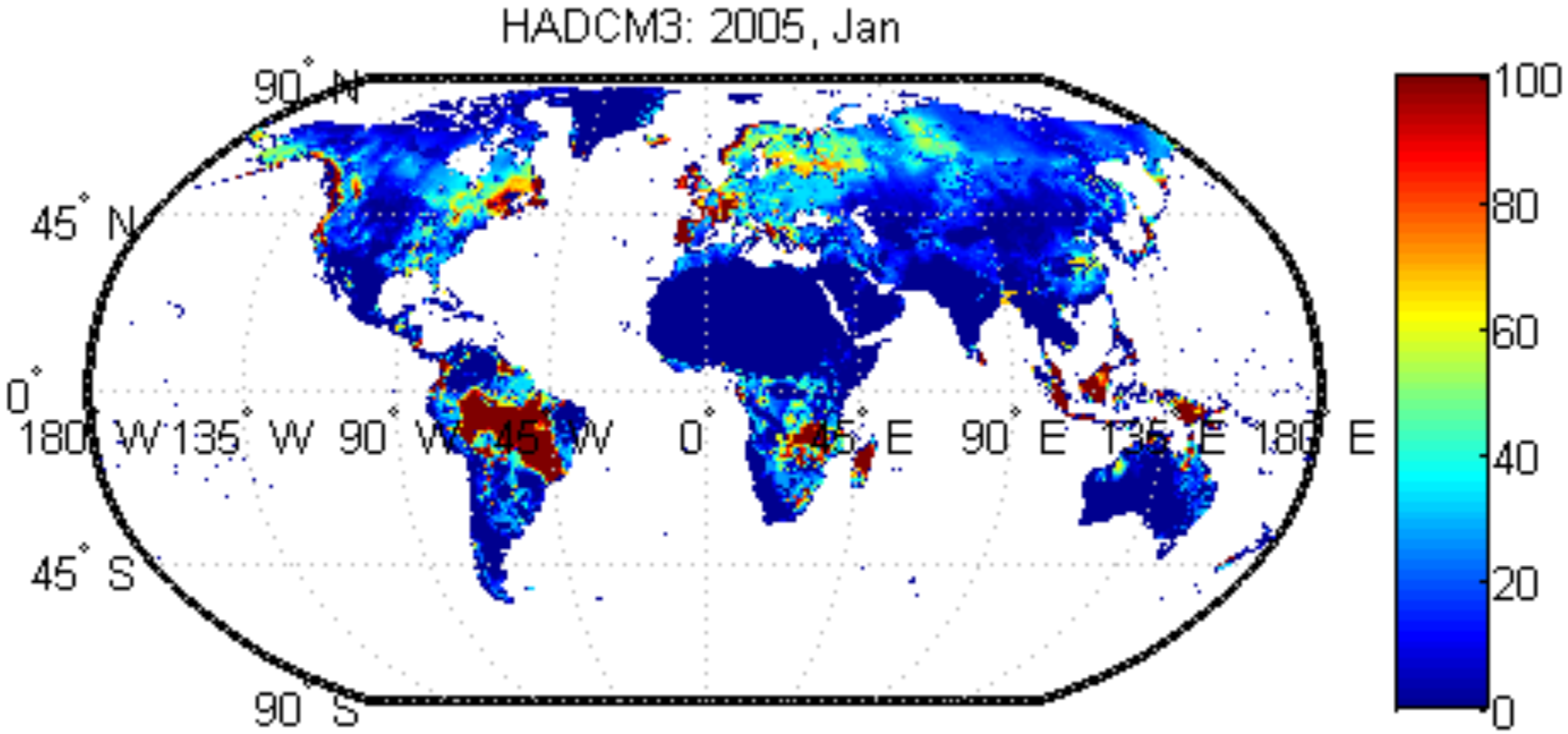
Coming from the Other Direction: Annual Water Supplies

(See Mohamad Hejazi's Talk from Yesterday)

Pacific Northwest NATIONAL LABORATORY

Proudly Operated by Battelle Since 1965

Climate change affects the availability of water resources in the future

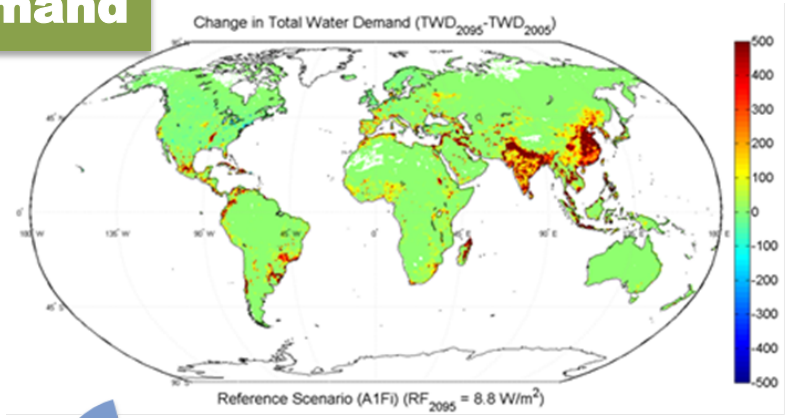


Hejazi et al. (2014). Hydrology and Earth System Sciences, 18, 2859-2883, doi:10.5194/hess-18-2859-2014

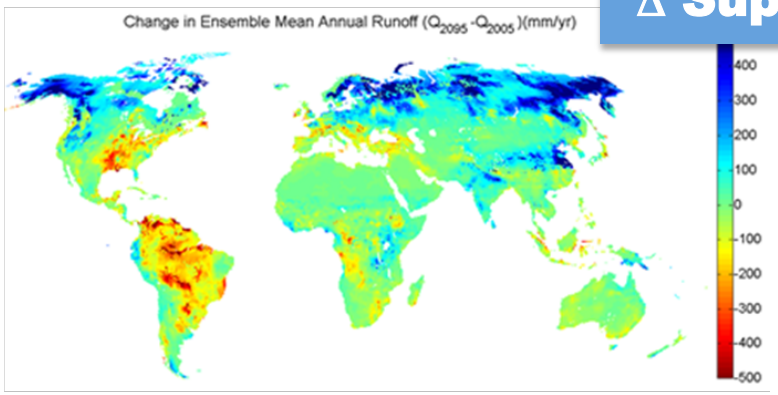
Water Scarcity: Where Supply and Demand Meet
(See Mohamad Hejazi's Talk from Yesterday)

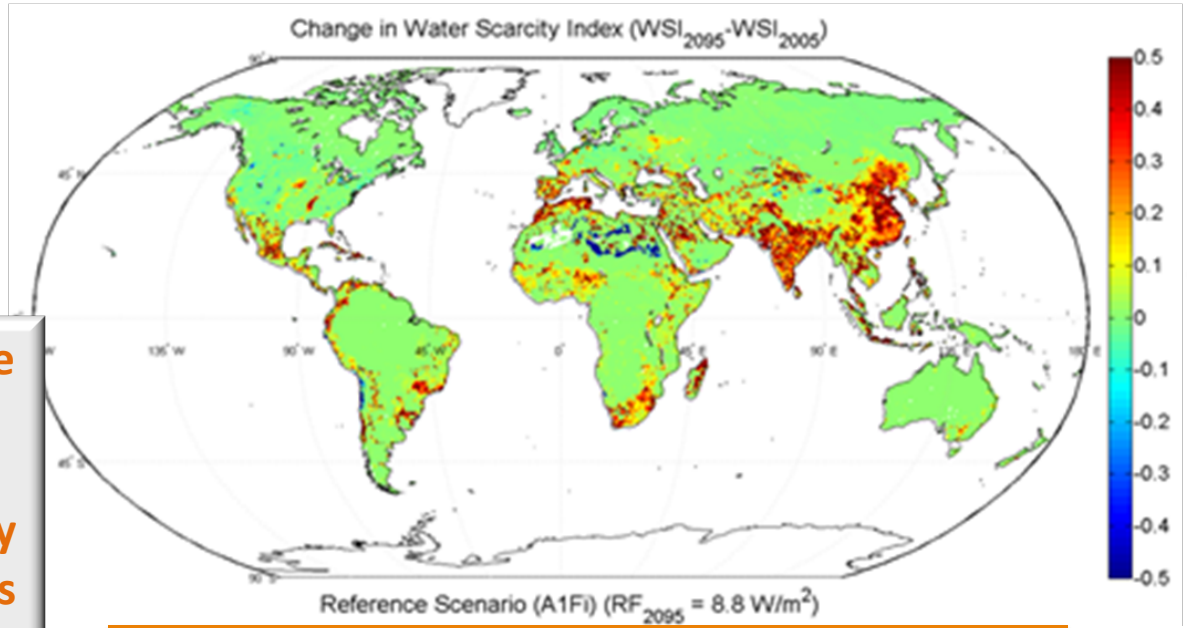
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Δ Demand



Δ Supply





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

Change in Scarcity

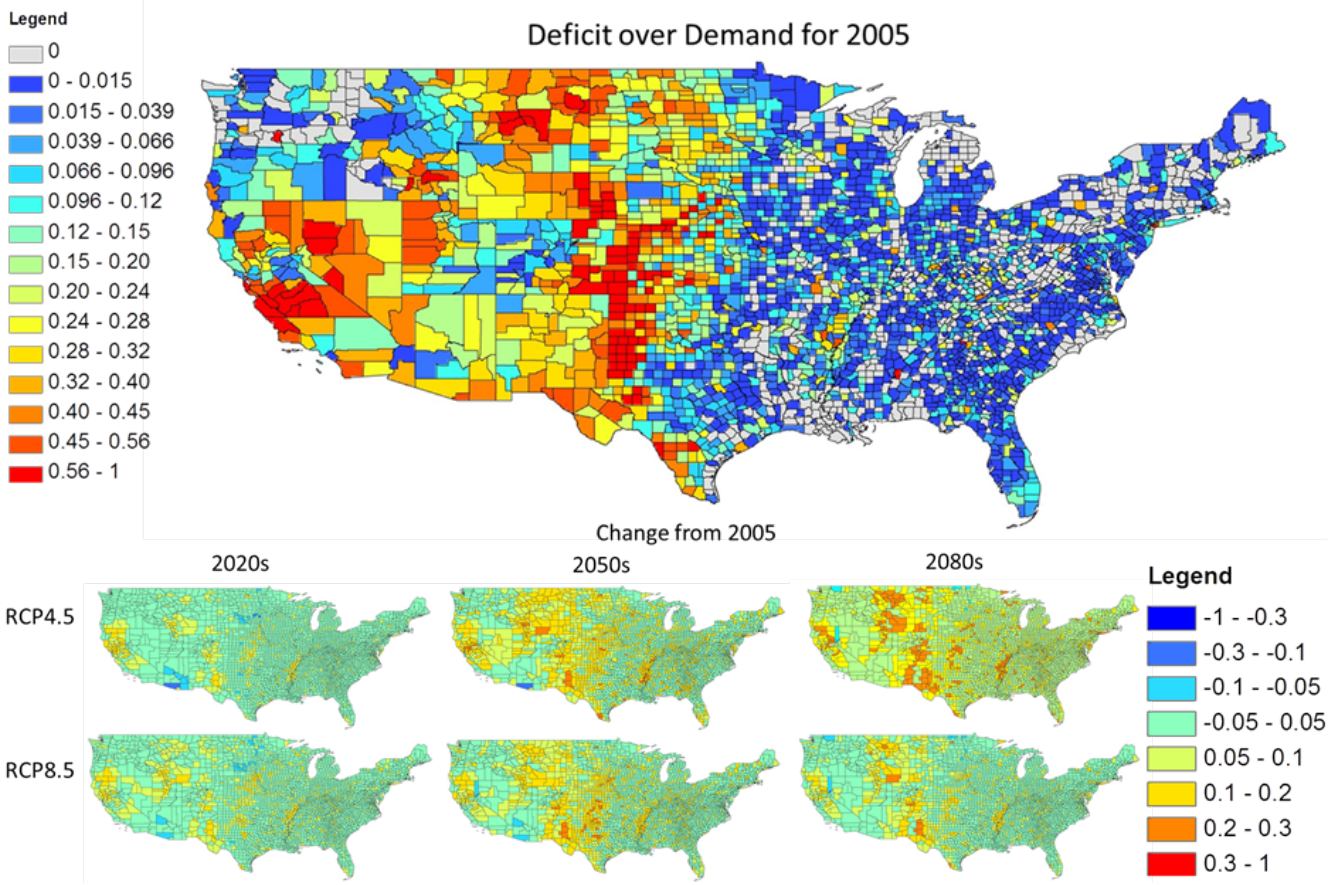
Source: Hejazi et al. (2014). Integrated assessment of global water scarcity over the 21st century: Global water supply and demand under extreme radiative forcing, Hydrology and Earth System Sciences Discussion, 10, 3327–3381, doi:10.5194/hessd-10-3327-2013.

Focusing on regional water scarcity through model coupling

(See Ruby Leung's Talk from Yesterday)

- Using an integrated modeling framework that includes GCAM-USA, a regional Earth system model, and a coupled hydrology-water management model, surface water deficit is projected to increase in both duration and magnitude in the future, with larger increase in RCP4.5 compared to RCP8.5

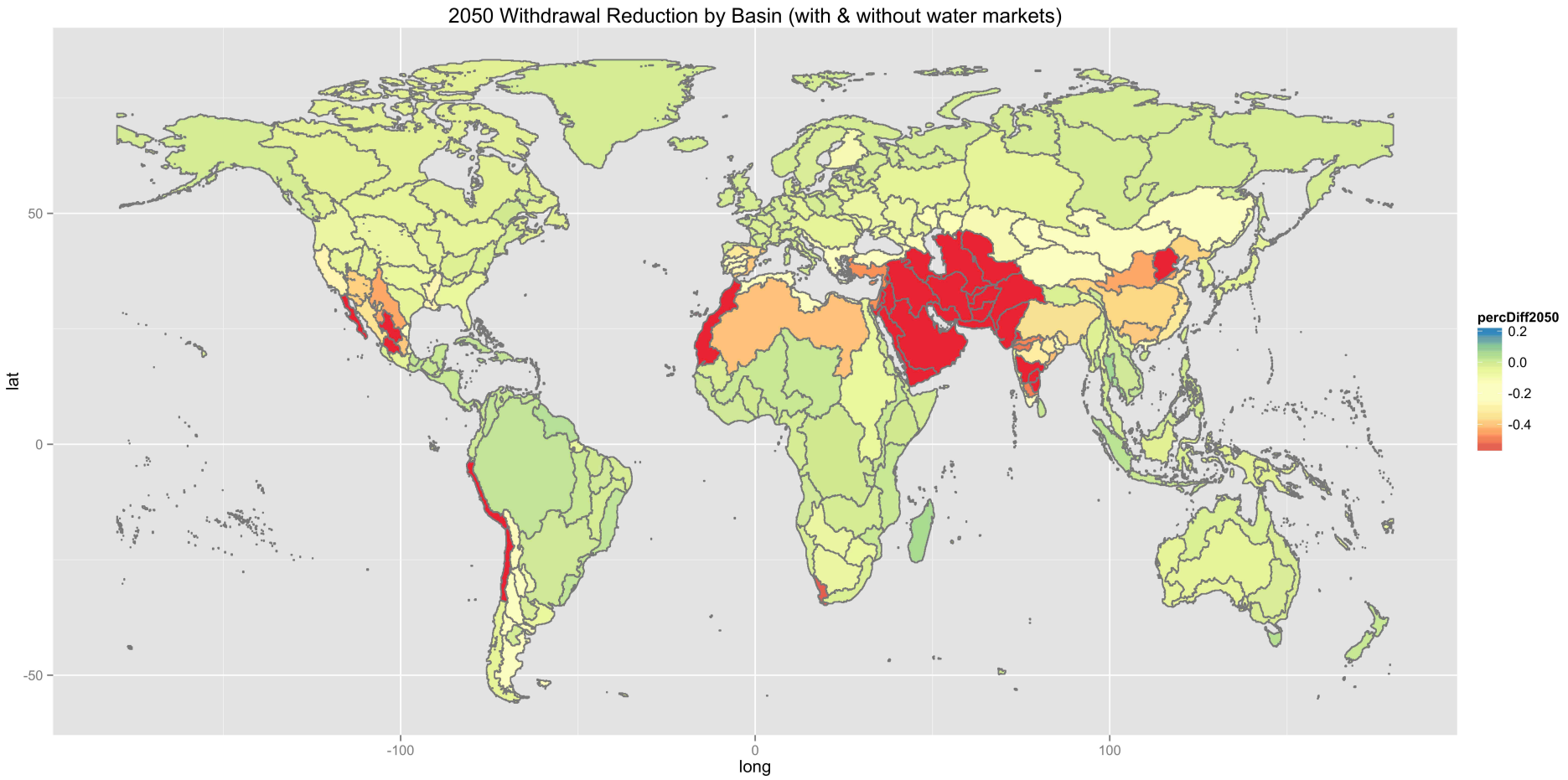
Annual county scale water deficit as a fraction of demand



The emerging frontier: balancing demand and supply in an integrated framework

(See Sonny Kim's Talk from Yesterday)

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



PRELIMINARY RESULTS: NOT FOR PUBLICATION OR DISTRIBUTION

Summary of Water Impacts

- Water impacts are confounded by the substantial uncertainty that attends projections of precipitation and runoff.
- The effects of changes in water supply are largely evident through impacts on other systems, notably energy and agriculture.
- Current IA modeling research is pushing to incorporate full feedbacks between water supply and demand.
- Challenges of temporal and spatial scale remain; these will be addressed both through improvements in temporal and spatial resolution in IA models and through model coupling.

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

Agriculture

Agriculture Impacts: Overview

Impact Sector	Climate Variable	Implications
Food & fiber crop yield	Temperature, precipitation, CO_2 concentration, ozone, pests, etc.	Land use/cover
Bioenergy yield	Temperature, precipitation, CO_2 concentration, ozone, pests, etc.	Land use/cover, Energy production (electricity, liquids, etc.)
Carbon storage of ecosystems	Temperature, precipitation, CO_2 concentration, ozone, pests, etc.	Emissions, emissions mitigation

Agriculture Impacts: Current Results

Scenarios and Methodology

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- Scenarios:

Name	2100 RF Level	Includes mitigation?	Includes climate change impacts?
RCP8.5	8.5 W/m^2	No	No
RCP6.0	6.0 W/m^2	Yes	No
RCP4.5	4.5 W/m^2	Yes	No
RCP2.6	2.6 W/m^2	Yes	No
RCP8.5, with Impacts	8.5 W/m^2	No	Yes
RCP6.0, with Impacts	6.0 W/m^2	Yes	Yes
RCP4.5, with Impacts	4.5 W/m^2	Yes	Yes
RCP2.6, with Impacts	2.6 W/m^2	Yes	Yes

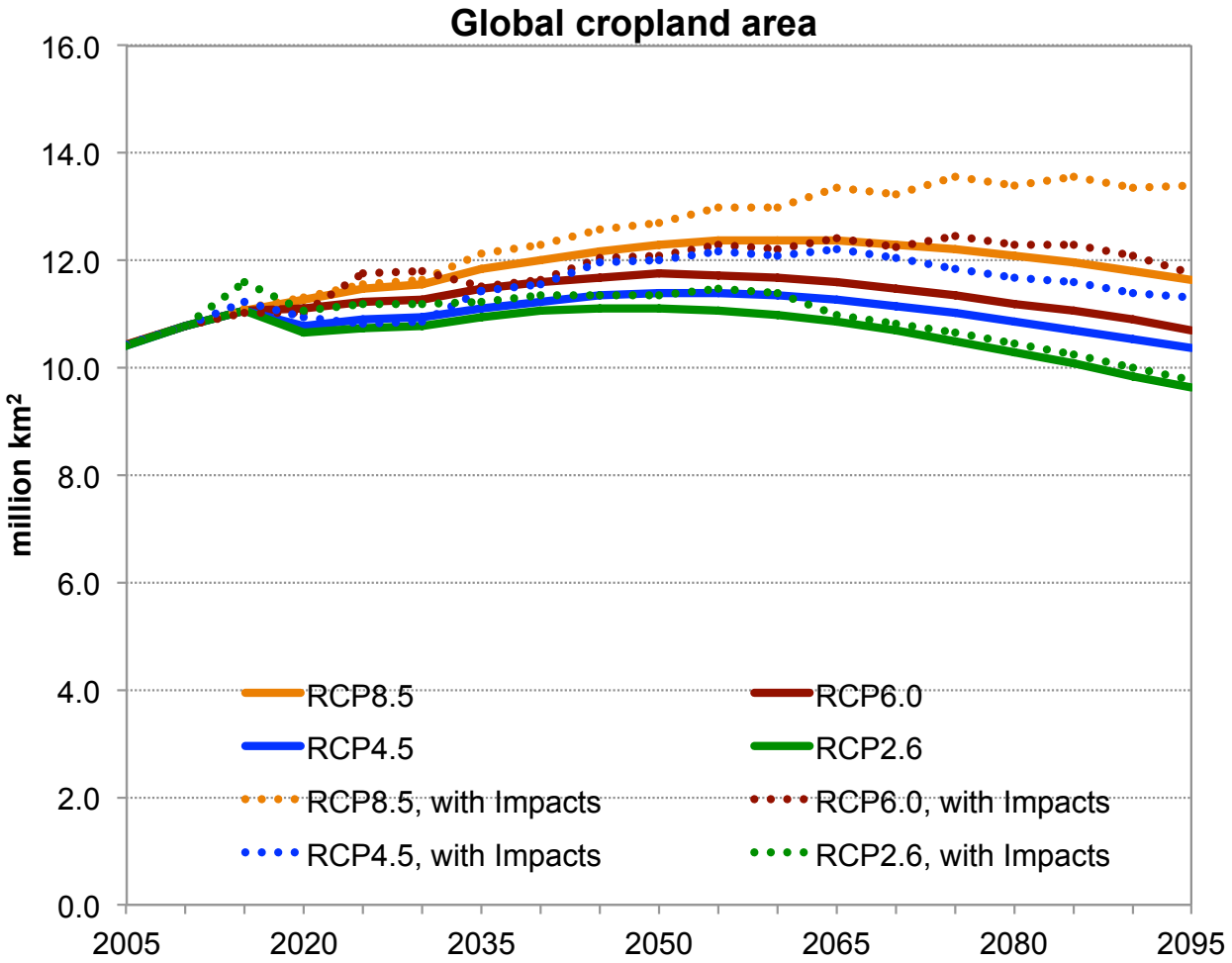
- Methodology:
  - We only considered agricultural commodities.
  - We only adjusted yields.
  - Data on yields is from LpJML model (run by PIK). Data is gridded, annual, for 12 crops. LpJML was forced with HadGEM2-ES climate data and excludes CO_2 fertilization effects.

Source: Kyle, P., C. Mueller, K. Calvin and A. M. Thomson (2014). "Meeting the Radiative Forcing Targets of the Representative Concentration Pathways in a World with Agricultural Climate Impacts." Earths Future 2(2): 83-98.

Agriculture Impacts: Current Results

Including climate change impacts results in an increase in global food & fiber area

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

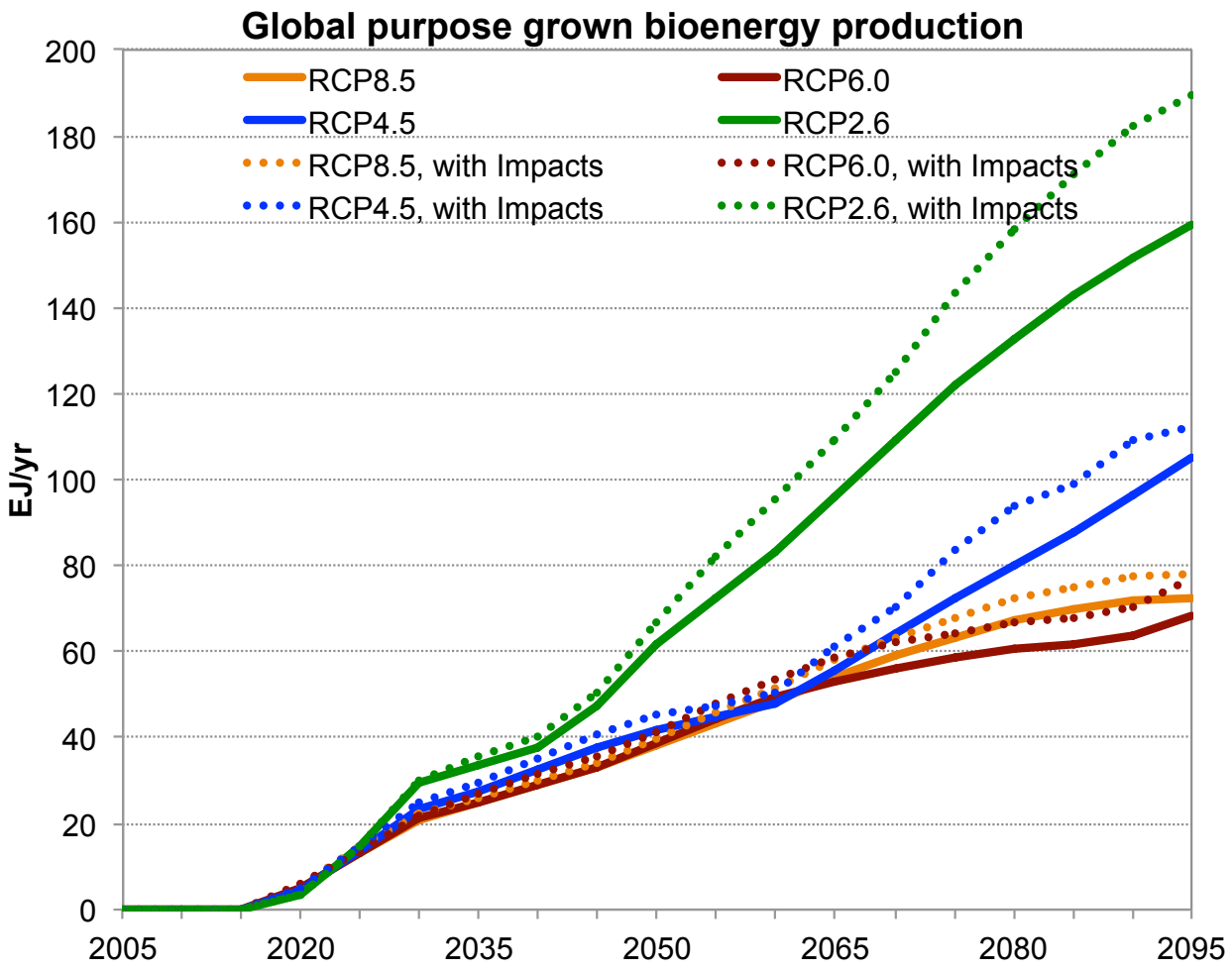


Source: Kyle, P., C. Mueller, K. Calvin and A. M. Thomson (2014). "Meeting the Radiative Forcing Targets of the Representative Concentration Pathways in a World with Agricultural Climate Impacts." Earths Future 2(2): 83-98.

Agriculture Impacts: Current Results

Including climate change impacts results in an increase in bioenergy production

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



Source: Kyle, P., C. Mueller, K. Calvin and A. M. Thomson (2014). "Meeting the Radiative Forcing Targets of the Representative Concentration Pathways in a World with Agricultural Climate Impacts." Earths Future 2(2): 83-98.

Agriculture Impacts: Current Results

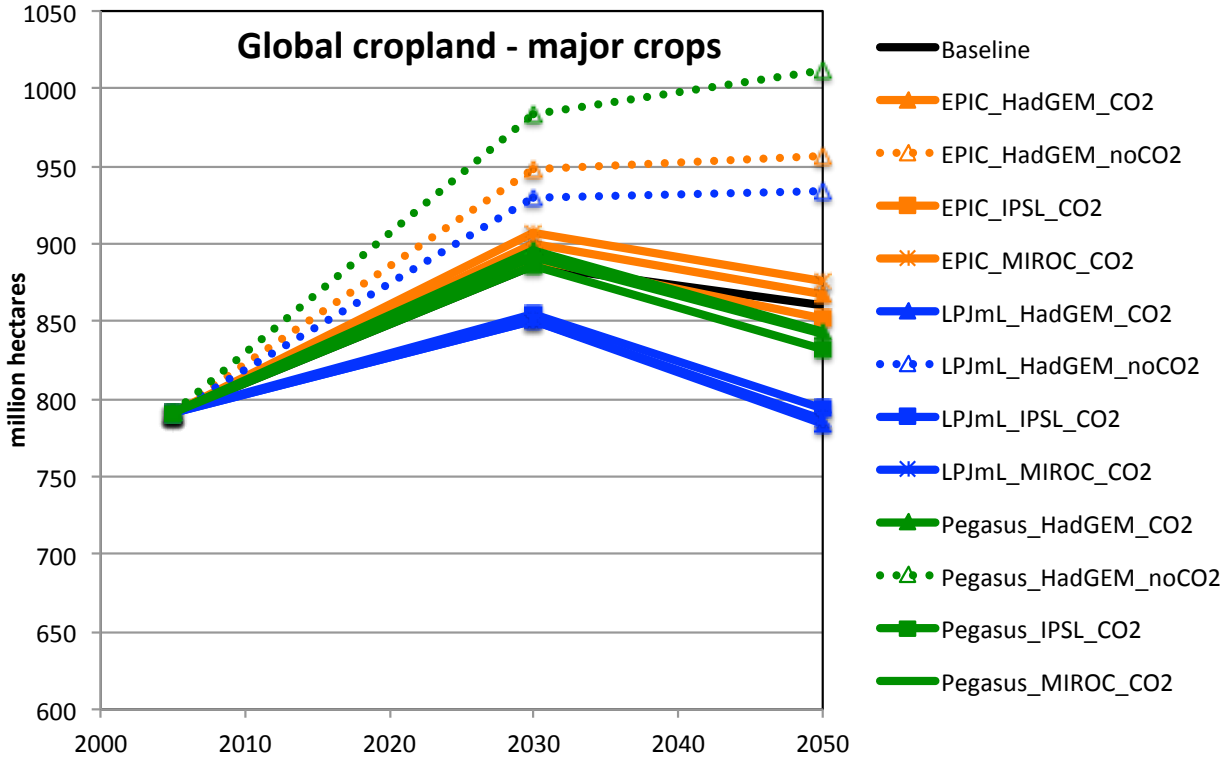
Significant uncertainty remains as to the effect of climate on agricultural productivity

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

From a high emissions scenario (RCP8.5, no climate policy)

Includes all grains, oil crops, and sugar crops

The greatest cropland requirements are in scenarios without CO_2 fertilization

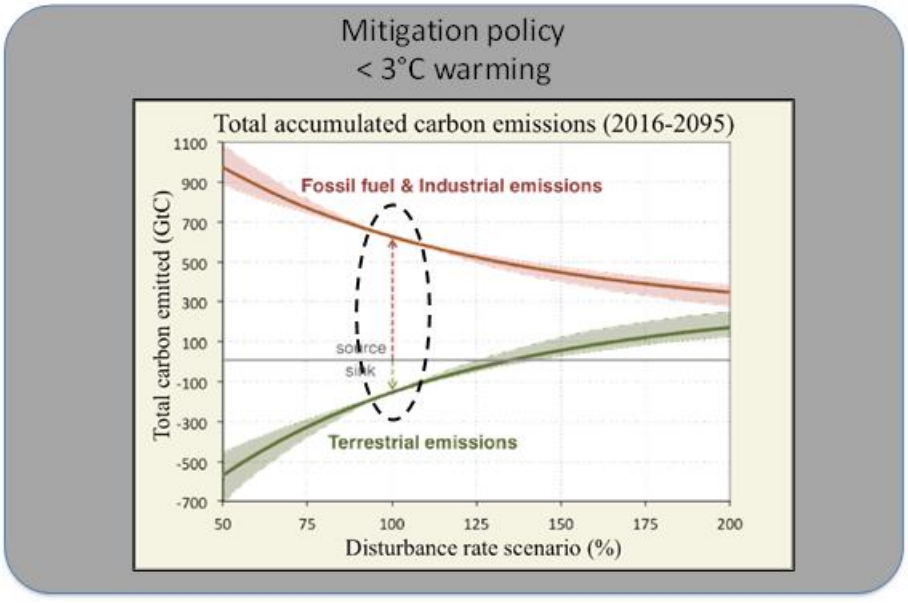


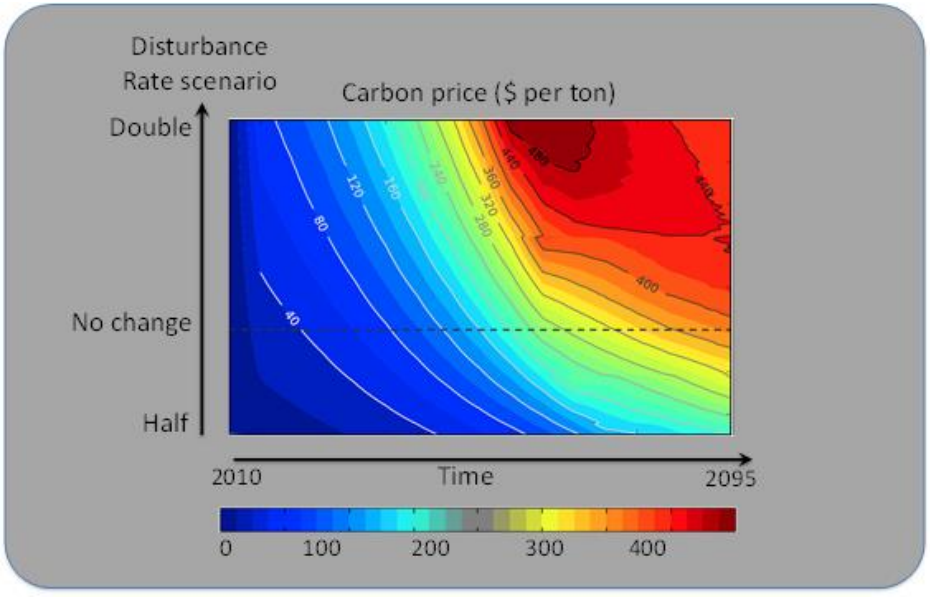
Forest Disturbance: Current Results

Higher rates of forest disturbance result in higher mitigation costs and more energy system mitigation.

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- Study examines the implications of limiting climate change to 3°C under a variety of assumptions about disturbances.
- Higher rates of disturbance result in higher land use change CO_2 emissions, and thus more mitigation effort is required in the energy system to compensate for those emissions.





Source: Le Page, Y., G. Hurtt, A. M. Thomson, B. Bond-Lamberty, P. Patel, M. Wise, K. Calvin, P. Kyle, L. Clarke, J. Edmonds and A. C. Janetos (2013). "Sensitivity of climate mitigation strategies to natural disturbances." Environmental Research Letters **8**(1).

Summary of Agricultural Impacts

- IA models are well-positioned to address longer-term trends agricultural impacts through changes in yield assumptions.
- In addition, global IA models are critical for understanding agricultural impacts because many agricultural markets are fundamentally global in nature – so impacts in one country may have a significant effect on agriculture in another.
- However, the linkage between climate projections and agricultural yields adds a significant layer of uncertainty; it is a major priority to be able to successfully model agricultural impacts.
- Key near-term research is to incorporate human decision making that better reflects annual, and even subannual variability in agricultural impacts.

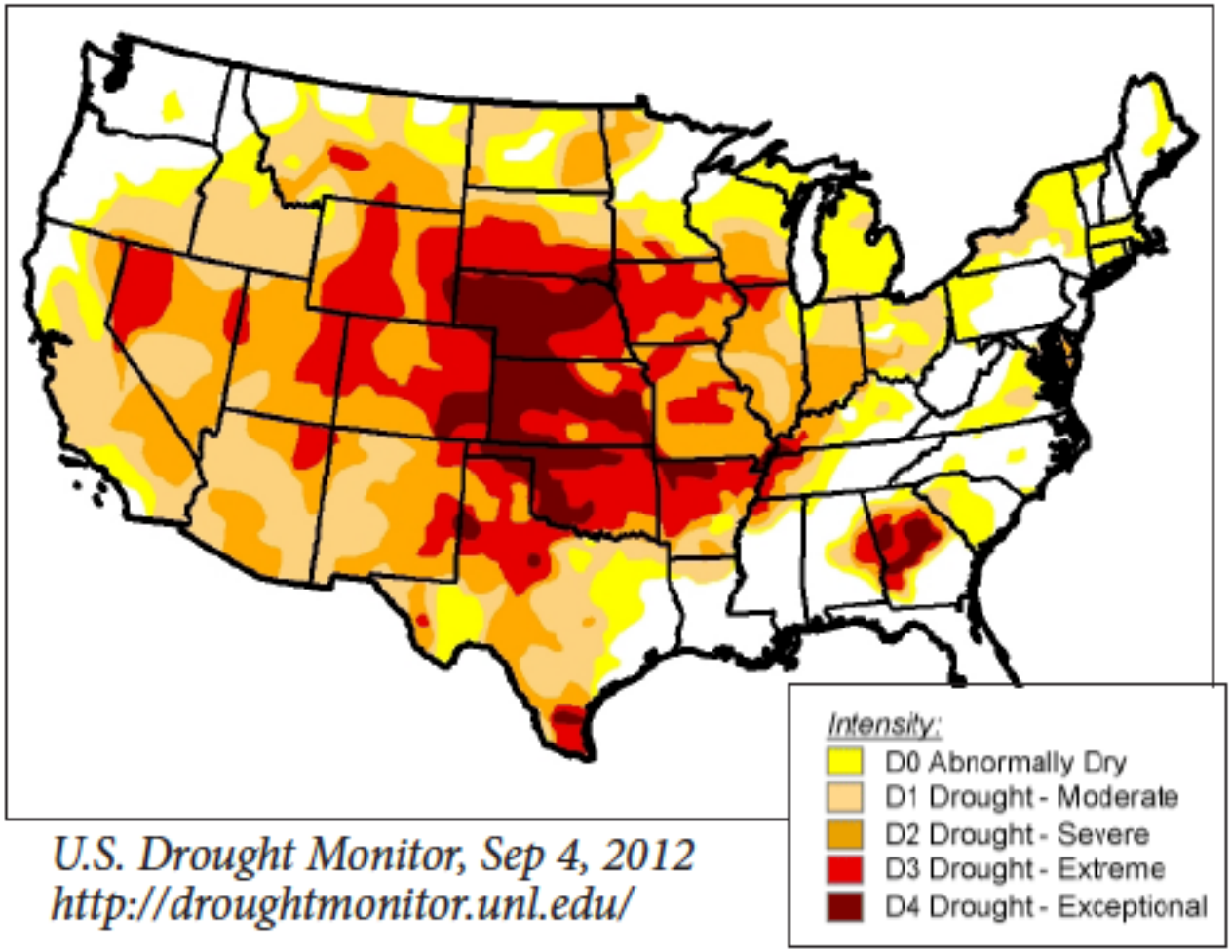
Challenges and Future Research Directions

Challenges in Modeling Impacts

- Modeling extreme events and short-term behavior
- Data availability, assimilation, and aggregation
- Modeling adaptation measures
- Spatial resolution

Motivation: 2012 USA Drought

- In Summer 2012, abnormally high temperatures and abnormally low rainfall led to a severe drought.
- As a result of the drought, corn yields averaged 123 bushels per acre, as opposed to the 166 bushels per acre projected.
- These declines in yield had implications for crop prices, livestock production, etc.

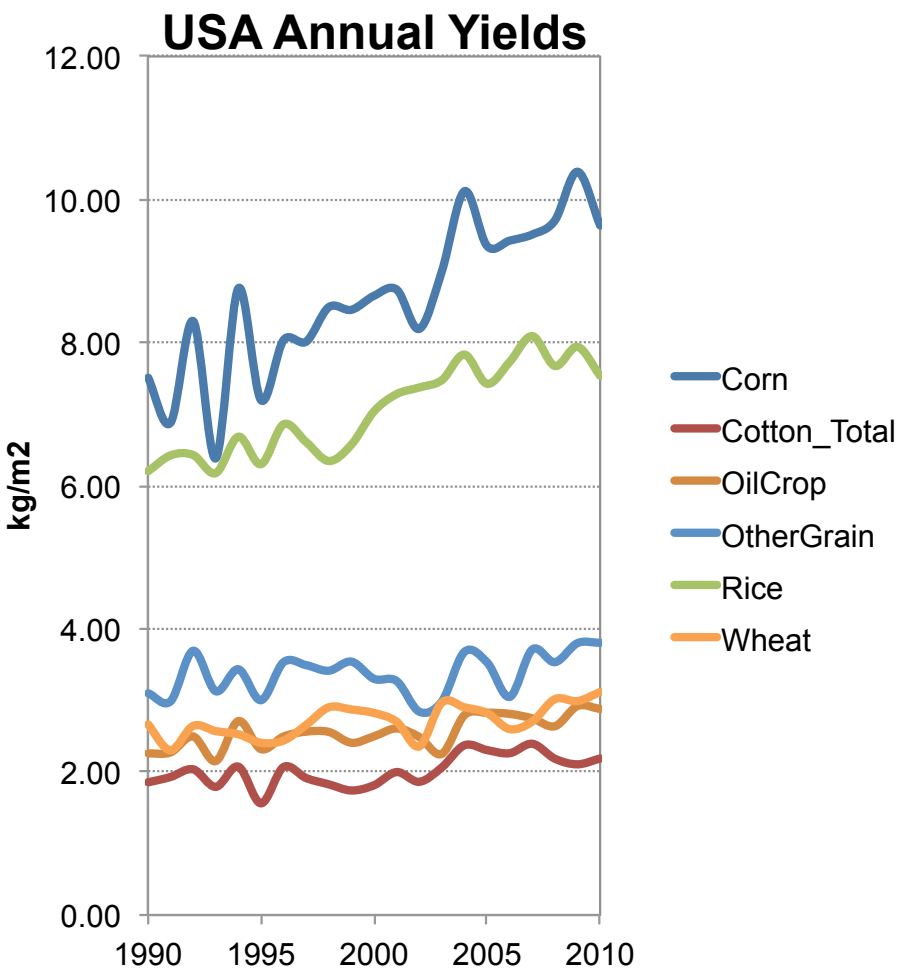


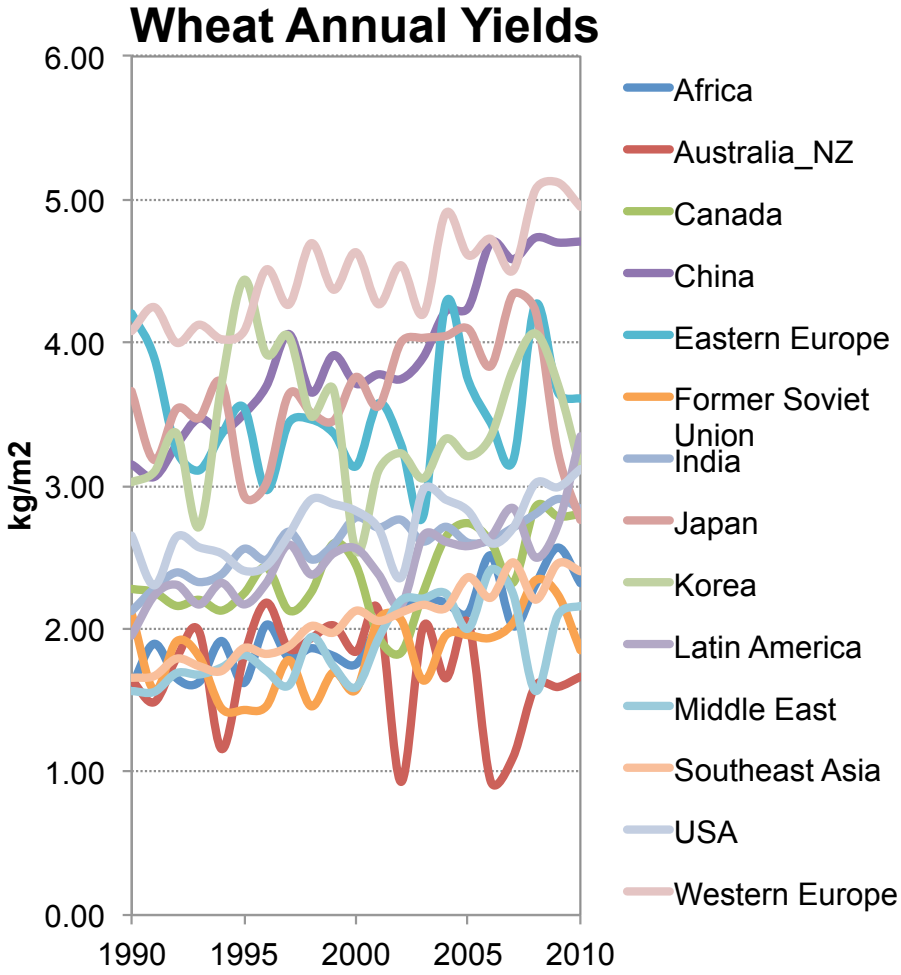
U.S. Drought Monitor, Sep 4, 2012
http://droughtmonitor.unl.edu/

Modeling Extreme Events in Current IAMs

Temporal resolution means we average away extremes

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



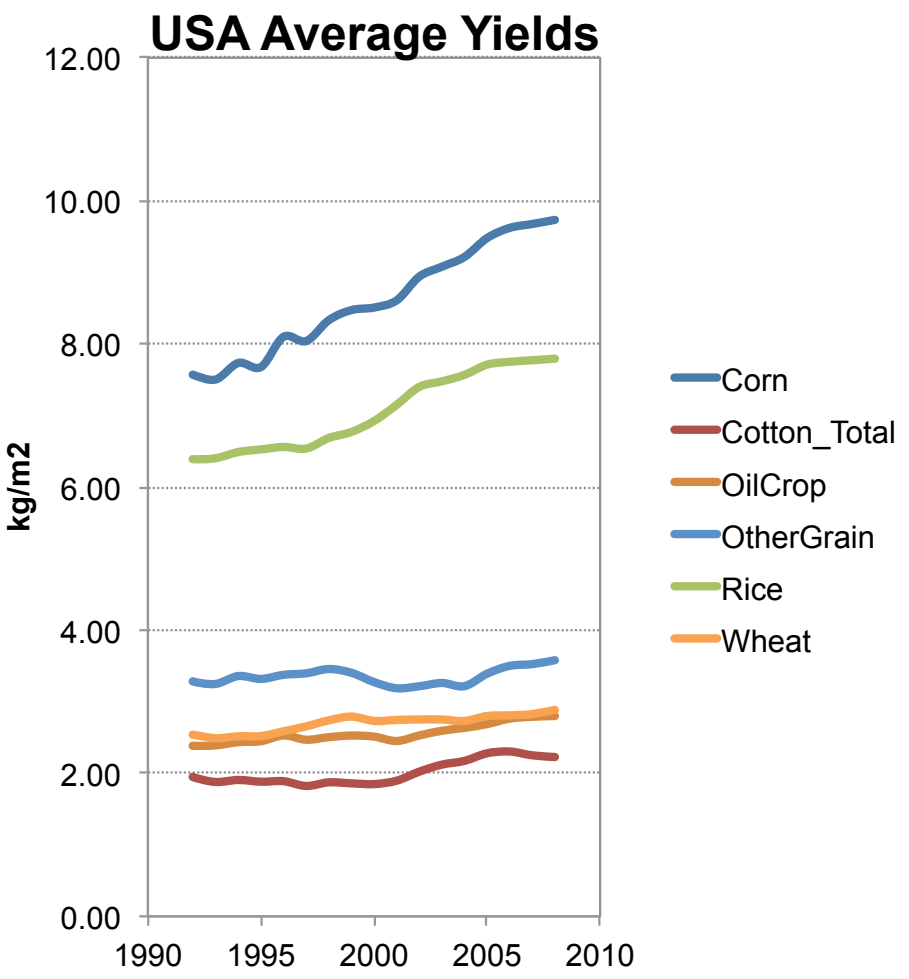


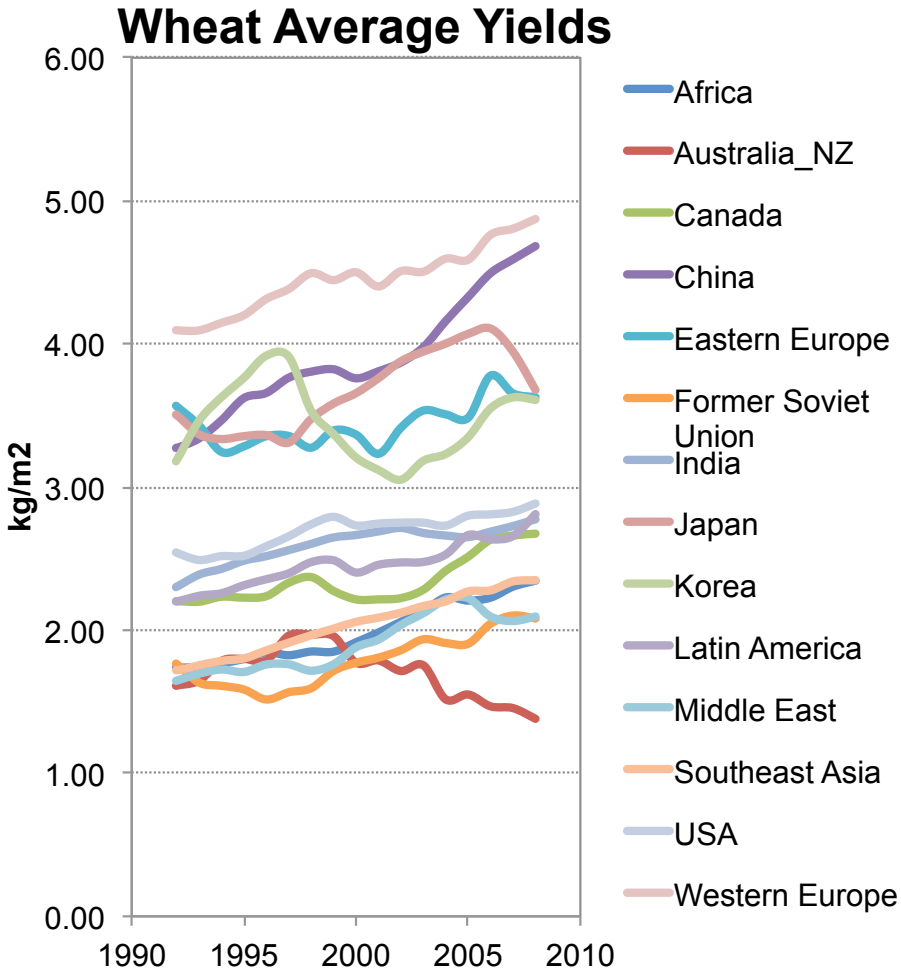
Source: Food and Agriculture Organization

Modeling Extreme Events in Current IAMs

Temporal resolution means we average away extremes

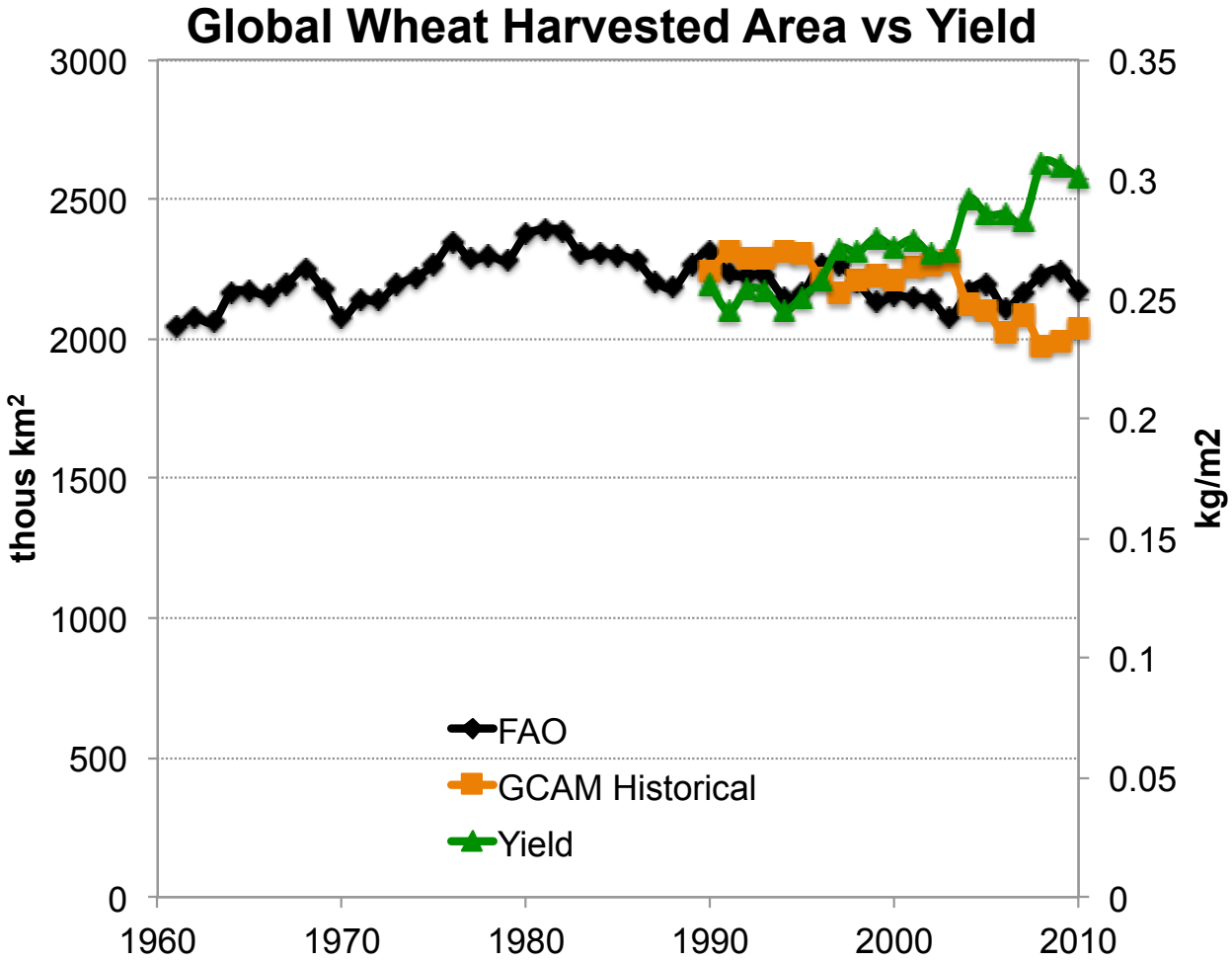
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965





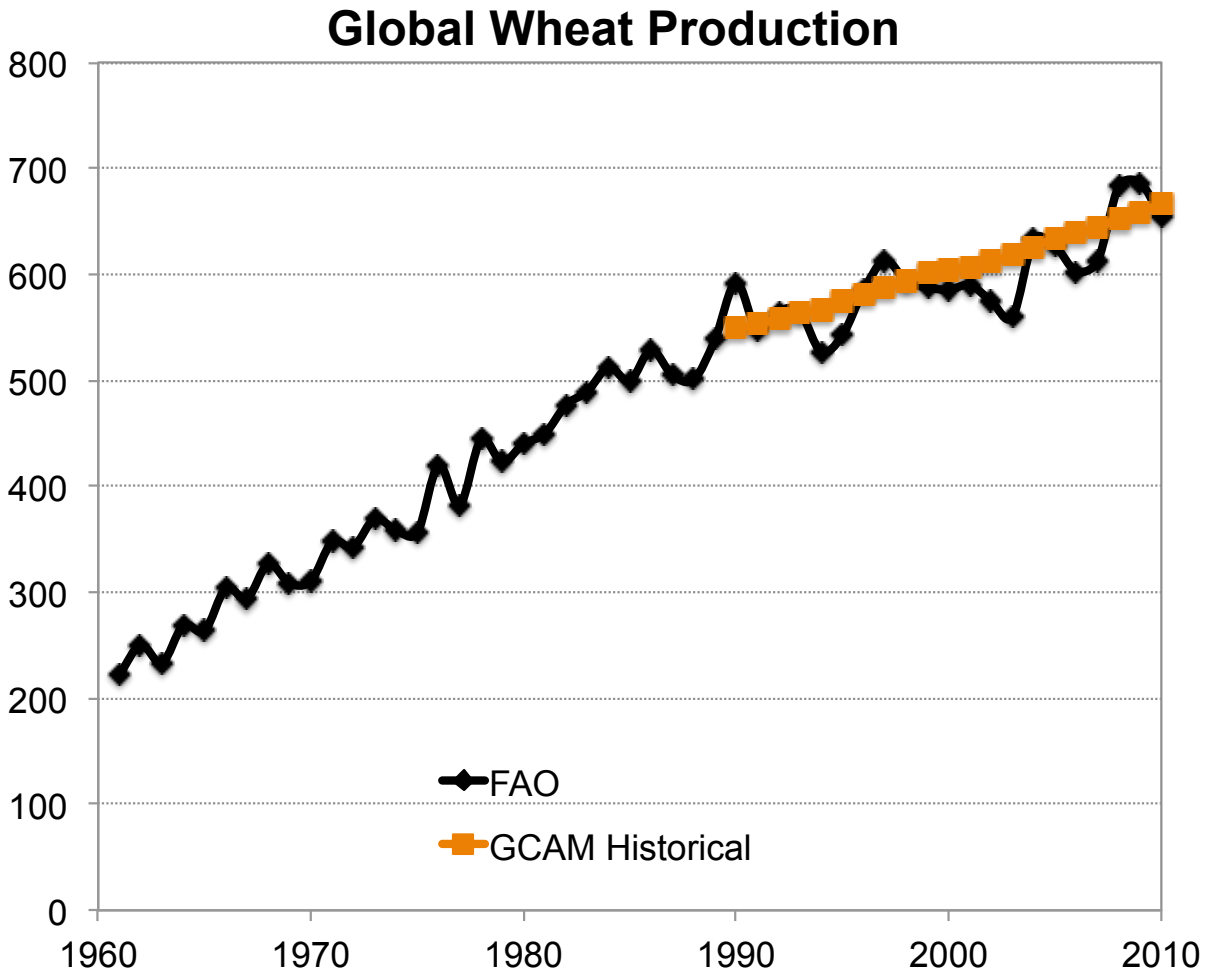
Modeling Extreme Events in Current IAMs

If you operate an IAM at annual timescale, anticipation occurs, and land is adjusted to compensate for future climate.



Modeling Extreme Events in Current IAMs

And, we miss production volatility (e.g., shortfalls, etc.).



Modeling Extreme Events in Future IAMs

How can we do better?

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- First, separate decisions from future climate response.
  - At the time planting decisions are made, land owners really only know past climate, not future. Decisions should be made based on this information.
- Second, incorporate climate data that reflects extreme events.
  - After the planting decision, additional information is necessary to tell the model that the climate is different from initial expectations.
- Third, enable the model to respond to the event in the manner people respond.
  - If crops fail in a given year, people respond by drawing down grain stocks or reducing demand.

Challenges in Modeling Impacts

- Modeling extreme events and short-term behavior
- Data availability, assimilation, and aggregation
- Modeling adaptation measures
- Spatial resolution

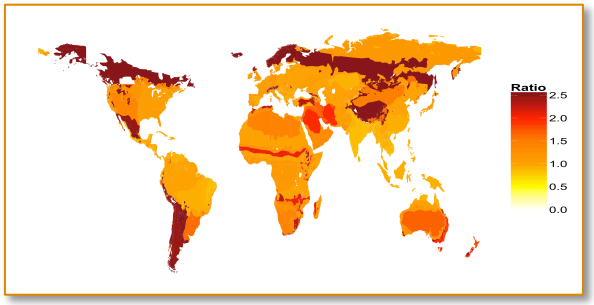
Data availability, aggregation, reconciliation

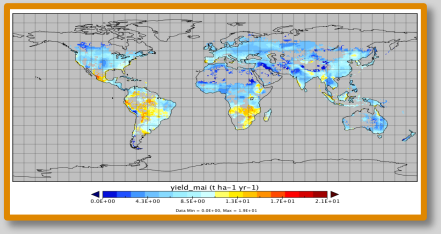
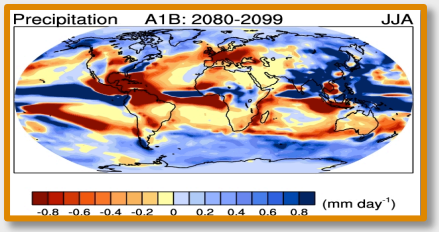
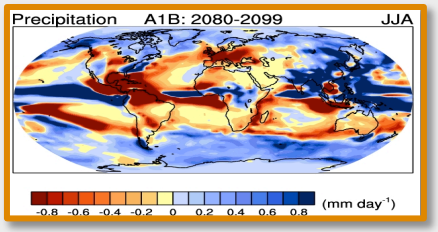
IAMs require data reflecting impacts for particular years, scenarios, and spatial resolutions

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

- **IAMs need change in yield & carbon density for each land type (e.g., forest, maize, etc.) and management practice (e.g., irrigated/rainfed) for each region/ AEZ combination in each future year.**

Rainfed Maize Yield in 2050



	Fully Coupled	Loosely Integrated
Earth System Model	Earth System Model Requires a model Spatial aggregation Possible translation into yield	 Requires a data archive Spatial aggregation
Emulator	 Requires climate data or emulation Possible pattern scaling Possible spatial aggregation Function mapping climate to yield	 Requires climate data or emulation Possible pattern scaling Possible spatial aggregation Function mapping climate to yield

Challenges in Modeling Impacts

- Modeling extreme events and short-term behavior
- Data availability, assimilation, and aggregation
- Modeling adaptation measures
- Spatial resolution

Modeling Climate Adaptation

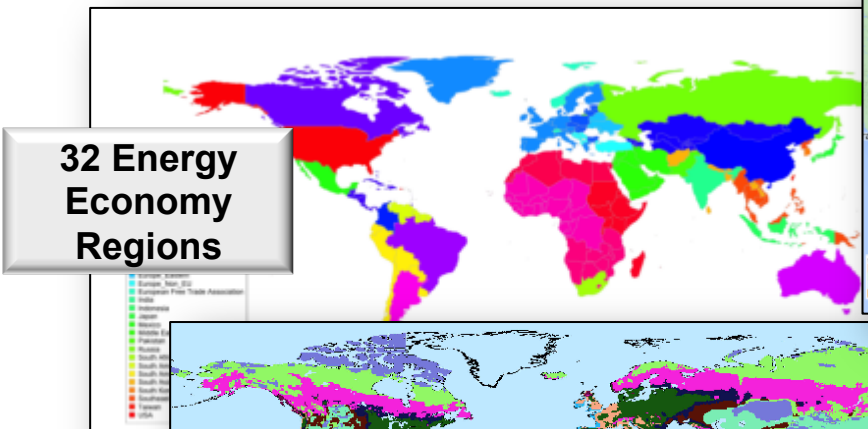
- Many adaptation measures are already included in IA models, e.g.,
  - Increases in air conditioning as temperatures rise
  - Shifting of crop production across regions
  - Changing of some management practices, like irrigation
  - Changes in energy production, both total and fuel mix
- However, currently, many IA frameworks are built to adapt *too well* to climate change either by foreseeing future change or by ignoring policies that prohibit adaptation (e.g., regulations on water withdrawals and the temperature of return flow)
- Additionally, some adaptation measures are more difficult to incorporate into IA models, e.g.,
  - Changes in crop breeding to produce climate-resilient crops
  - Changes in domestic water consumption in response to scarcity
  - Migration

Challenges in Modeling Impacts

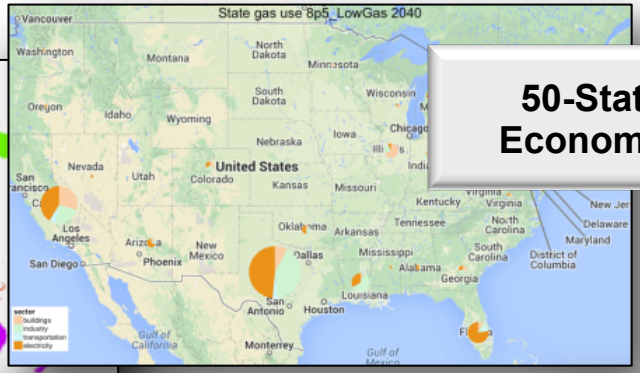
- Modeling extreme events and short-term behavior
- Data availability, assimilation, and aggregation
- Modeling adaptation measures
- Spatial resolution

The Capability to Explore Impacts at Multiple Resolutions is Critical

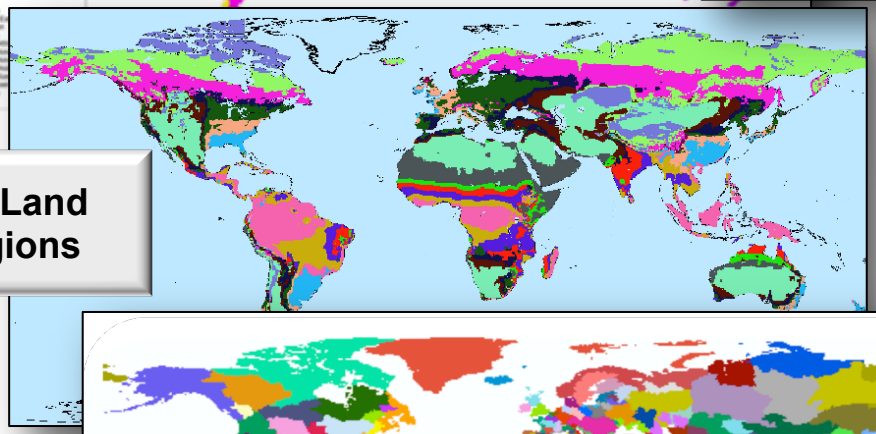
Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*



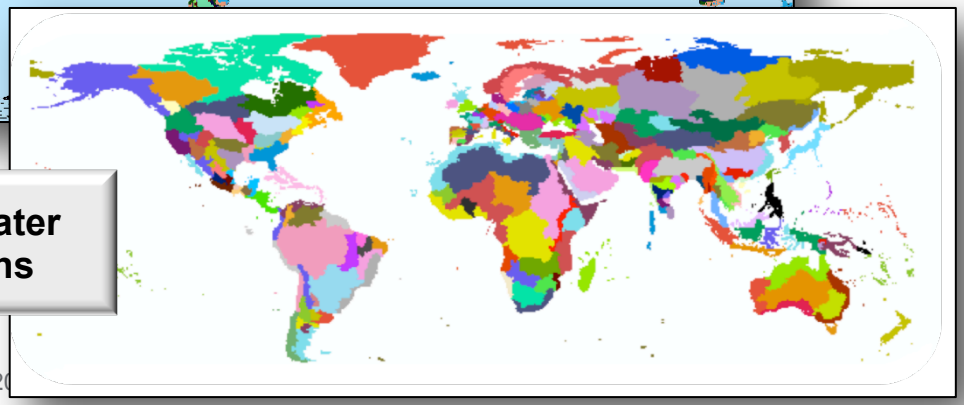
32 Energy Economy Regions



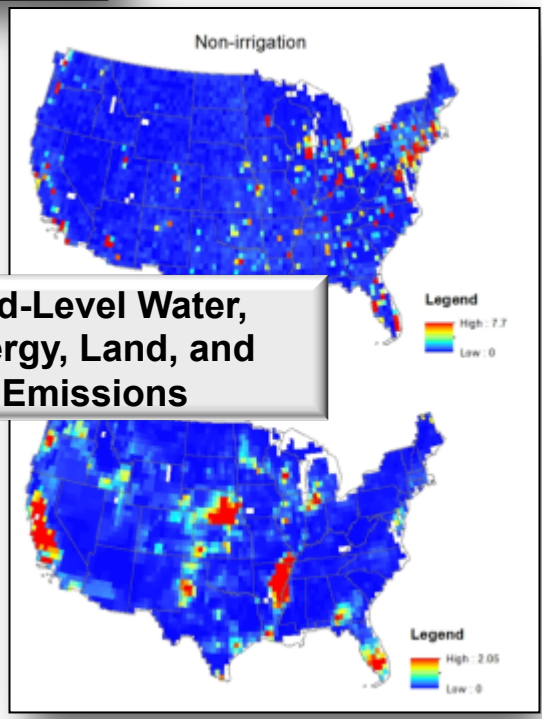
50-State Energy Economy Regions



283 Land Regions



233 Water Basins



Grid-Level Water, Energy, Land, and Emissions

Concluding Thoughts

Concluding Thoughts

- Efforts to model impacts in integrated assessment models are underway. Initial experiments have focused on the effect of climate change on energy, water, and land. By doing these analyses in an IAM, we can assess feedbacks among these systems (e.g., the effect of agricultural impacts on bioenergy and electricity production).

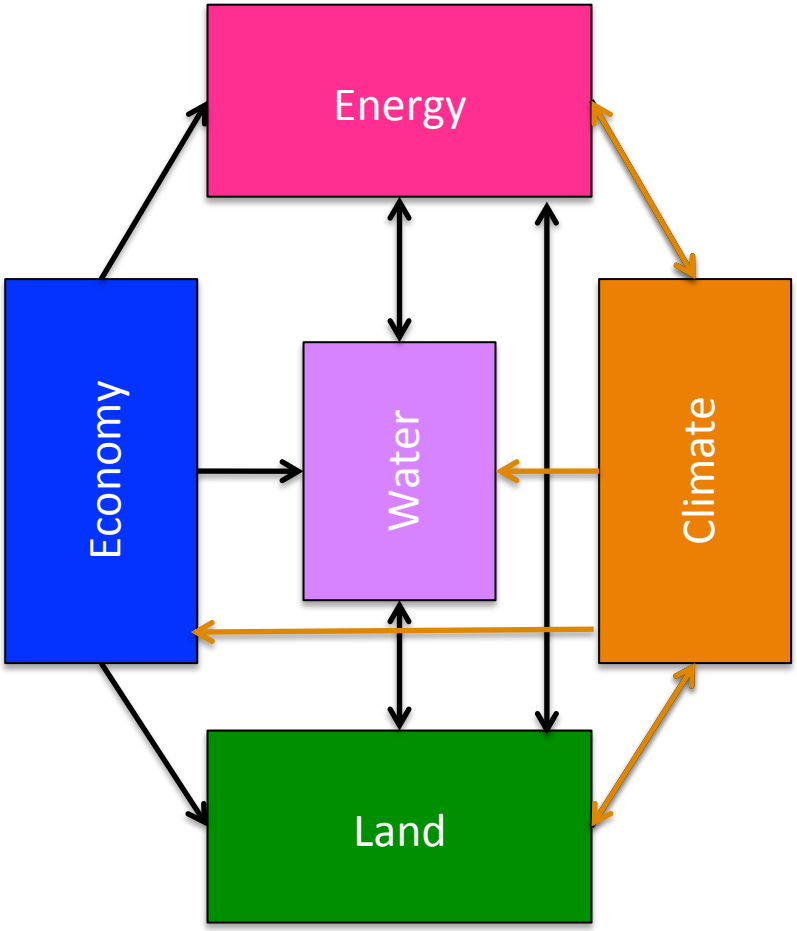
- Many challenges exist in modeling impacts, including:
  - Modeling extreme events and short-term behavior
  - Data availability, assimilation, and aggregation
  - Modeling adaptation measures
  - Spatial resolution

Pacific Northwest
NATIONAL LABORATORY
Proudly Operated by Battelle *Since 1965*

THANK YOU!!

katherine.calvin@pnnl.gov

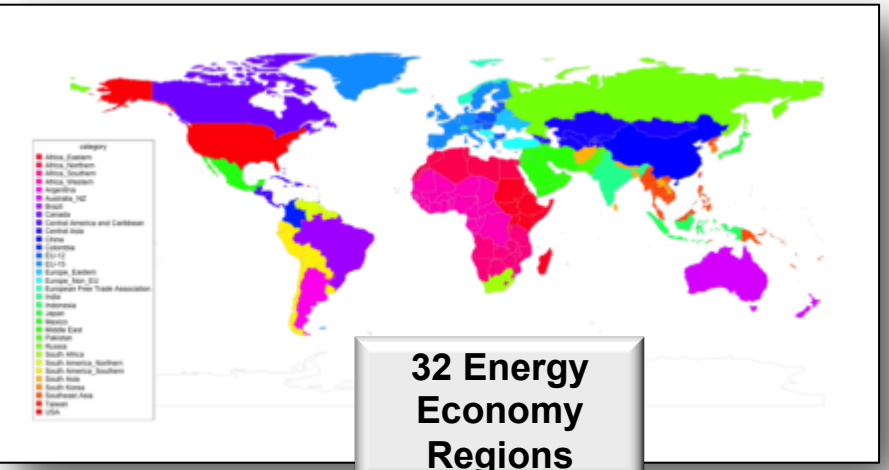
1. How does climate influence human systems (e.g., via energy, water, or land)?



- Climate can enter through energy, water, land, or other avenues.
- Highly-resolved IAMs represent these three systems, along with the economy, allowing for these linkages to be explored.
- In addition, these IAMs capture the relationships between energy, water, land, and the economy, meaning that indirect interactions can be explored.
- Finally, IAMs are built to simultaneously explore impacts and mitigation.

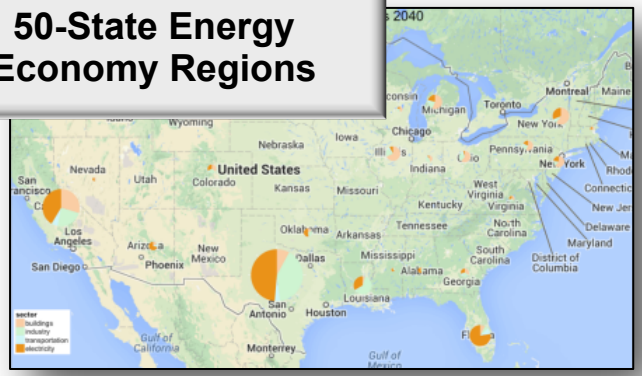
3. At what regional scale are we considering the impacts?

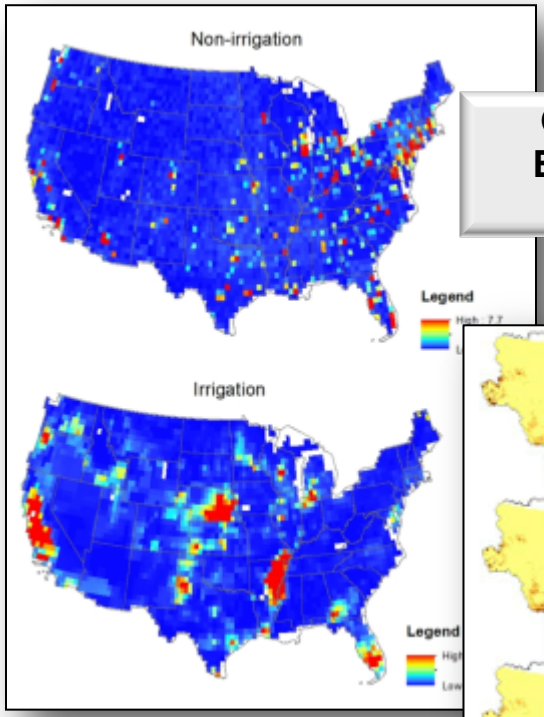
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



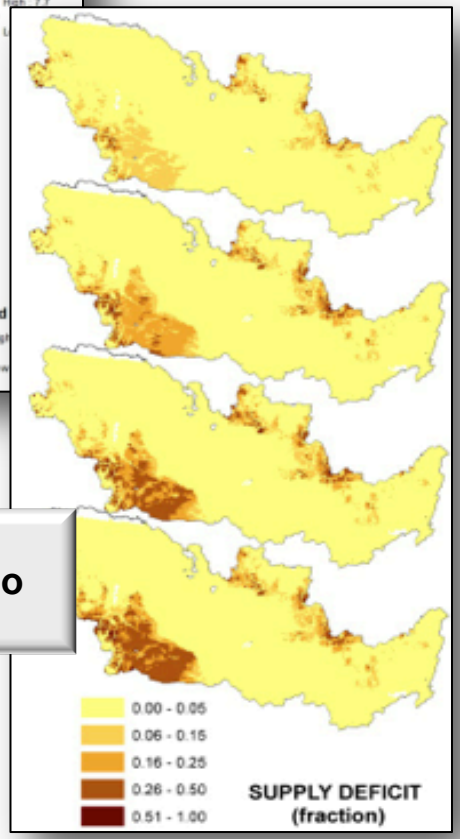
32 Energy Economy Regions

50-State Energy Economy Regions





Grid-Level Water, Energy, Land, and Emissions



Missouri, Upper Mississipi, and Ohio River Basins

4. How is climate represented?

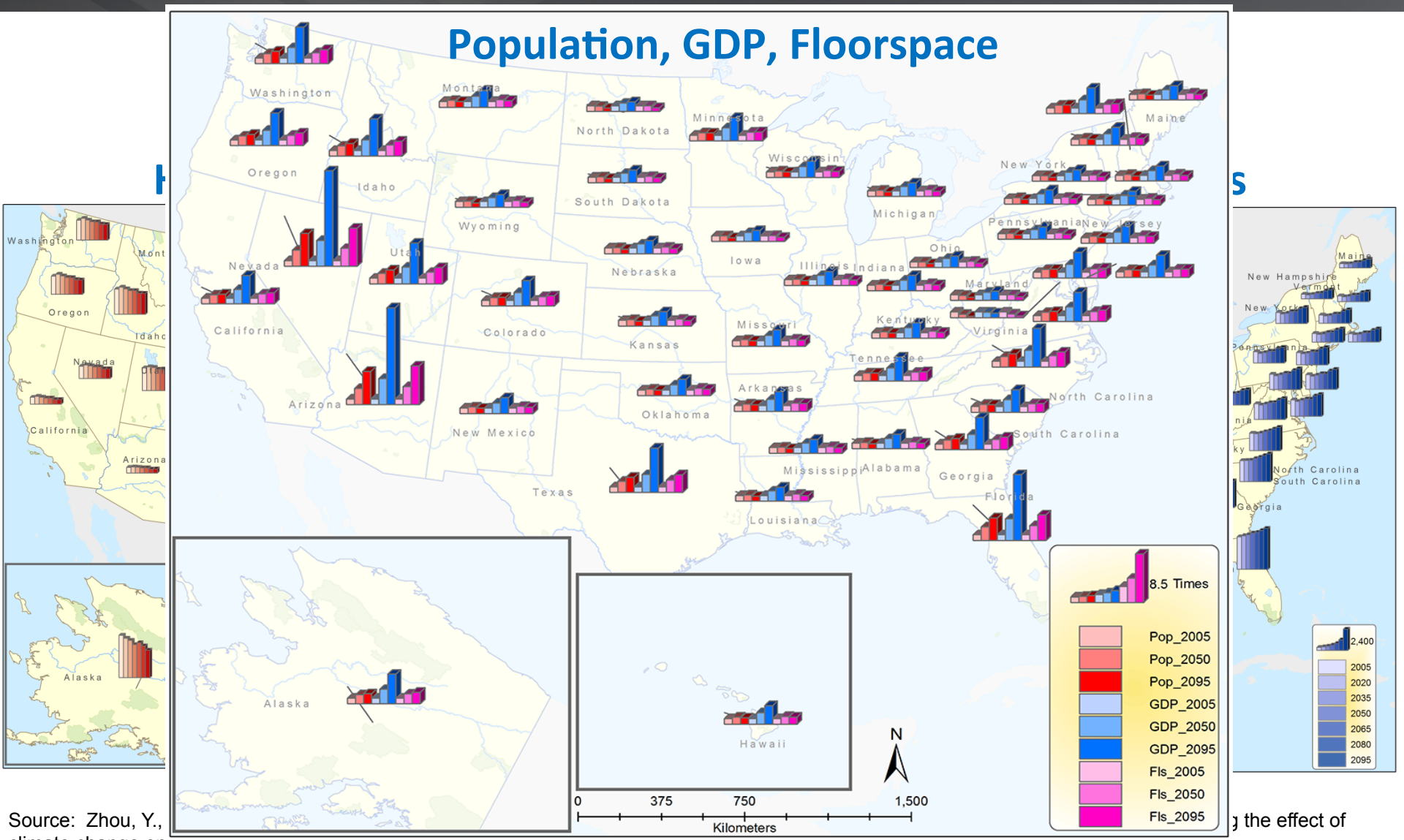
Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

	Fully Coupled	Loosely Integrated
Earth System Model	Calculate change in cooling degree days based on temperature from the Earth System Model at each time step (or iterate within a time step)	Calculate change in cooling degree days based on temperature from the CMIP5 archive and input into the IAM
Emulator	Calculate change in cooling degree days based on temperature from the emulator at each time step (or iterate within a time step)	Calculate change in cooling degree days based on temperature from the emulator offline and input into the IAM

Building Energy Impacts: Current Results

Demand in GCAM is a Function of Socioeconomics and Climate

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965



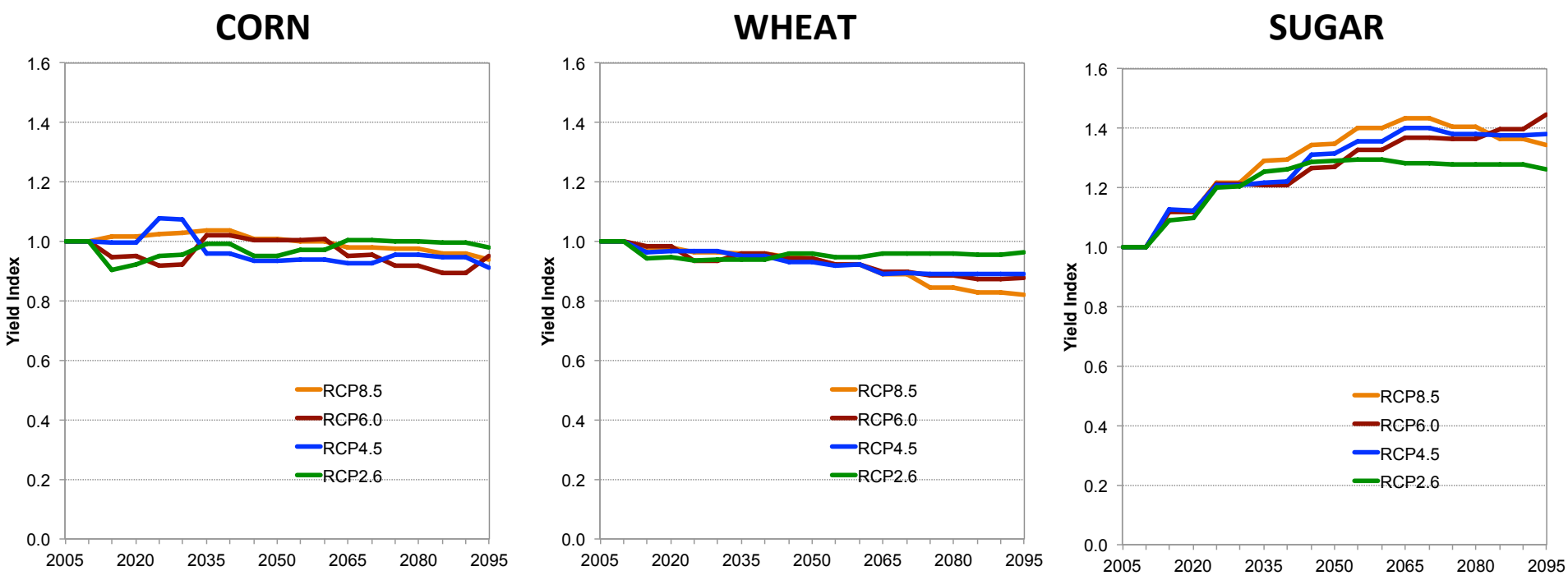
Source: Zhou, Y., ... the effect of climate change on U.S. state-level buildings energy demands in an integrated assessment framework." Applied Energy 113(0): 1077-1088.

Agriculture Impacts: Current Results

Change in Yield Varies by Crop and Region. Global average yields increase for sugar and decrease for wheat.

Pacific Northwest NATIONAL LABORATORY
Proudly Operated by Battelle Since 1965

Global average change in yield



Source: Kyle, P., C. Mueller, K. Calvin and A. M. Thomson (2014). "Meeting the Radiative Forcing Targets of the Representative Concentration Pathways in a World with Agricultural Climate Impacts." Earths Future 2(2): 83-98.