Modeling Climate Impacts and Adaptation: An analytical framework and application in U.S. agriculture sector

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Motivation

- The integrated assessment models (IAMs) have made significant advancements in representing socioeconomic-energy-land-climate systems and evaluating climate mitigation strategies.

- Increasingly, IAMs are expanded to incorporate impacts of climate change on energy, land and ecosystems, and evaluate the costs and benefits of response options.

- Representation and analysis of adaptation responses using IAMs is still limited, giving the challenges with representing complex human-natural systems and processes and diverse adaptation response options, especially at finer scales.

- Improving the modeling and analytical foundation of climate adaptation is important to:
  - estimate the costs, benefits and welfare impacts of adaptation responses.
  - evaluate interactions and tradeoffs of mitigation and adaptation responses.
  - understand the feedback of adaptation responses to socioeconomic, energy, land, and climate systems.

- These require modeling approaches that both enhance IAMs and expand IAMs by coupling models, data...
Analytical Framework

• Integrated, multi-scale modeling framework to evaluate climate impacts and adaptation responses
  • Connect broad socioeconomic drivers (e.g., population growth, technological changes, trade) with impacts and responses at regional and local levels
  • Use interdisciplinary approach that couples different models, data and methods

• Welfare analysis framework that centers around evaluating multiple dimensions of human welfare, including economic, social, and environmental outcomes
  • Understand interactions and tradeoffs

• Analysis design guided by decision-relevant questions
  • Selection of study region, impacts and adaptation responses, welfare metrics
Study Design

• Model climate change impacts on U.S. agriculture, focusing on economic and regional environmental outcomes in the Upper Mississippi River Basin

• Multi-model, multi-scale modeling that couples an IAM (GCAM) with global crop yield emulator (Persephone) and biophysical watershed model (SWAT) to evaluate climate impacts and adaptation responses
Flexible Time Scale
GCAM Core runs at 5 years; capability to run at one year;
ancillary models run at finer scale

Community Model

Global Coverage
32 Energy & Economy Regions
384 Land Regions
235 Water Basins
Reduced-Form ESM (Hector)

Flexible Scale

Market Equilibrium Solution
Persephone

- AgMIP Coordinated Climate Crop Modelling Project (C3MP) emulator (site-specific crop models)
- Rainfed and irrigated yield impacts
  - C3MP models show more negative response for irrigated corn in UMRB than for rainfed in HadGEM_ES RCP 8.5 (2050)
- Four crops
  - Corn
  - Rice
  - Soybean
  - Wheat
- Long-term trends
SWAT: coupled terrestrial-aquatic watershed model

• **A river basin-scale model**
  - Cropland
  - Urban
  - Forest
  - River network

• **Processes**
  - Hydrology
    - green water and blue water
  - Biophysical and biogeochemical
    - Crop growth, N, P, C cycling
    - Pathogen, pesticide, heavy metal
  - Human activities
    - Industry discharge, septic
    - Crop rotation, fertilizer, conservation practices
    - Deforestation, forestation
    - Rainfall harvest

• **Output**
  - Quality and quantity of surface and ground water
  - Predict the environmental impact of land management practices and land use patterns.

• **Application areas**
  - Climate Change
  - Best Management Practices (agriculture and urban)
  - Biofuel
  - TMDL (Total Maximum Daily Load)
  - Freshwater availability
Upper Mississippi River Basin (UMRB)

- UMRB is critical to regional economy and ecosystems
  - 5 states, 60 counties
  - Commercial navigation
  - 92% of all US agricultural exports
- Agriculture: a major economic sector
  - 60% of land use
  - 2.1 million farms, over 6 million people in farm households
- Agriculture also a major contributor to water pollution
  - Runoffs and sedimentation
  - Nitrogen discharge links to dead zone in Golf of Mexico
Modeling Approach:
Climate Only (GCM to SWAT)

Direct climate change impacts
Δ temp (soil organic matter decomp)
Δ precip (heavy precip events → runoff)
Modeling Approach:
Land Use Only (GCAM to SWAT)

**GCAM**
- Economic effects of cc impacts
- U.S. adaptation (e.g., irrig. tech)

**SWAT**
- Regional water quality and quantity effects in UMRB

Demand-driven changes
Δ cropland use (area)
Modeling Approach:
Climate + Land Use (GCM to GCAM to SWAT)

GCM
HadGEM2_ES
RCP 8.5 Results

Δ temp
Δ precip

Persephone
- Emulator of C3MP
- Global impacts on crop yields (irrig. & rainfed)
  - corn, rice, soybean, wheat

Δ crop yield

GCAM
- Economic effects of cc impacts
  - U.S. adaptation (e.g., irrig. tech)

SWAT
- Regional water quality and quantity effects in UMRB

Demand-driven changes
Δ cropland use (area)
Modeling Approach: Everything (Future)

- **GCM**
  - HadGEM2_ES
  - RCP 8.5 Results
  - Δ temp
  - Δ precip

- **Persephone**
  - Emulator of C3MP
  - Global impacts on crop yields (irrig. & rainfed)
  - corn, rice, soybean, wheat
  - Δ crop yield

- **GCAM**
  - Economic effects of cc impacts
  - U.S. adaptation (e.g., irrig. tech)
  - Δ crop yield

- **SWAT**
  - Regional water quality and quantity effects in UMRB
  - Δ cropland use (area)

**Direct climate change impacts**
- Δ temp (soil organic matter decomp)
- Δ precip (heavy precip events → runoff)

**Demand-driven changes**
- Δ cropland use (area)
Climate Change Inputs in UMRB

Change in temperature and precipitation from RCP8.5 GCM projections.

Results from HadGEM2 are shown in orange.
GCAM Results for the UMRB

- Cropland change in 2050 compared to 2010 driven primarily by increased demand
  - ↑5.0% for Reference, due to increase population and income
  - Little area for cropland extensification
    - No “other arable” land in this basin
    - Conversion primarily from forest and pasture lands, both Reference and RCP 8.5

- Climate change has small effects on land use change in UMRB
  - Water stress in this region is low, even under RCP 8.5
  - Positive climate impacts on wheat yields (strong CO₂ fertilization effect)
  - Negative climate impacts on corn yields result in production losses, rather than extensification
  - ↑5.3% HadGEM 8.5, demand + climate effects
  - Forest and pasture losses ~4%-10% greater under RCP 8.5 than Reference
SWAT Results: Water Quality under Climate Change in UMRB

% Change in Nitrate and Nitrite Load in UMRB (from 1960-1999)

- Climate Only (GCM to SWAT)
- Land Use Only (GCAM to SWAT)
- Climate + Land Use (GCM to GCAM to SWAT)
SWAT Results: Climate change exacerbates Dead Zone in the Gulf of Mexico

- Strong correlation between hypoxic zone area and May Nitrate+Nitrite load (Turner and Rabalais 2016).
- An empirical relationship derived by Whittaker et al. (2014) is used to project future trend of dead zone of gulf of Mexico.
Key Insights

• GCAM shows small effects of climate change and adaptation response in the U.S. agriculture sector, partially driven by the crop yields model

• SWAT analysis shows climate change has significant impacts on water quality; land use change from future agricultural demand drives further changes in water quality outcomes

• The analysis demonstrates the merits of a multi-scale, multi-model framework that evaluates multi-dimensional welfare impacts of climate change and adaptation responses beyond what an IAM-only approach can accomplish
Lessons learned and modeling challenges

• Coupling GCAM with SWAT expands the capability of an IAM to evaluate ecosystem and environmental impacts of climate change at finer scale

• GCAM provides socioeconomic drivers (e.g., land use change) in SWAT to evaluate environmental effects

• Coupling GCAM with SWAT poses challenges:
  • these two types of models represent earth system with different scales (e.g. input data resolution, operating at global vs regional scale)
  • SWAT and GCAM represent land management with different details
  • dynamic coupling of GCAM and SWAT would require substantial revision of codes of both models

• Implementing adaptation measures in GCAM also requires substantial model development
Future Work

• Investigate crop yields effects

• Expand scenarios analysis:
  • Combined effects of climate change and land use change on water quality
  • Mitigation scenario (e.g., RCP 4.5)
  • Additional adaptation responses

• GCAM-SWAT coupling:
  • explore how environmental costs estimated by SWAT can be incorporated in crop production function in GCAM
  • reconcile GCAM and SWAT with respect to land management
  • identify socio-economic-environmental interactions across different regions
  • Carbon balance of different land uses from SWAT to GCAM
Thank You

For any questions or follow up, please contact Jia Li (li.jia@epa.gov)

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