USDA Economic Research Service
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Large-scale biomass supply for carbon sequestration

Ron Sands
USDA Economic Research Service

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Economics of Climate Change

Research Questions

1. What are the economic impacts of climate change on world and U.S. agriculture?
2. What is agriculture's contribution to achieving net-zero U.S. greenhouse gas emissions?

This requires an economic model that can simulate six major drivers of global change into the future:

- population
- per capita income growth
- dietary preference
- agricultural productivity
- climate change effects on agriculture, and
- large-scale demand for bioenergy as part of a climate change mitigation strategy.

Approach

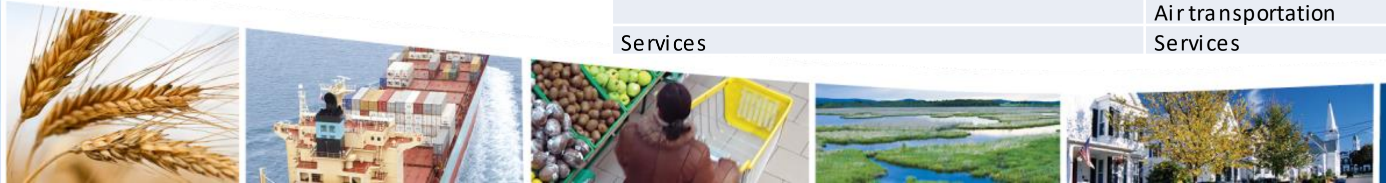
- This presentation considers two drivers
  - Bionergy as part of a climate change mitigation strategy
  - Agricultural productivity
- Net-zero carbon dioxide (CO_2) emissions required to stabilize CO_2 concentrations in the atmosphere
- Simulation of global energy and agriculture in a general equilibrium model to 2100
- Scenarios similar to Energy Modeling Forum 33 study
- Impacts on world agricultural indicators
  - Food calories consumed
  - Crop calories produced
  - Land area for all crops (including bioenergy crops)
  - Land area for food crops
  - Crop yield
  - Food price index

Future Agricultural Resources Model (FARM)

Global computable general equilibrium model with 13 world regions, 38 production sectors, and five-year time steps from 2011 through 2101.

Region name	Notes
Sub-Saharan Africa	
India	
Other Asia (south)	
Brazil	
Other South America	Including Central America, Caribbean, and Mexico
Middle East and North Africa	Including Turkey
Economies in Transition	Russia, Belarus, Ukraine, Kazakhstan, Kyrgyzstan, Armenia, Azerbaijan, Georgia, Tajikistan, Turkmenistan, and Uzbekistan
China	
Southeast and East Asia	Including Japan
United States	
Canada	
Europe	Including Estonia, Latvia, and Lithuania
Australia and New Zealand	Including Oceania

Group	Subgroup	Production Sector
Primary agriculture	Crops	Wheat
		Paddy rice
		Other grains
		Oilseeds
		Sugar (cane and beet)
		Vegetables and fruits
		Plant fibers
		Other crops
	Animal products	Cattle and other ruminants
		Raw milk
		Wool
		Other animal products
	Fisheries	Fish
	Forestry	Forestry
Food processing		Vegetable oils
		Processed rice
		Sugar
		Beverages and tobacco products
		Other food
		Meat from cattle and other ruminants
		Dairy products
		Other meat products
Energy	Production	Coal
		Crude oil
		Natural gas
	Transformation	Refined coal and petroleum products
		Electricity
Energy-intensive industries		Wood products
		Paper and pulp
		Chemicals, rubber, and plastic
		Nonmetallic minerals
		Iron and steel
		Nonferrous metals
Other industry		Other industry
Transportation		Land transportation
		Water transportation
		Air transportation
Services		Services



Energy and emissions indicators for mitigation scenarios

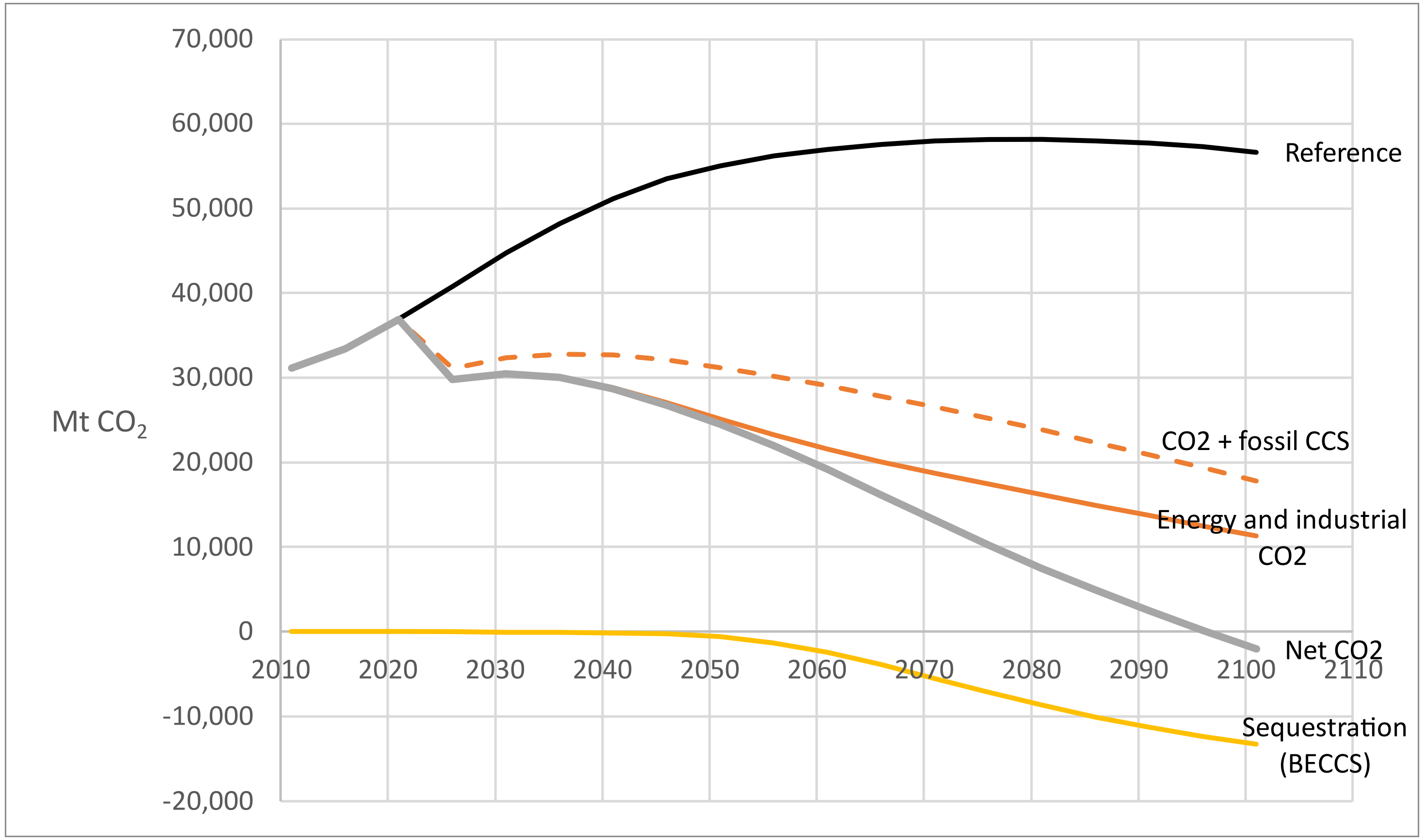
- To assess the impact of large-scale biomass production on agriculture, we first construct six non-mitigation scenarios that vary across population growth, and agricultural productivity growth
- We then repeat the scenarios with a CO_2 price path that incentivizes large-scale biomass production
- Mitigation scenarios are shown here
- A central mitigation scenario is in blue bold type
- Productivity variants are in bold black type

Year	Mitigation	Population	Agricultural productivity growth	Diet	Energy crop area (Mha)	Bioenergy production (EJ)	CCS biomass (Mt CO_2)	CCS fossil (Mt CO_2)	Net CO_2 emissions (Mt CO_2)
2100	None	U.N. medium	Medium	Income-driven	25	15			56,800
2100	Net Zero CO_2	U.N. medium	Medium	Static	354	164	13,340	6,410	-1,820
2100	**Net Zero CO_2**	**U.N. medium**	**Medium**	**Income-driven**	**327**	**160**	**13,110**	**6,640**	**-1,600**
2100	Net Zero CO_2	U.N. low	Medium	Income-driven	442	166	13,760	4,170	-5,870
2100	Net Zero CO_2*	U.N. high	Medium	Income-driven	236	149	12,080	9,760	4,220
2100	**Net Zero CO_2**	**U.N. medium**	**Low**	**Income-driven**	**298**	**158**	**13,070**	**6,650**	**-1,460**
2100	**Net Zero CO_2**	**U.N. medium**	**High**	**Income-driven**	**356**	**161**	**13,140**	**6,620**	**-1,680**

Notes: *The mitigation scenario with high population growth does not achieve net-zero CO2 emissions. Reference (non-mitigation) emissions range from 41,200 (low population) to 75,270 (high population) Mt CO2 in year 2100.

World CO_2 emissions: Central Net Zero scenario

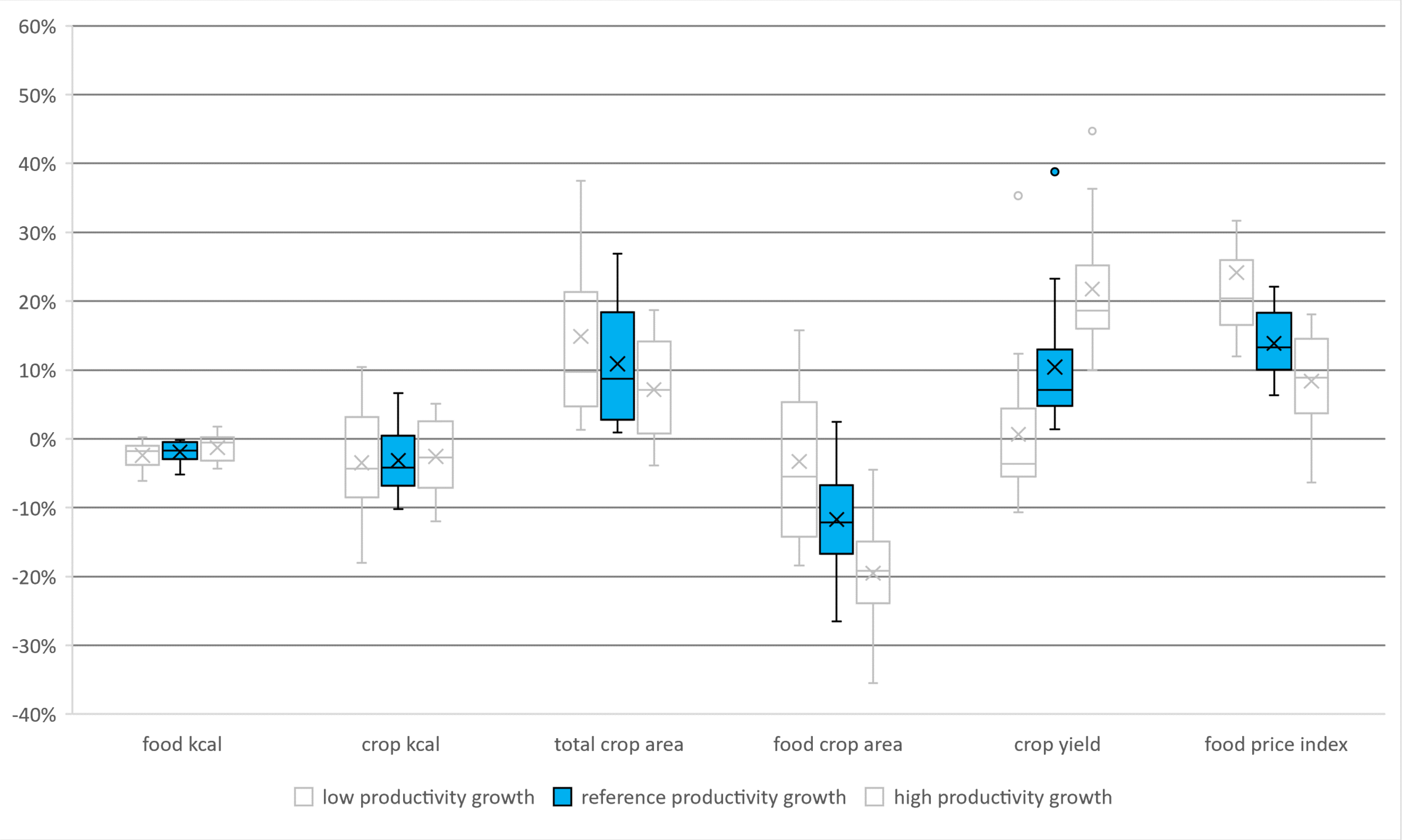
- In the central mitigation scenario, net CO_2 emissions decline from a world reference scenario of 56,800 $MtCO_2$ to negative 1,600 $MtCO_2$ in 2100
- This represents the difference between 11,520 $MtCO_2$ emitted from energy and industry, and 13,110 $MtCO_2$ sequestered through bioenergy with carbon dioxide capture and storage (BECCS)
- CO_2 capture and storage is available for electricity generation, from either fossil fuels or biomass
- Total sequestration equals 13,110 $MtCO_2$ from BECCS plus 6,640 $MtCO_2$ from fossil-fuel electricity generation
- This quantity of negative emissions from BECCS uses 327 million hectares (Mha) of cropland to produce 160 exajoules of biomass energy



Notes: FARM model simulations begin in 2011, the GTAP version 9 base year, with five-year time steps through 2101. World population growth is from the U.N. medium-fertility scenario; income growth is from Shared Socio-economic Pathway 2 (SSP 2), the "middle-of-the-road" scenario. The difference between the dashed orange line and the solid orange line is CCS used for fossil-fuel electricity generation.

Large-scale biomass and agricultural indicators

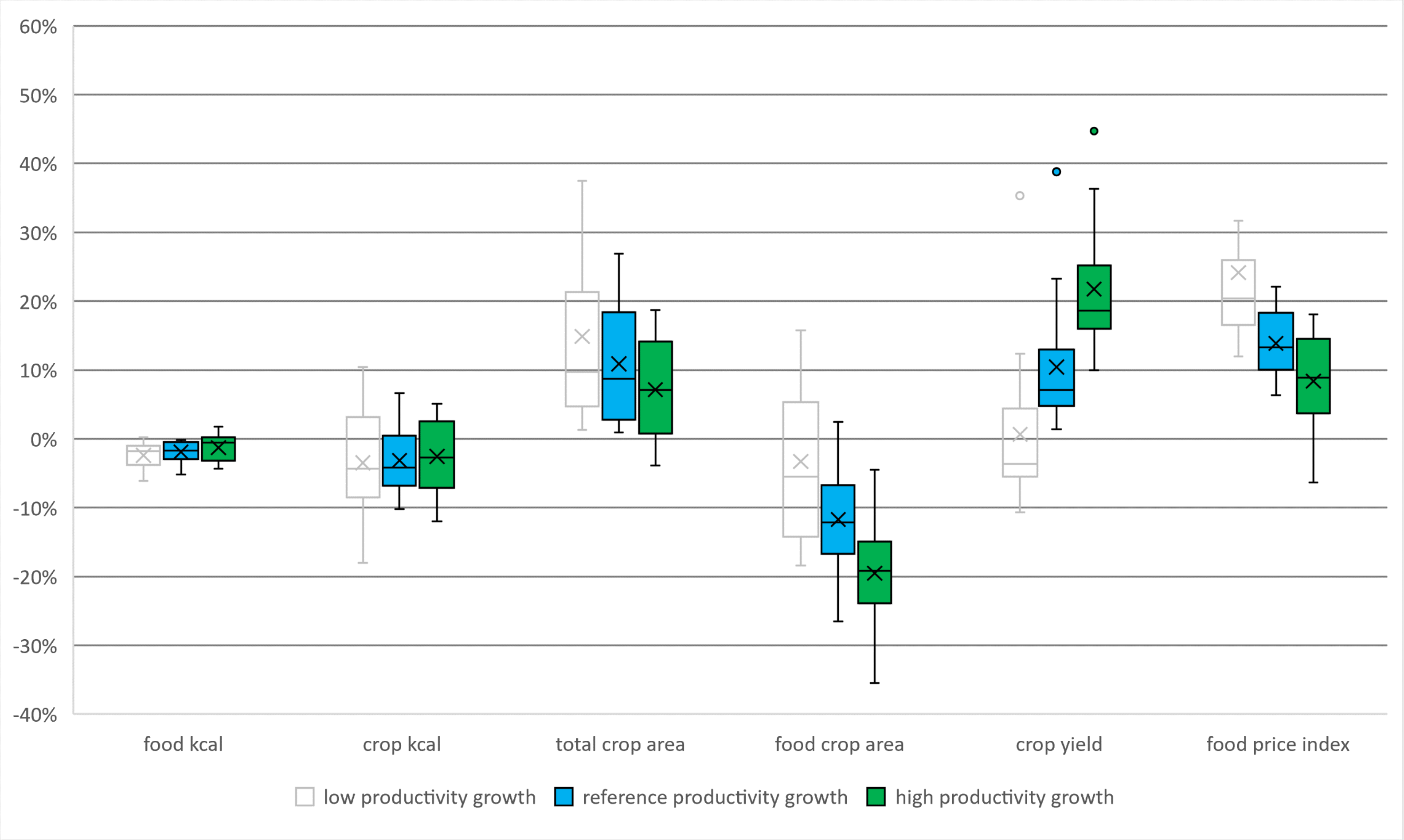
- Introduction of large-scale bioenergy production impacts six agricultural indicators
- Impacts are shown as percentage changes relative to the central non-mitigation scenario
- Blue box-and-whisker symbols show the effect on agricultural indicators in the central mitigation scenario
- The cost of mitigation is reflected as an increase in the food price index due to greater competition for land
- Total crop area increases, and food crop area decreases, to accommodate production of energy crops
- Each hectare of land receives additional inputs (e.g., capital, labor, fertilizer) which increases yield but also the cost of production



Notes: Each box-and-whisker symbol displays variation across 13 world regions. “food kcal” is world food consumption in calories. “crop kcal” is world crop production in calories. Indicators adjust to keep food consumption near its level in the reference scenario. Total crop area includes food crops, non-food crops (e.g., cotton and hay), and bioenergy crops.

Large-scale biomass and agricultural indicators

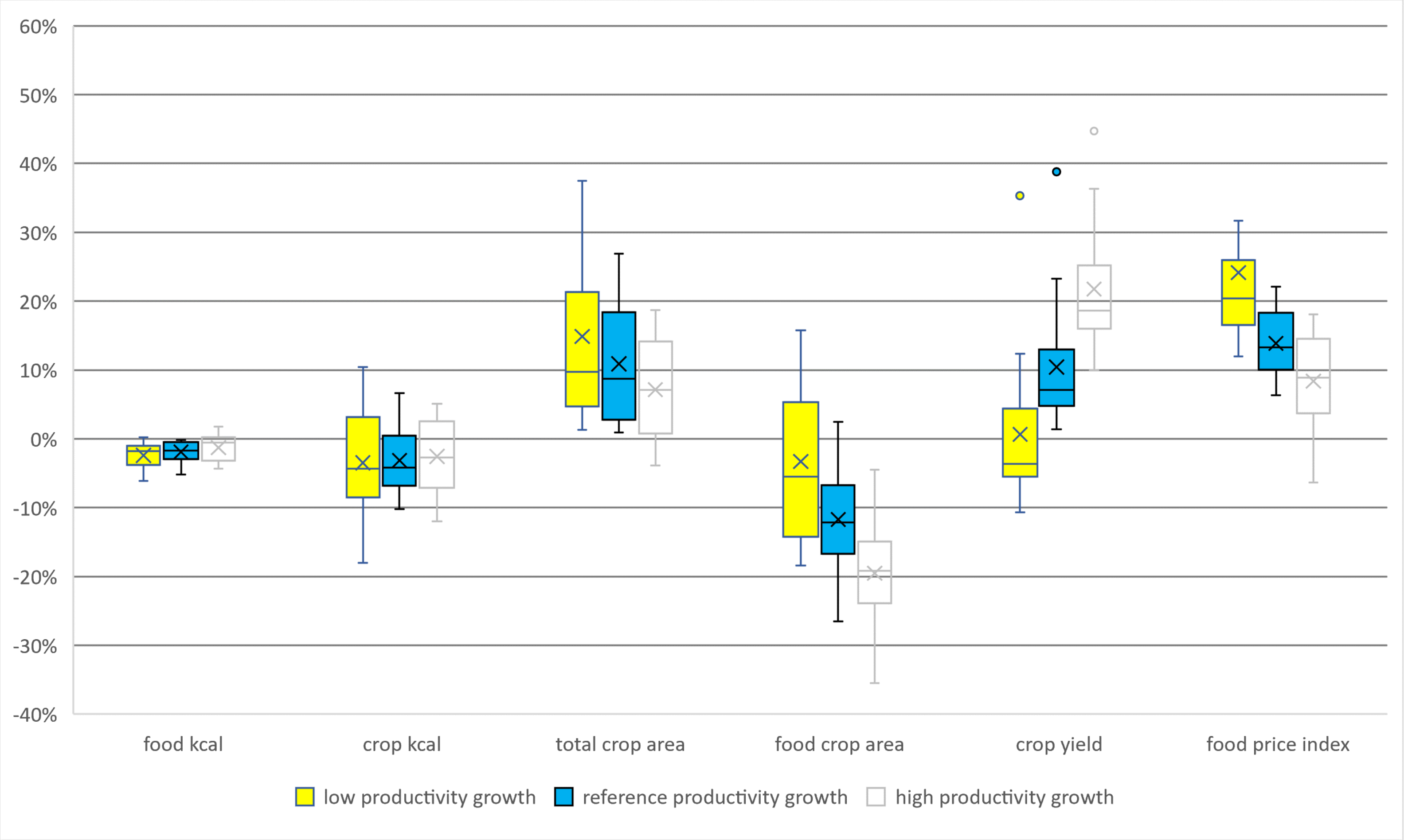
- Introduction of large-scale bioenergy production impacts six agricultural indicators
- Impacts are shown as percentage changes relative to the central non-mitigation scenario
- Green box-and-whisker symbols show the effect on agricultural indicators in the high-productivity scenario
- The cost of mitigation is reflected as an increase in the food price index due to greater competition for land
- Total crop area increases, and food crop area decreases, to accommodate production of energy crops
- Each hectare of land receives additional inputs (e.g., capital, labor, fertilizer) which increases yield but also the cost of production



Notes: Each box-and-whisker symbol displays variation across 13 world regions. “food kcal” is world food consumption in calories. “crop kcal” is world crop production in calories. Indicators adjust to keep food consumption near its level in the reference scenario. Total crop area includes food crops, non-food crops (e.g., cotton and hay), and bioenergy crops.

Large-scale biomass and agricultural indicators

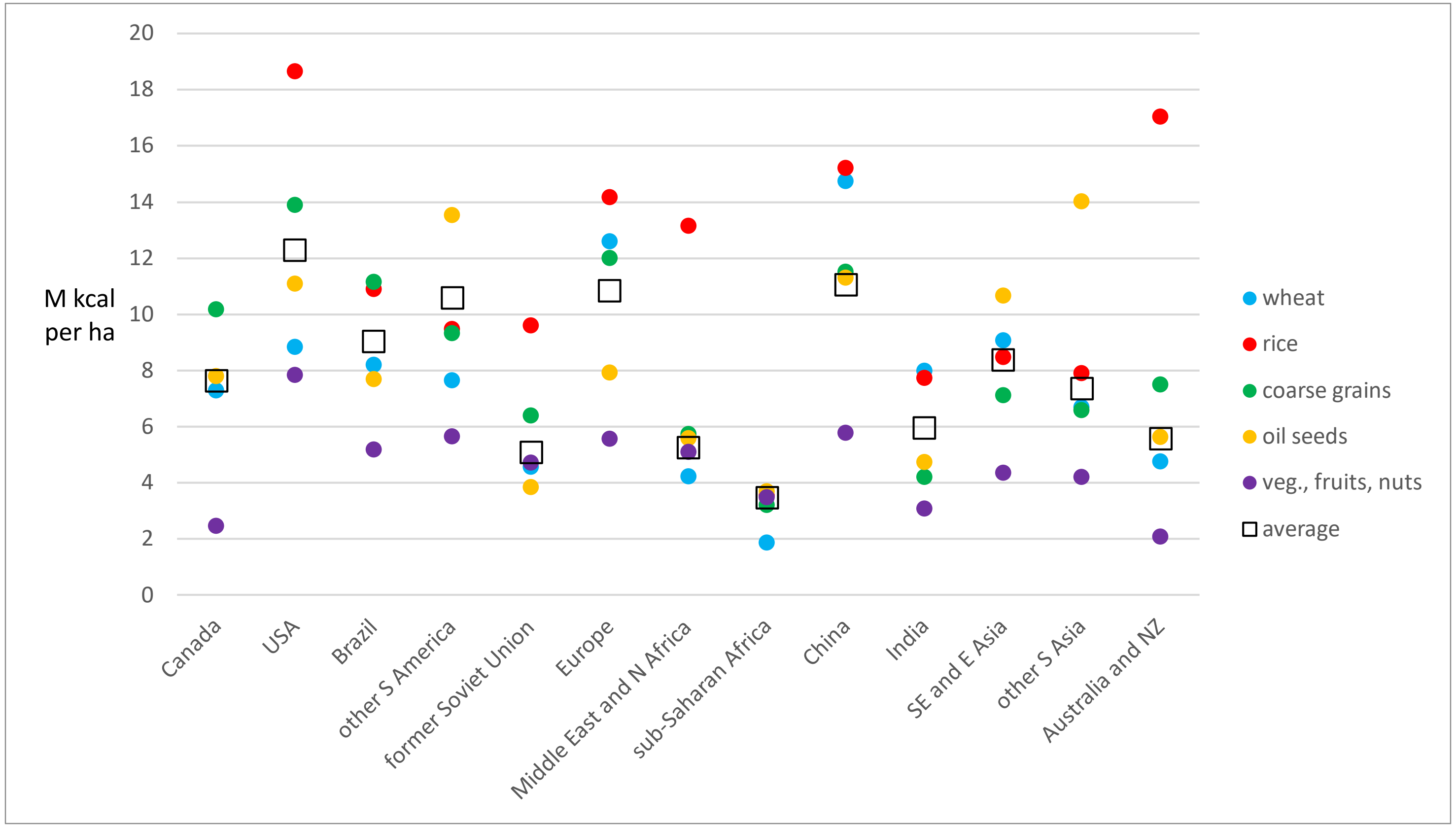
- Introduction of large-scale bioenergy production impacts six agricultural indicators
- Impacts are shown as percentage changes relative to the central non-mitigation scenario
- Yellow box-and-whisker symbols show the effect on agricultural indicators in the low productivity scenario
- The cost of mitigation is reflected as an increase in the food price index due to greater competition for land
- Total crop area increases, and food crop area decreases, to accommodate production of energy crops
- Each hectare of land receives additional inputs (e.g., capital, labor, fertilizer) which increases yield but also the cost of production



Notes: Each box-and-whisker symbol displays variation across 13 world regions. “food kcal” is world food consumption in calories. “crop kcal” is world crop production in calories. Indicators adjust to keep food consumption near its level in the reference scenario. Total crop area includes food crops, non-food crops (e.g., cotton and hay), and bioenergy crops.

Yield of major crops by world region

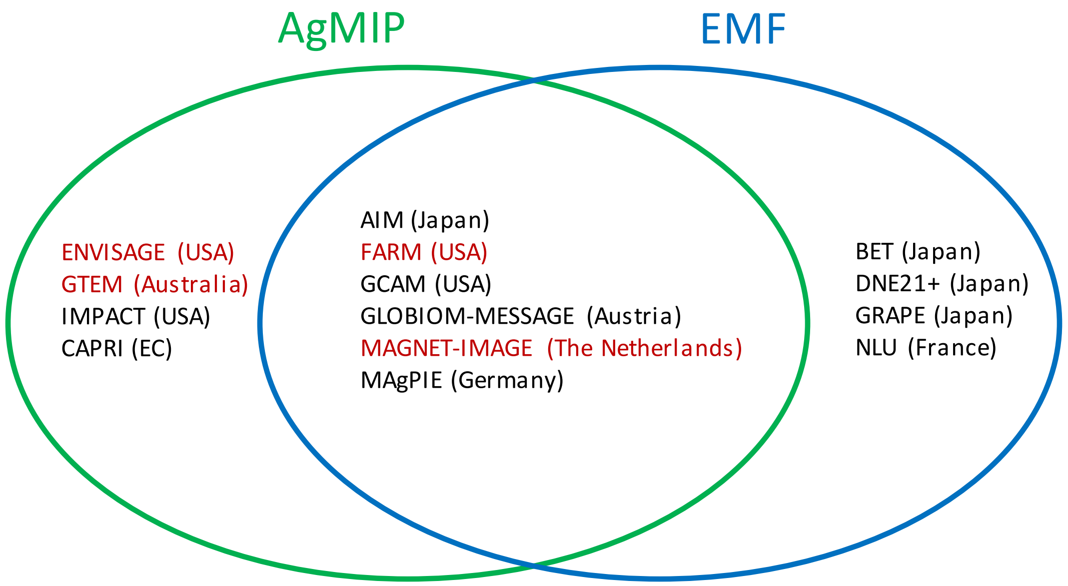
- Historical (2011) crop yields for 13 world regions in FARM are displayed, with yield calculated as million kcal per ha
- Calories are a convenient unit of measurement, as they can be used to compare across all crops
- Average crop yield in sub-Saharan Africa is much lower than any other world region and provides motivation for constructing productivity growth scenarios
- Productivity assumptions are based on a general theme of closing yield gaps



Note: The FARM model has 13 world regions, listed along the horizontal axis.

Model Intercomparison Projects (MIPs)

- Gold standard for assessment of climate change science, impacts, and mitigation
- Prominent MIPs
  - Coupled Model Intercomparison Project (CMIP)
  - Agricultural Model Intercomparison and Improvement Project (AgMIP)
  - Stanford Energy Modeling Forum (EMF)
- Features of MIPs
  - Multi-model
  - Scenario based
  - Multi-disciplinary
  - Sustained effort over many years



Global Economic Models

- AgMIP global economics modeling group
  - Mix of partial and general equilibrium models
  - Coordinated scenarios, time horizon, world regions, and agricultural commodity groups
- Overlap with global modeling teams in Stanford Energy Modeling Forum

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Climate change effects on agriculture: Economic responses to biophysical shocks

Gerald C. Nelson[a,1], Hugo Valin[b], Ronald D. Sands[c], Petr Havlik[b], Helal Ahammad[d], Delphine Deryng[e], Joshua Elliott[f,g], Shinichiro Fujimori[h], Tomoko Hasegawa[h], Edwina Heyhoe[d], Page Kyle[i], Martin Von Lampe[j], Hermann Lotze-Campen[k], Daniel Mason d'Croz[a], Hans van Meijl[l], Dominique van der Mensbrugghe[m], Christoph Müller[k], Alexander Popp[k], Richard Robertson[a], Sherman Robinson[a], Erwin Schmid[n], Christoph Schmitz[k], Andrzej Tabeau[l], and Dirk Willenbockel[o]

[a]Environment and Production Technology Division, International Food Policy Research Institute, Washington, DC 20006-1002; [b]International Institute for Applied Systems Analysis, Ecosystems Services and Management Program, A-2361 Laxenburg, Austria; [c]Resource and Rural Economics Division, Economic Research Service, US Department of Agriculture, Washington, DC 20250; [d]Australian Bureau of Agricultural and Resource Economics and Sciences, Canberra, ACT 2601, Australia; [e]Tyndall Centre for Climate Change Research and School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, United Kingdom; [f]University of Chicago Computation Institute, Chicago, IL 60637; [g]Columbia University Center for Climate Systems Research, New York, NY 10025; [h]National Institute for Environmental Studies, Center for Social and Environmental Systems Research, Tsukuba, Ibaraki 305-8506, Japan; [i]Joint Global Change Research Institute, Pacific Northwest National Laboratory, College Park, MD 20740; [j]Trade and Agriculture Directorate, Organisation for Economic Cooperation and Development, 75775 Paris Cedex 16, France; [k]Potsdam Institute for Climate Impact Research, 14473 Potsdam, Germany; [l]LEI (Agricultural Economics Research Institute), Wageningen University and Research Centre, 2585 DB, The Hague, The Netherlands; [m]Agricultural Development Economics Division, Food and Agriculture Organization of the United Nations, I-00153 Rome, Italy; [n]University of Natural Resources and Life Sciences, Vienna, 1180 Vienna, Austria; and [o]Institute of Development Studies, University of Sussex, Brighton BN1 9RE, United Kingdom

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Agricultural production is sensitive to weather and thus directly affected by climate change. Plausible estimates of these climate change impacts require combined use of climate, crop, and economic models. Results from previous studies vary substantially due to differences in models, scenarios, and data. This paper is part of a collective effort to systematically integrate these three types of models. We focus on the economic component of the assessment, investigating how nine global economic models of agriculture represent endogenous responses to seven standardized climate change scenarios produced by two climate and five crop models. These responses include adjustments in yields, area, consumption, and international trade. We apply biophysical shocks derived from the Intergovernmental Panel on Climate Change's representative concentration pathway with end-of-century radiative forcing of 8.5 W/m^2. The mean biophysical yield effect with no incremental CO_2 fertilization is a 17% reduction globally by 2050 relative to a scenario with unchanging climate. Endogenous economic responses reduce yield loss to 11%, increase area of major crops by 11%, and reduce consumption by 3%. Agricultural production, cropland area, trade, and prices show the greatest degree of variability in response to climate change, and consumption the lowest. The sources of these differences include model structure and specification; in particular, model assumptions about ease of land use conversion, intensification, and trade. This study identifies where models disagree on the relative responses to climate shocks and highlights research activities needed to improve the representation of agricultural adaptation responses to climate change.

climate change adaptation | model intercomparison | integrated assessment | agricultural productivity

Climate change alters weather conditions and thus has direct, biophysical effects on agricultural production. Assessing the ultimate consequences of these effects after producers and consumers respond requires detailed assessments at every step in the impact chain from climate through to crop and economic modeling.

Comparisons of results from global studies that have attempted such model integration in the past show substantial differences in effects on key economic variables. Studies in the early 1990s found that climate change would have limited agricultural impacts globally, but with varying effects across regions (1–3). Adaptation and carbon dioxide (CO_2) fertilization effects were the two largest sources of variation in the results. New simulation approaches emerged in the mid-2000s, with gridded representation of yield impacts and more comprehensive coverage of variability in climate model projections (4, 5). However, these studies still relied on a single crop model and a single economic model. The number of economic models used for these types of analysis has remained relatively limited, and there has been no attempt to compare their behavior systematically. The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (6) renewed the call to "enhance crop model intercomparison" and noted that "economic, trade and technological assumptions used in many of the integrated assessment models to project food security under climate change were poorly tested against observed data" (ref. 6, p. 285).

This paper is part of a collective effort (7) to make progress in this direction by systematically integrating results from the three types of models—climate, crop, and economic—to assess how agriculture responds to climate change. The modeling chain is portrayed in Fig. 1. General circulation models (GCMs) use a

Significance

Plausible estimates of climate change impacts on agriculture require integrated use of climate, crop, and economic models. We investigate the contribution of economic models to uncertainty in this impact chain. In the nine economic models included, the direction of management intensity, area, consumption, and international trade responses to harmonized crop yield shocks from climate change are similar. However, the magnitudes differ significantly. The differences depend on model structure, in particular the specification of endogenous yield effects, land use change, and propensity to trade. These results highlight where future research on modeling climate change impacts on agriculture should focus.

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The authors declare no conflict of interest.

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Data deposition: A data file, a metadata file, and R code to generate the graphs are stored and made available on the Agricultural Model Intercomparison and Improvement Project Web site, www.agmip.org, and the Inter-Sectoral Impact Model Intercomparison Project Web site, www.isi-mip.org. They are also available as Datasets S1, S2, and S3.

[1]To whom correspondence should be addressed. E-mail: nelson.gerald.c@gmail.com.

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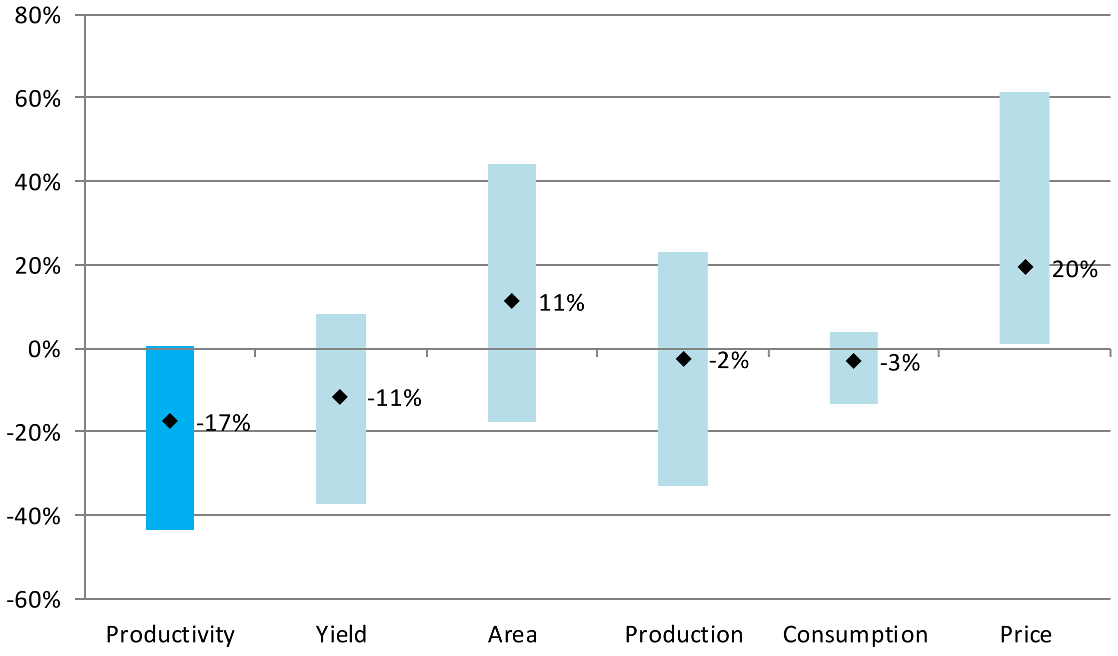
Economic responses to a decline in agricultural productivity due to climate change in 2050



Change in Productivity is the exogenous shock. All other changes are endogenous responses relative to baseline. The black diamond is the average (mean) percent change with climate change compared to no climate change in year 2050; the height of a column is the range across climate models, crop models, and nine economic models. Results are a world average across major field crops: wheat, rice, coarse grains, and oil seeds.

Source: Nelson et al. (2014) "Climate change effects on agriculture: Economic responses to biophysical shocks," *Proceedings of the National Academy of Sciences*, Vol. 111(9): 3274-3279.

Discussion

Role of Agricultural Productivity Growth

- Reducing cost of future agricultural production (offsetting negative impacts from climate change)
- Reduce pressure on land base for growing food crops and energy crops
- Reducing greenhouse gas emissions from agriculture (e.g., nitrous oxide emissions from fertilizer)

Modeling Challenges

- Representing technologies that can reduce net CO_2 emissions to zero
  - Bioenergy with carbon dioxide capture and storage
  - Direct air capture
  - Renewable diesel
  - Sustainable aviation fuels
- Energy Modeling Forum 37 study
  - Net zero U.S. carbon dioxide emissions by 2050
  - Closer look at other bioenergy pathways