GCAM Bioenergy and Land Use Modeling (BETO 1.1.1.7) 2023 Project Peer Review

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Data, Modeling, and Analysis

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Overview: Bioenergy and Terrestrial Carbon in an Integrated Economic Context of Energy and Land Use

- This project builds on years of analysis for BETO analyzing the potential roles, scales, and impacts of the production and use of bioenergy in the multisector context of domestic and global energy, land use, and carbon management.

- Much of the research is centered around improving the structural detail and bioenergy technology parameterization in the PNNL Global Change Analysis Model (GCAM), a prominent integrated, multisector community model of regional and global energy, land use, and emissions to the year 2100.

- Beginning with this new project phase (FY22), we have broadened the scope to look at bioenergy, land use, and terrestrial carbon more holistically.
  - Continue to model and study bioenergy technologies,
  - While pursuing new research to explore multisector, direct and indirect impacts of strategies for terrestrial carbon enhancement considering domestic and global agriculture.

1) Approach: Bioenergy in an Integrated Context

- General: identify bioenergy questions for which our longer-term, integrated approach offers complementary insights to life cycle, technology, and systems models.
- Leverage the broader program of GCAM development and bring those capabilities.
- Vet bioenergy model and data developments through GCAM core model committee.
- Coordinate with other BETO projects to discuss methodologies and technology and system parameterizations.
  - Coordination effort with NREL's Biomass Scenario Model (BSM) studying US ethanol production under carbon incentives (in review at *Environmental Research Letters*).
  - Current contracted partner relationship with NREL under BETO on terrestrial carbon modeling.

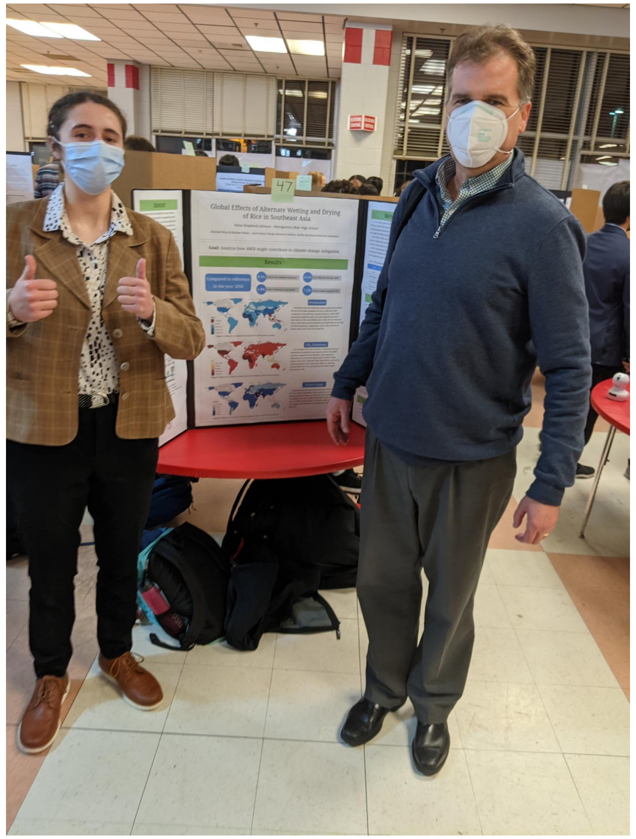
1) Approach: Current Efforts

- 1) Integrated analysis of terrestrial carbon banking/enhancement strategies.
  - In partnership with NREL.
  - Quantifying direct and indirect, domestic and global multisector potential scale and impacts.
  - Completed first study on biochar.
  - Currently researching and modeling no-till and cover crops.

- 2) Integrated modeling of technology-specific energy inputs to agriculture.
  - Goal to represent options for energy and emissions reduction for crop production.

- 3) Integrated modeling of refining, jet fuel, and biojet pathways.
  - In the context of long-term domestic and global aviation demand.
  - Effort is in the beginning stages Winter 2023.

1) Approach: DEI and Go/No-Go Milestones

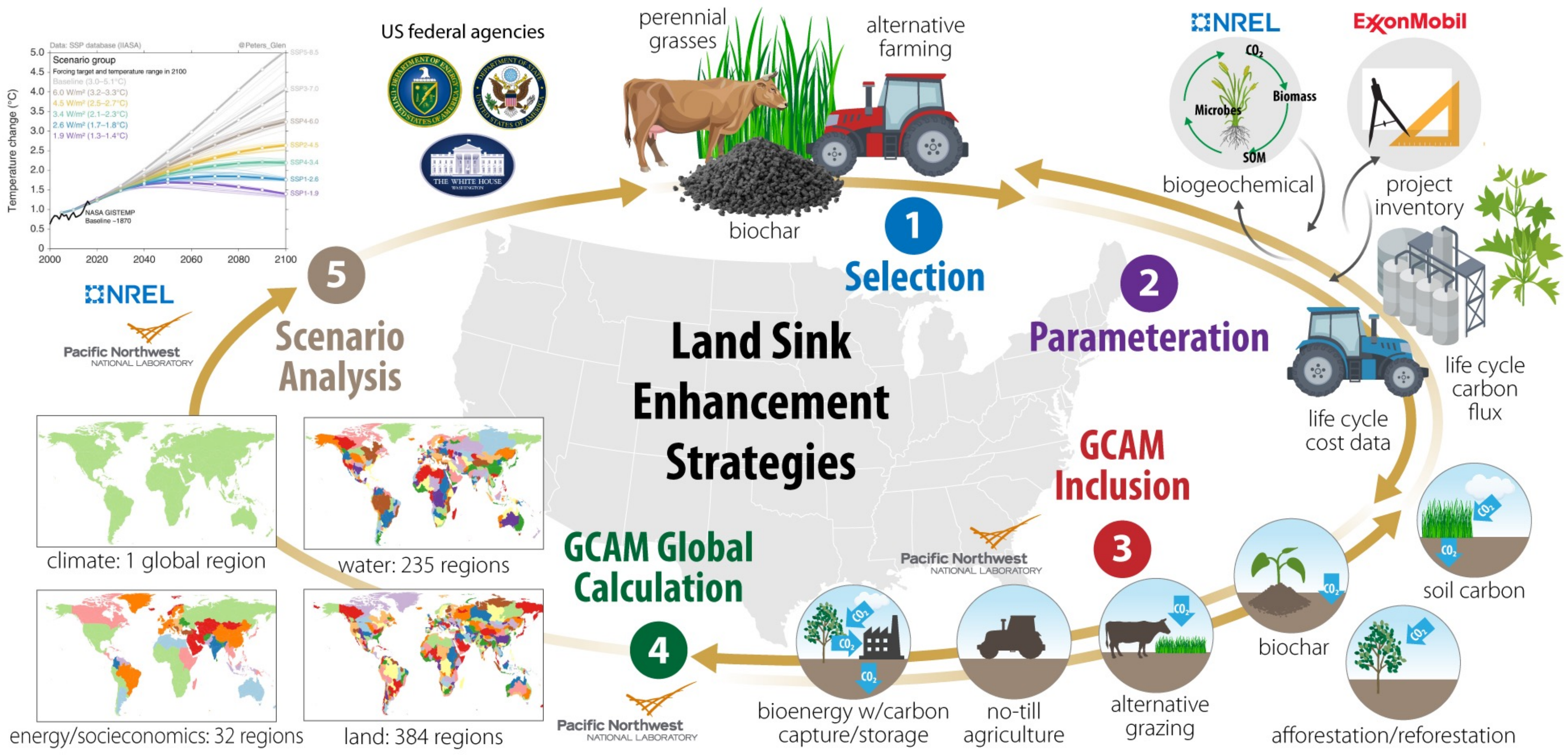


- **Inclusion/Outreach**: We hired a local (DC-area) high school student as a summer intern and participated in her senior project.
  - Student used our GCAM model to study impact of alternative rice cultivation practices with less water on greenhouse gas emissions.
  - Modeled the impact of reduced regional rice yields on international rice trade, increased production in other regions, and resulting land use change emissions.

- **Go/no go Milestone** was met December 31, 2022, by demonstrating the viability of modeling terrestrial carbon banking strategies in GCAM and quantifying the multisector, global impacts.
  - Presented at the Integrated Assessment Modeling Consortium (IAMC) in November.
  - Presented at the American Geophysical Union (AGU) in December.

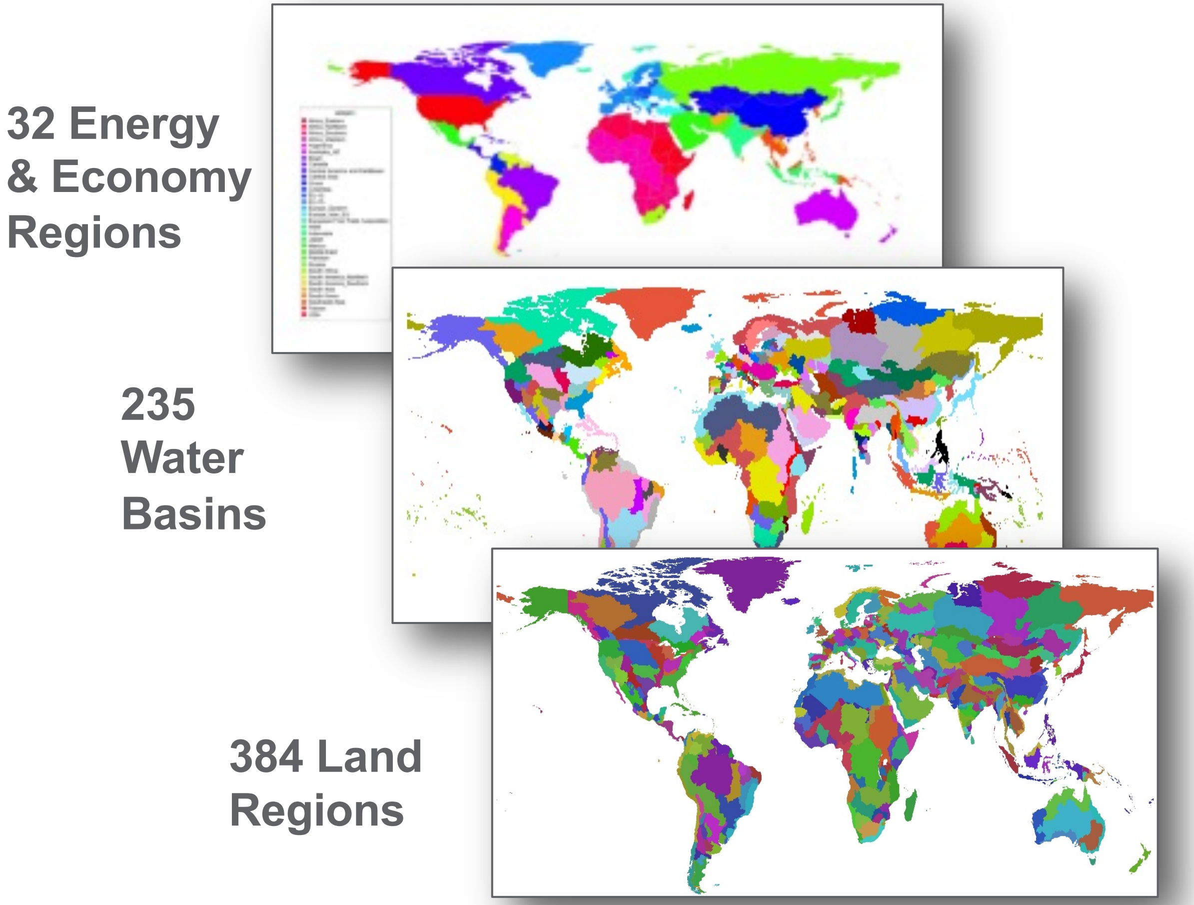
1) Approach: Terrestrial Carbon Modeling - in Partnership with NREL (BETO 1.1.1.8)

- **Objective:** Quantify the potential impacts of domestic terrestrial ecosystem carbon sink expansions on global agriculture production, land use, and resulting emissions.



1) Approach: GCAM 6.0 (PNNL Global Change Analysis Model)

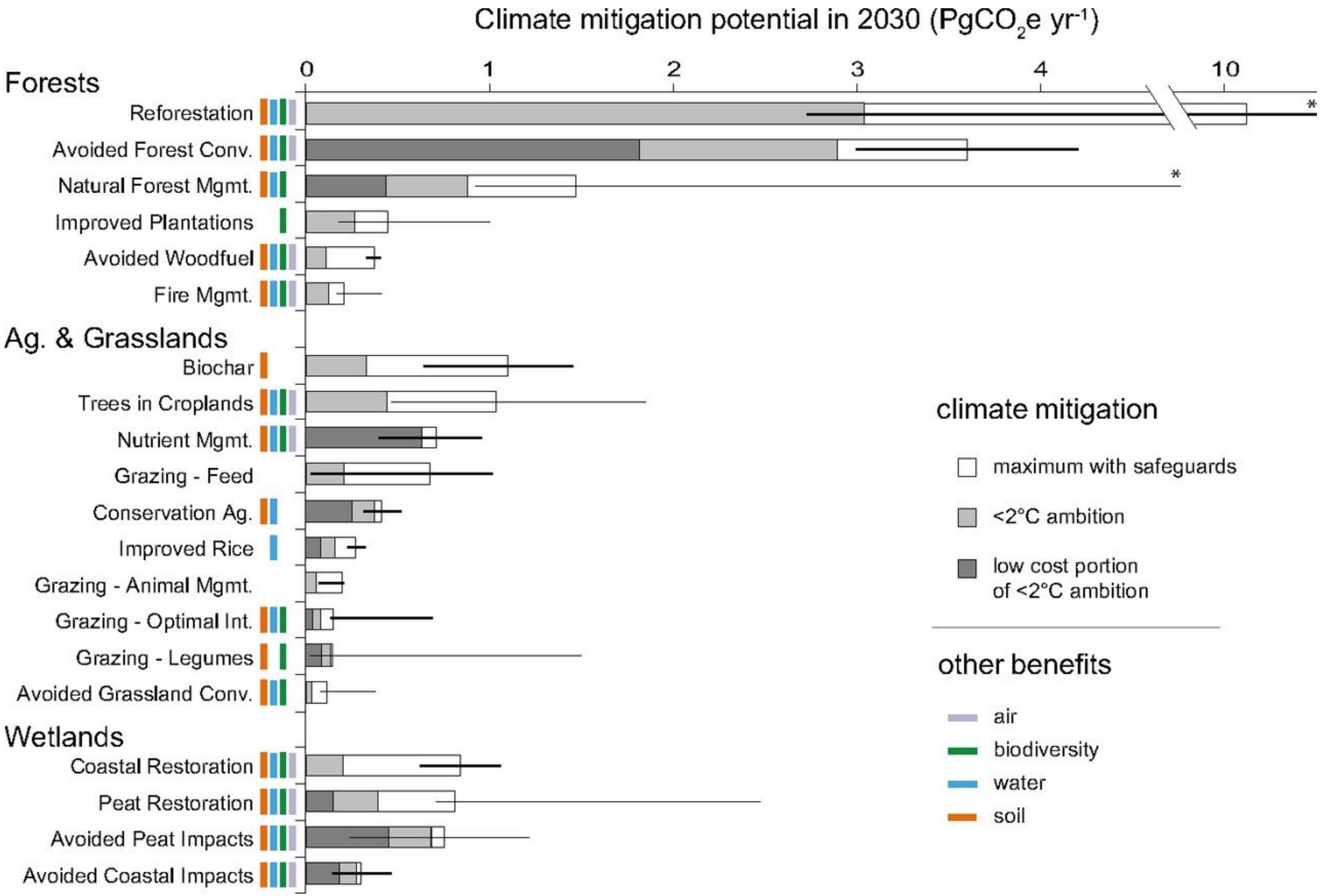
Global Coverage



- 32 Energy/Economic regions for modeling supplies/demands of energy
- 384 Land use regions for crop and forest production based on water basins

- Economically and physically links long-term (to year 2100) Energy, Agriculture, Land, Water, and Emissions.
- Models domestic energy and agriculture production, consumption, and trade.
- Bioenergy Crops, Ag. and Forestry Residues, Wastes, and 1st-gen sources.
- Bioenergy technologies in all energy transformation and demand sectors.
- Economic and physical representation of all commercial land uses and natural land categories contained in each land region.

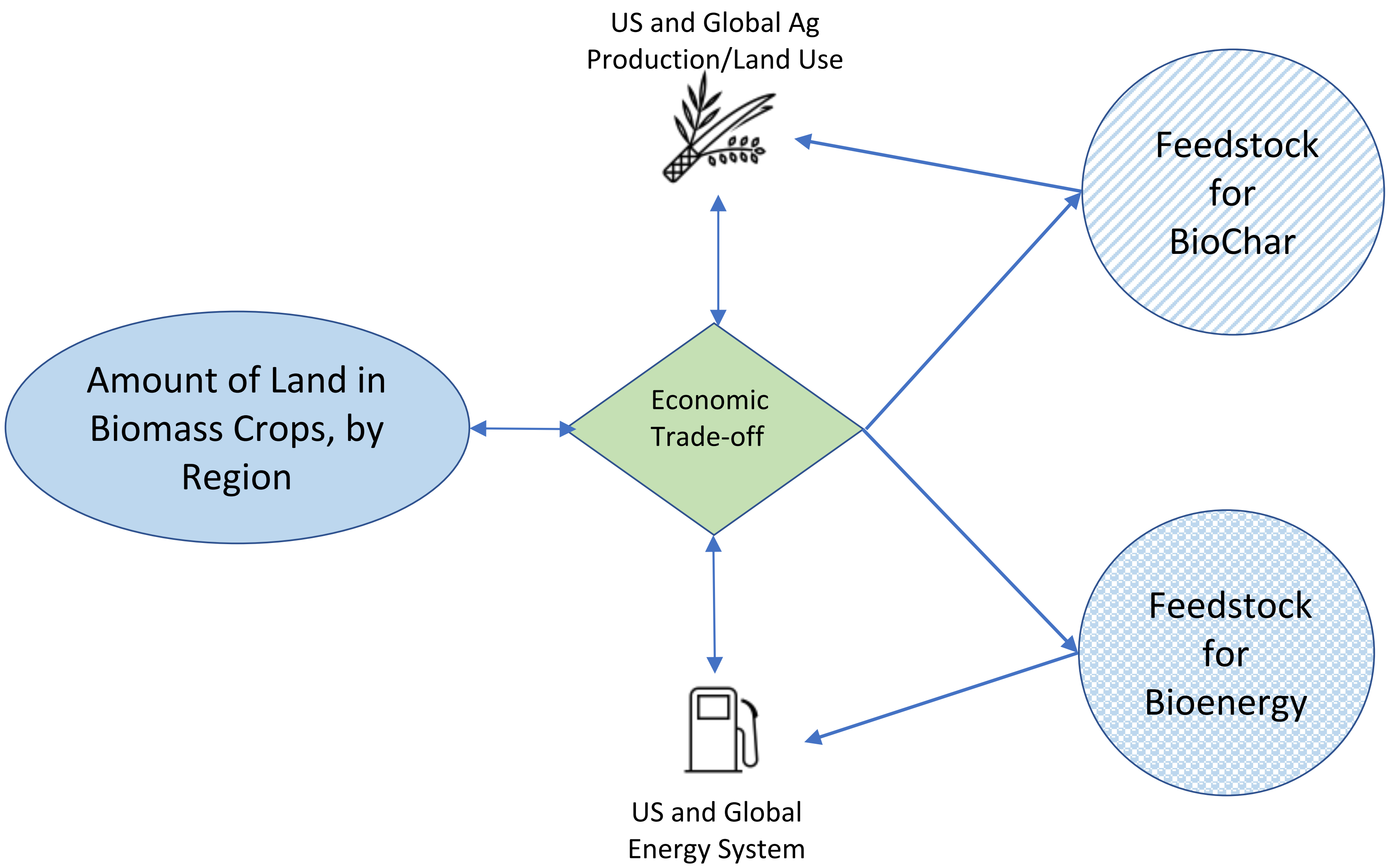
1) Approach: Context for Terrestrial Carbon Options



Griscom et al, 2017. “Natural Climate Solutions.” *PNAS.*

- These are well-founded but mainly static estimates considering sustainability without changing cropland and other boundary conditions.
- Our approach here is to use integrated economic modeling that considers trade-offs and dynamic responses in energy and agriculture to carbon incentives.

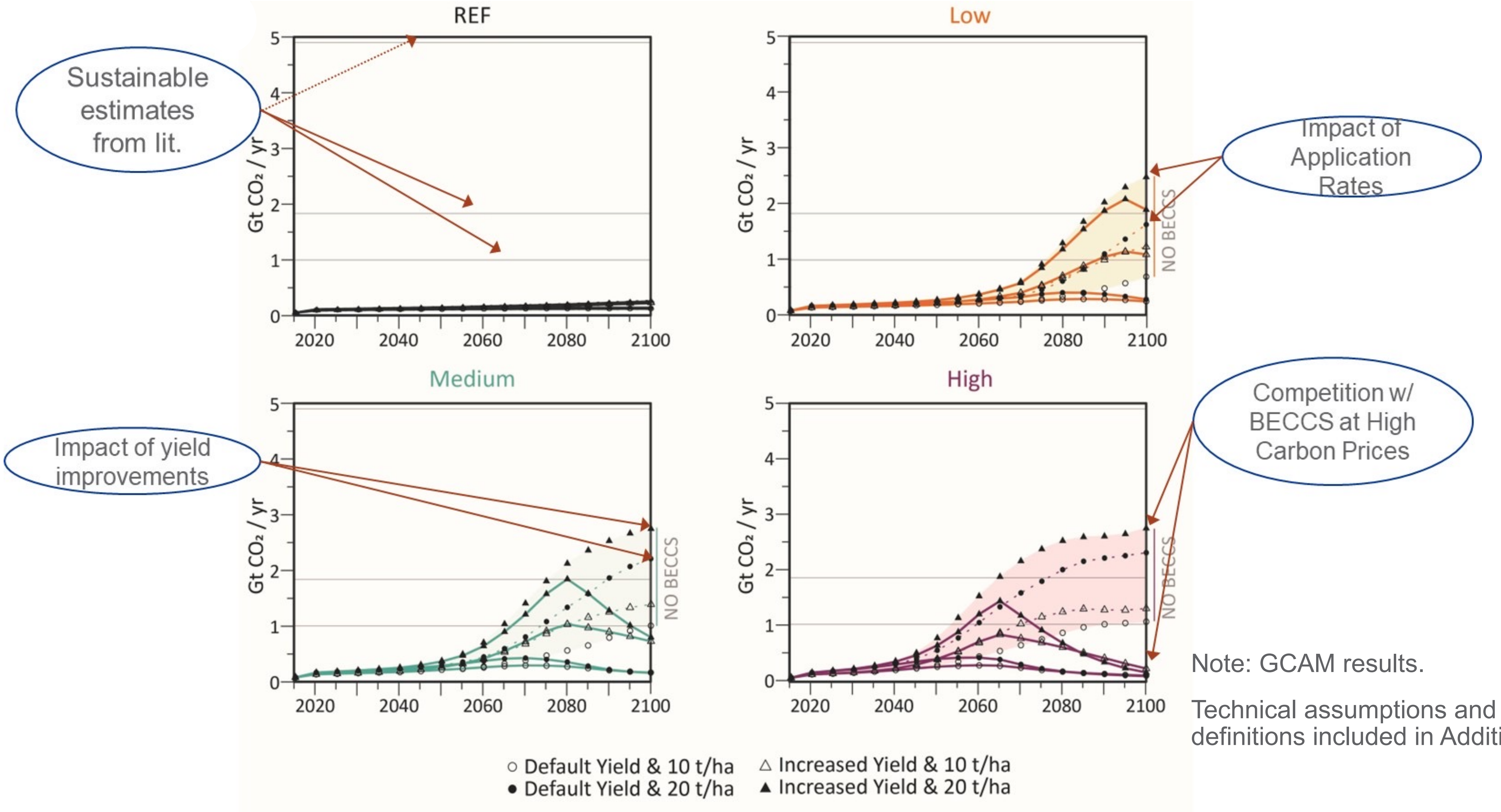
2) Progress and Outcomes: Analysis of Bioenergy and Biochar in GCAM



- Biochar production competes for feedstocks.
- Biochar can be used to sequester carbon and improve crop yields.
- The economics of carbon is measured in the context of energy and agriculture markets, regional/global.
- Note: we modeled slow pyrolysis to maximize biochar carbon.

- Manuscript on Biochar (Bergero et al.) in review
- GCAM Biochar functionality included as part of Carbon Dioxide Removal options in Fuhrman et al. 2023 in *Nature Climate Change*

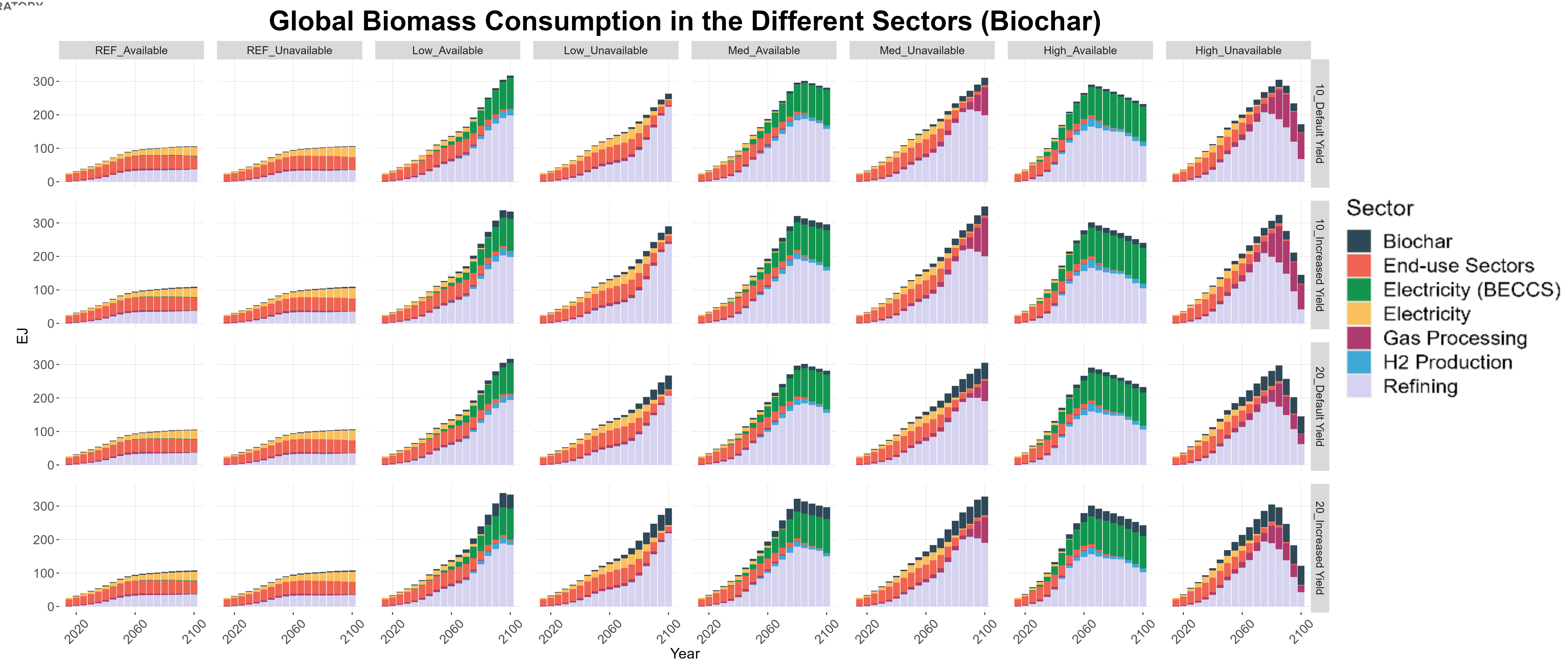
2) Biochar scale depends on trade-offs among carbon prices, yield impacts, application rates, and BECCS



Note: GCAM results.

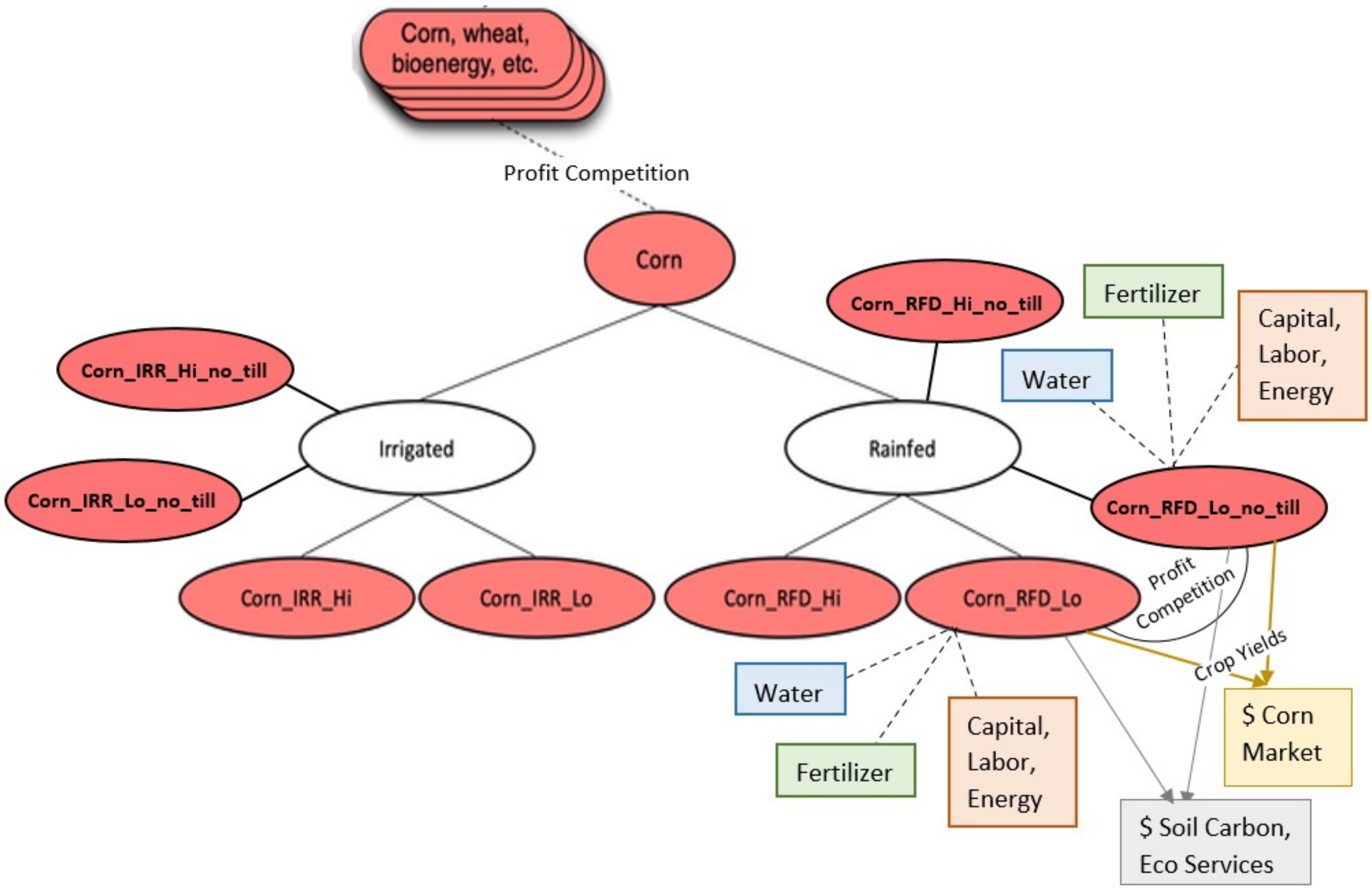
Technical assumptions and scenario definitions included in Additional Slides

2) Biochar in Context with Bioenergy (GCAM Results)



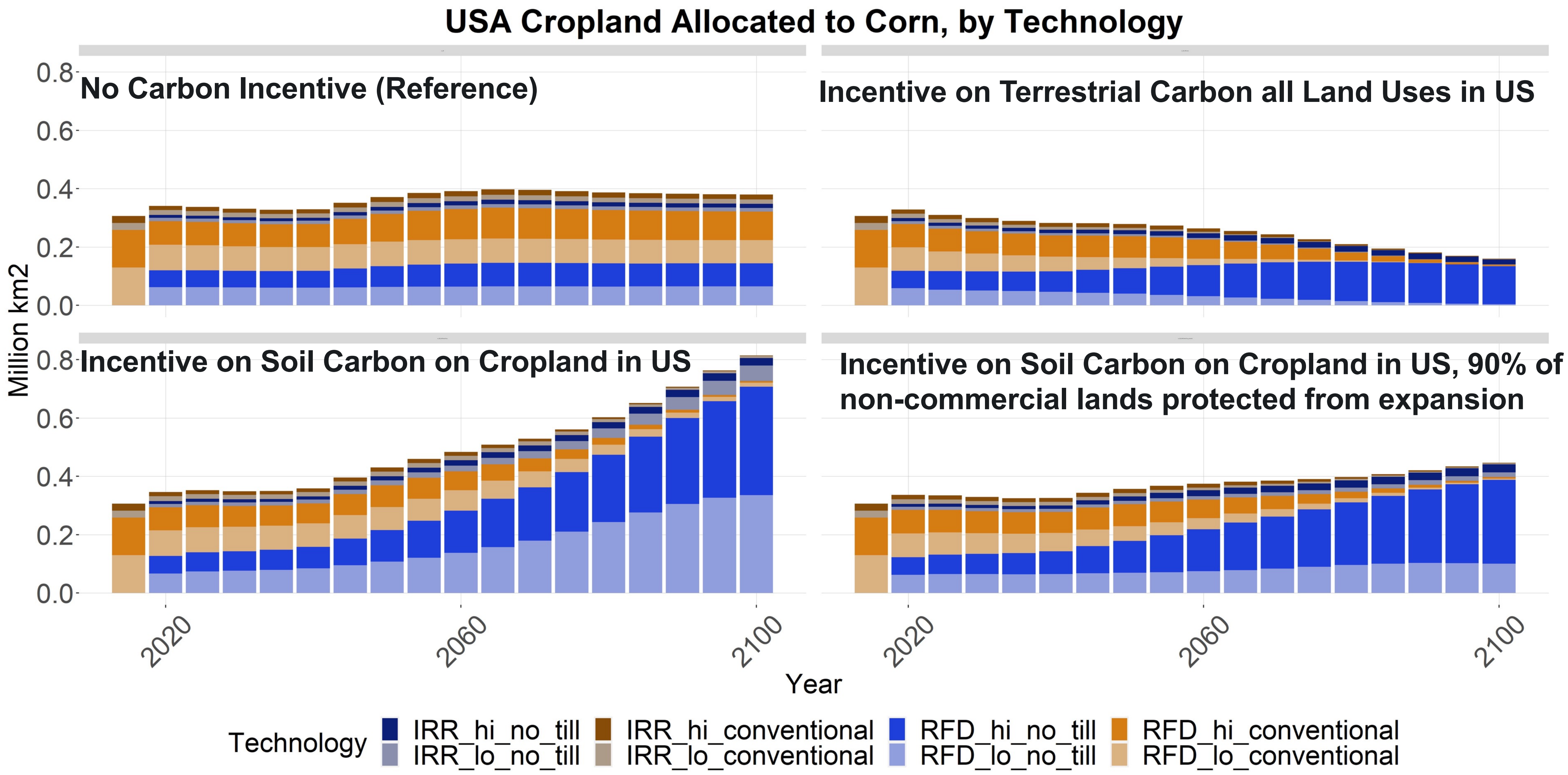
- While the global quantities of biomass, including for biochar, grow substantially, biochar production does not crowd out or dominate the demand for biomass for energy.

2) Progress: Modeling the Economic Dynamics of No-Till Technologies in GCAM (example of corn)



- NREL biogeochemical modeling (DayCent) to compute physical parameters.
- Crop yields and soil organic carbon contents for each option from DayCent.
- Economic trade-off between conventional till and no-till depending on yields, soil carbon, corn prices, and valuation of carbon.
- Corn production will feed back into the global market, affecting prices and production everywhere.

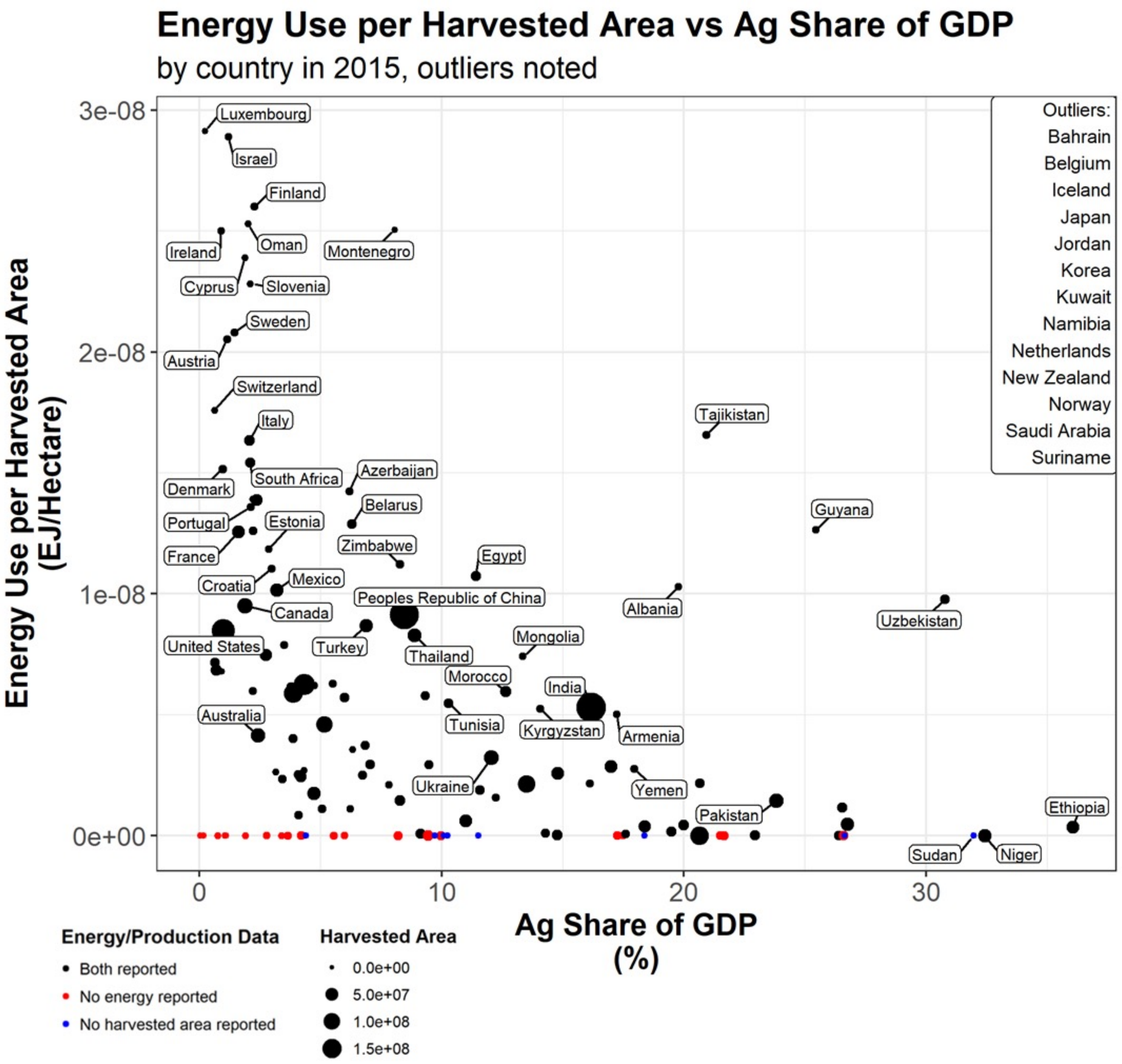
2) Progress: No-Till Scenario Results Depend on the Incentive Structure (Early GCAM Results)



- Carbon incentive increases share of no-till in all cases.
- Incentive coverage (types of land uses) drives dynamics of cropland expansion or contraction with global multisectoral impacts on production and terrestrial carbon.

2) Progress: Modeling Agricultural Energy Consumption by Technologies/Practices in US and Other Regions

- Data research shows that the agricultural share of GDP is a useful an indicator of the level of mechanization within countries' agriculture sectors.
- Countries with smaller agricultural shares of GDP are generally more mechanized.
- While there is much variability, smaller ag share of GDP countries (higher income countries) trend toward higher levels of energy consumption per harvested area.



3) Impact: Importance of Multisector, Integrated Analysis of Bioenergy and Land Use

- Bioenergy is unique in that it is intrinsically linked in many ways to multiple aspects of the energy and land use systems.
  - Thus, it has a complex impact on carbon management, but also provides opportunities.
- GCAM, because of its global, multisectoral, integrated dynamic representation of these systems, provides a holistic perspective which complements focused bioenergy analysis tools such as LCAs and Techno-Economic Assessments.
- The impact of this project's analysis of measures for increasing terrestrial carbon in cropland is that it considers actions in a global, integrated economic context.
  - Cropland measures will lead to incentives for cropland expansion or contraction, which will result in corresponding changes in land in other uses, with a resultant impact on total terrestrial carbon emissions/uptake.
  - Cropland measures in one region will affect international agriculture production and trade, which will also have an impact on total terrestrial carbon emissions/uptake.

3) Impact: GCAM Community Model

- GCAM is an open source and open data community model.
  - GCAM community model: Download and documentation at http://jgcri.github.io/gcam-doc/index.html
  - GCAM has an international user base and has been downloaded thousands of times.
  - GCAM has been used extensively by PNNL and collaborators in several countries such as India, Canada, China, Spain, Pakistan, and Colombia.
  - GCAM has a long record of participation in international forums with leading international integrated assessment modeling teams such as the Intergovernmental Panel on Climate Change (IPCC) and the Stanford Energy Modeling Forum (EMF).
  - Modeling capability and data are accessible to community model users and consumers of analysis in the industry, research and policy communities.
- Finally, the BETO project helps bioenergy to be considered comprehensively and at the state of the art in GCAM analysis for BETO, other DOE, EPA, energy firms, and the international user community.

Summary

- We have continued to advance our study of bioenergy, but with this project we are adding to that a more holistic analysis of land as part of carbon management.
  - GCAM project provides integrated perspective that complements more detailed and focused technology, regional, and process-specific analysis.
- We are building joint capability with NREL on modeling terrestrial carbon.
- We have completed our first study of biochar – a topic which clearly requires an analysis platform that integrates agriculture, land, and energy.
- We have begun our study of no-till crops, and we have presented early scenarios at international forums.
  - Our NREL partners are researching parameterizations of cover crops and will look for other practices that are relevant.
- By project end, we will perform an integrated analysis of these practices using GCAM, considering the land use and energy systems and technology options there, and assess the potential scale, roles, impacts, and factors that affect these outcomes.

Quad Chart Overview

Timeline
- Project start date: Oct. 1, 2021
- Project end date: Sep 30, 2024

	$550,000	$725,000 (FY 2021-2022)

TRL at Project Start:
TRL at Project End:

Project Goal
The goal of this project is to provide quantitative analysis of the potential scale and impact of bioenergy and land use in the long-term, global, integrated economic context of energy, land, and carbon.

End of Project Milestone
Complete studies of the global impacts of terrestrial carbon banking strategies, the possibilities for reducing agriculture energy consumption and emissions, and the integrated impact of bioenergy pathways for US and global aviation.

Funding Mechanism
BETO National Laboratory Call, 2021.

Project Partners
- NREL BETO Project 1.1.1.8

*Only fill out if applicable.

Additional Slides

Biochar Study: Biochar Technical Assumptions

Metric	Value	Units	Source
Levelized Capital and O&M Cost	45.93	2007 USD per ton of feedstock	Roberts et al. 2010
Biomass input	3.65	Tons of feedstock per ton of biochar	
Gas input*	0.2	GJ per dry ton of biochar	
Syngas co-product*	20.1	GJ per dry ton of biochar	
Net syngas co-product	19.9	GJ per dry ton of biochar	

*Note that we assume that the gas or thermal input to the pyrolysis facility is met by a fraction of the syngas co-product, which means there is no modeled energy input for biochar production.

Roberts, K. G., Gloy, B. A., Joseph, S., Scott, N. R. & Lehmann, J. Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. *Environmental Science & Technology 44*, 827–833 (2010).

Biochar Study: Biochar Demand and Application Assumptions

Metric	Value	Units	Source
Application rate	10 20	Tons of biochar per hectare	Ye et al. 2020
Yield Improvements	12 (tropical irrigated) 19 (tropical rainfed) 10 (temperate irrigated) 15 (temperate rainfed)	Percentage	NREL analysis
Carbon Sequestered	70	Percentage of Carbon in the Biochar Produced that is Recalcitrant	Wang et al. 2016

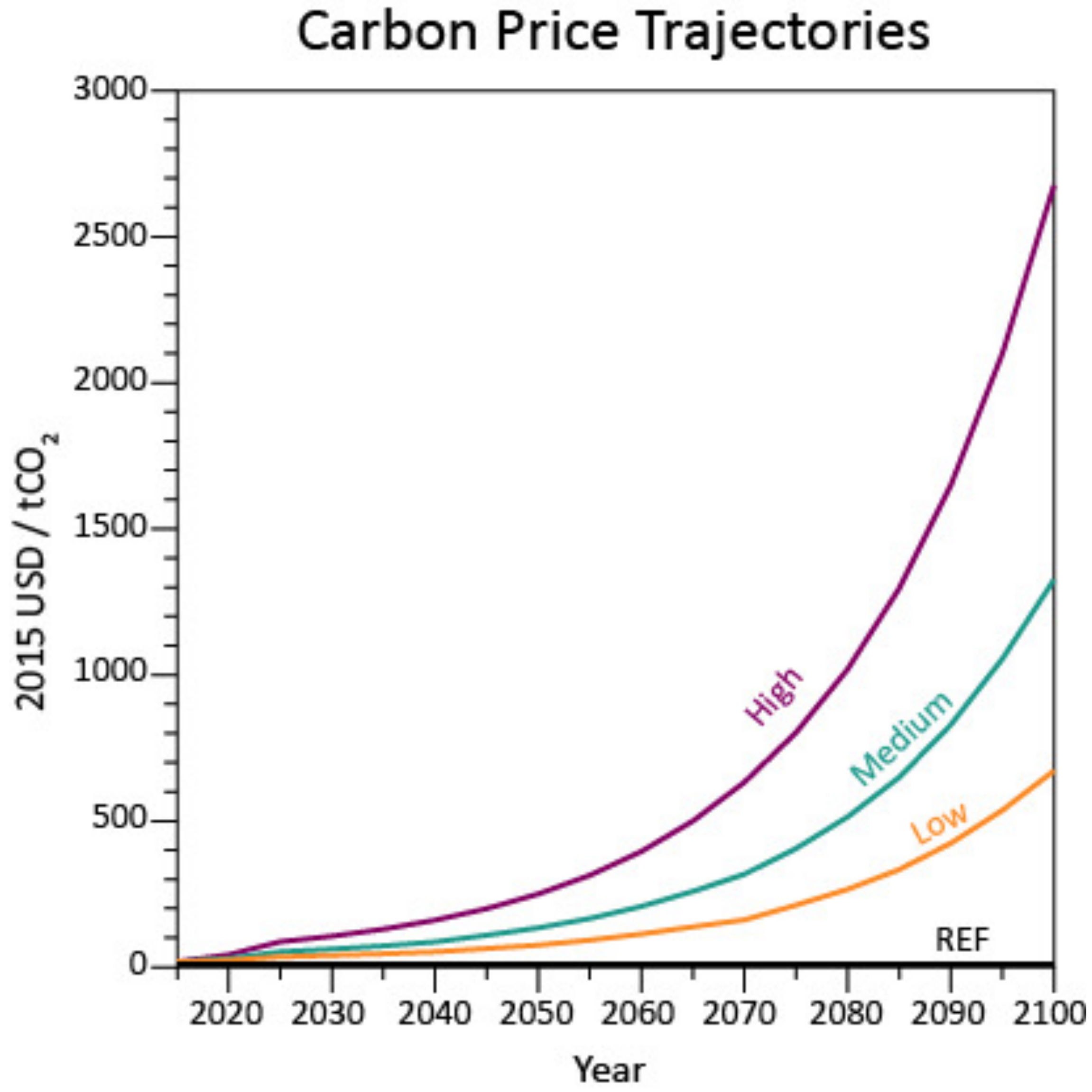
Ye, L. et al. Biochar effects on crop yields with and without fertilizer: A meta-analysis of field studies using separate controls. *Soil Use and Management* 36, 2–18 (2020).

Wang, J., Xiong, Z. & Kuzyakov, Y. Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB Bioenergy 8,* 512–523 (2016).

Biochar Study: Scenario Assumptions

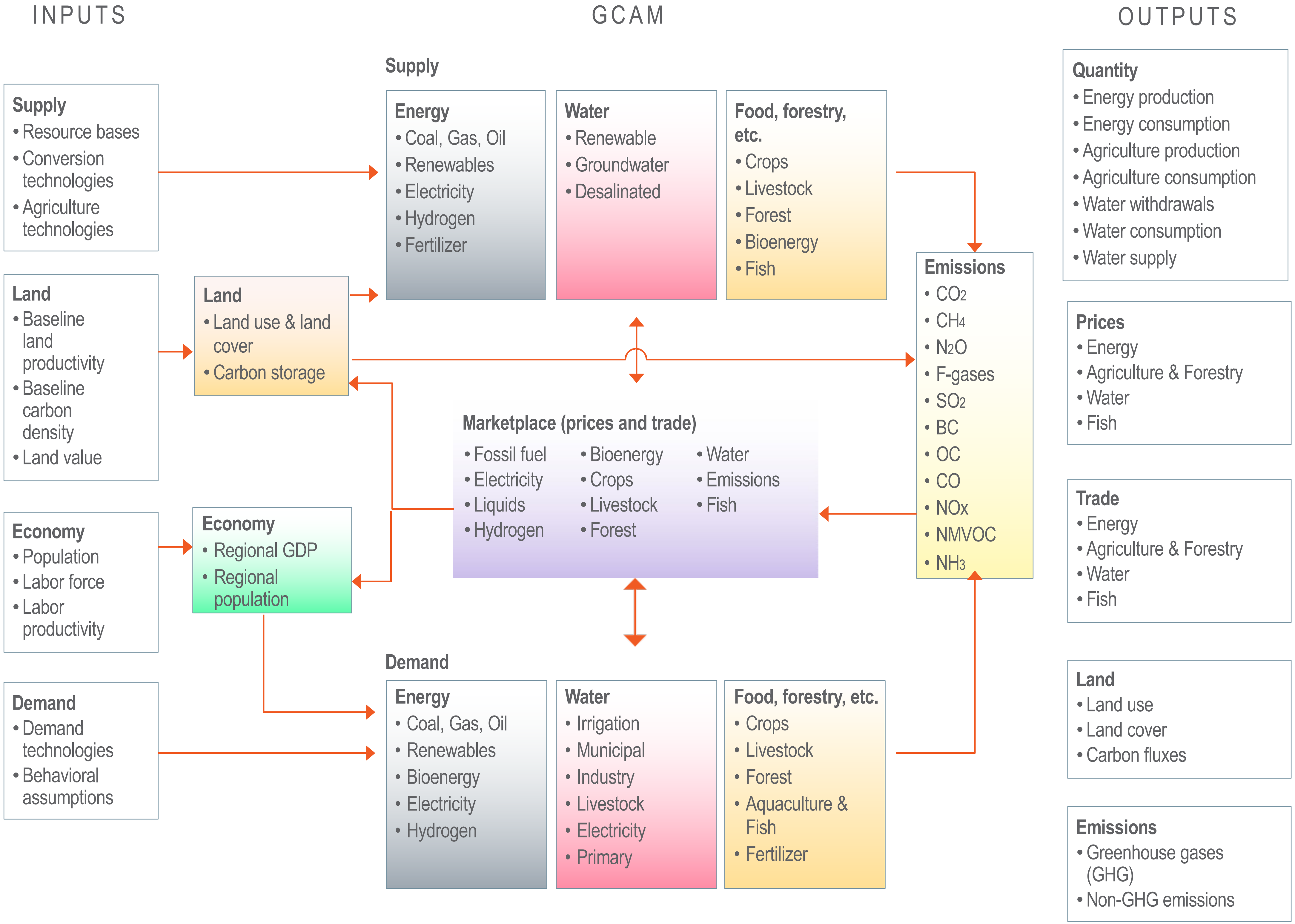
Component	Variations	Acronym	Description
Carbon Price	No carbon price	REF	Carbon prices trajectories. We are modeling four trajectories: a no carbon price (“REF”), and three carbon price pathways. The High case is consistent with a 2.6 W/m^2 global warming potential by 2100 in GCAM v5.3. The Medium trajectory has prices that are half of the High case. The Low case has a carbon price trajectory that is half of the Medium trajectory. For more details refer to SM1 and SM2
	High	High	
	Medium	Med	
	Low	Low	
Application Rates	0 tons/hectare	0	The application rates are assumed as either 10 (“10”) or 20 (“20”) tons per hectare, applied only once during the modeled years (2020-2100). There is an application rate of 0 tons per hectare for the 4 scenarios that do not have biochar.
	10 tons/hectare	10	
	20 tons/hectare	20	
Yield Impacts	Default GCAM increase	DY	In GCAM historical yields depend on production and land allocation. Future agriculture productivity increases are assumed based on FAO’s estimates (“DY”). We have increased those estimates following the explanation on section 2.3 to reflect the benefits of the biochar applied to the soil (“IY).
	Biochar application yield increase	IY	
BECCS	BECCS Available	BECCS	GCAM uses BECCS in three energy transformation sectors: electricity generation, refining, and hydrogen production. We have decided to either allow BECCS (“BECCS”) or not (“noBECCS") for these transformation pathways.
	BECCS Unavailable	noBECCS	

Biochar Study: Carbon Price Assumptions

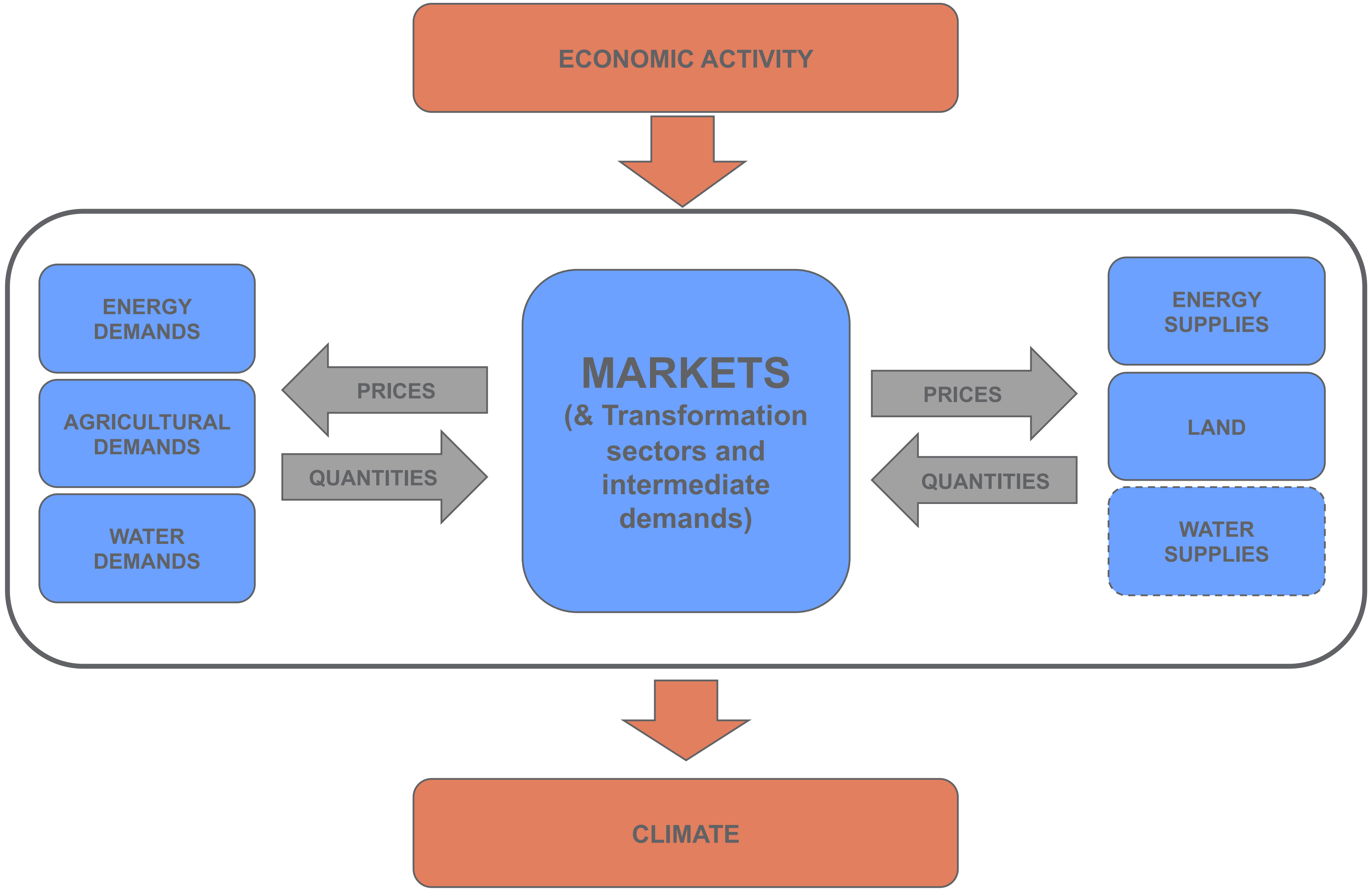


The four carbon price trajectories in this study: High, Medium, Low and Reference. High carbon price trajectories are those required to meet a radiative forcing of 2.6 W/m2 by 2100 in default GCAM v5.3 (without biochar or any further changes from this study). The Medium carbon price trajectory is half of the High price, and the Low carbon price trajectory is half of the Medium price.

What’s inside the GCAM?

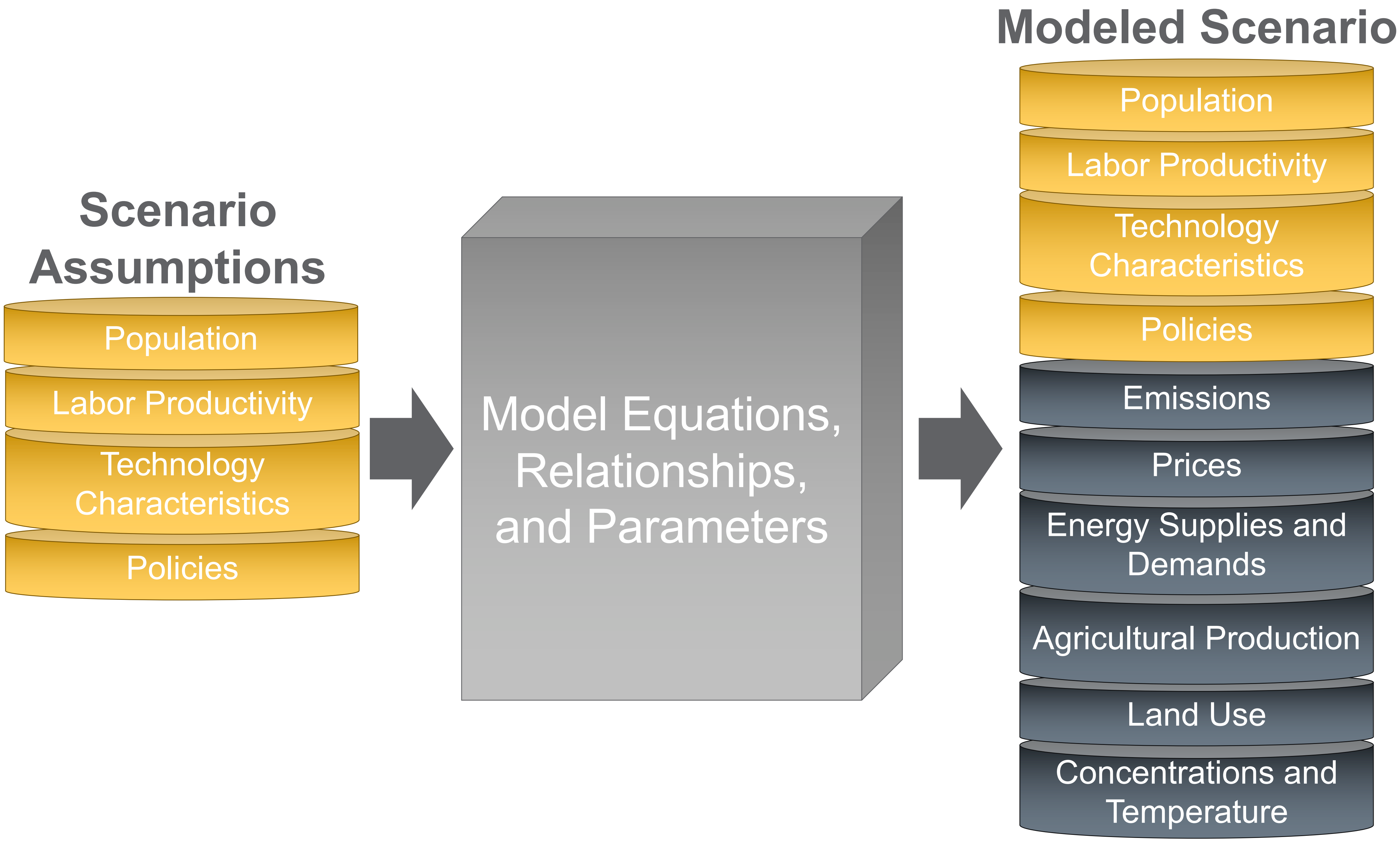


GCAM Solution Approach: Economic Equilibrium

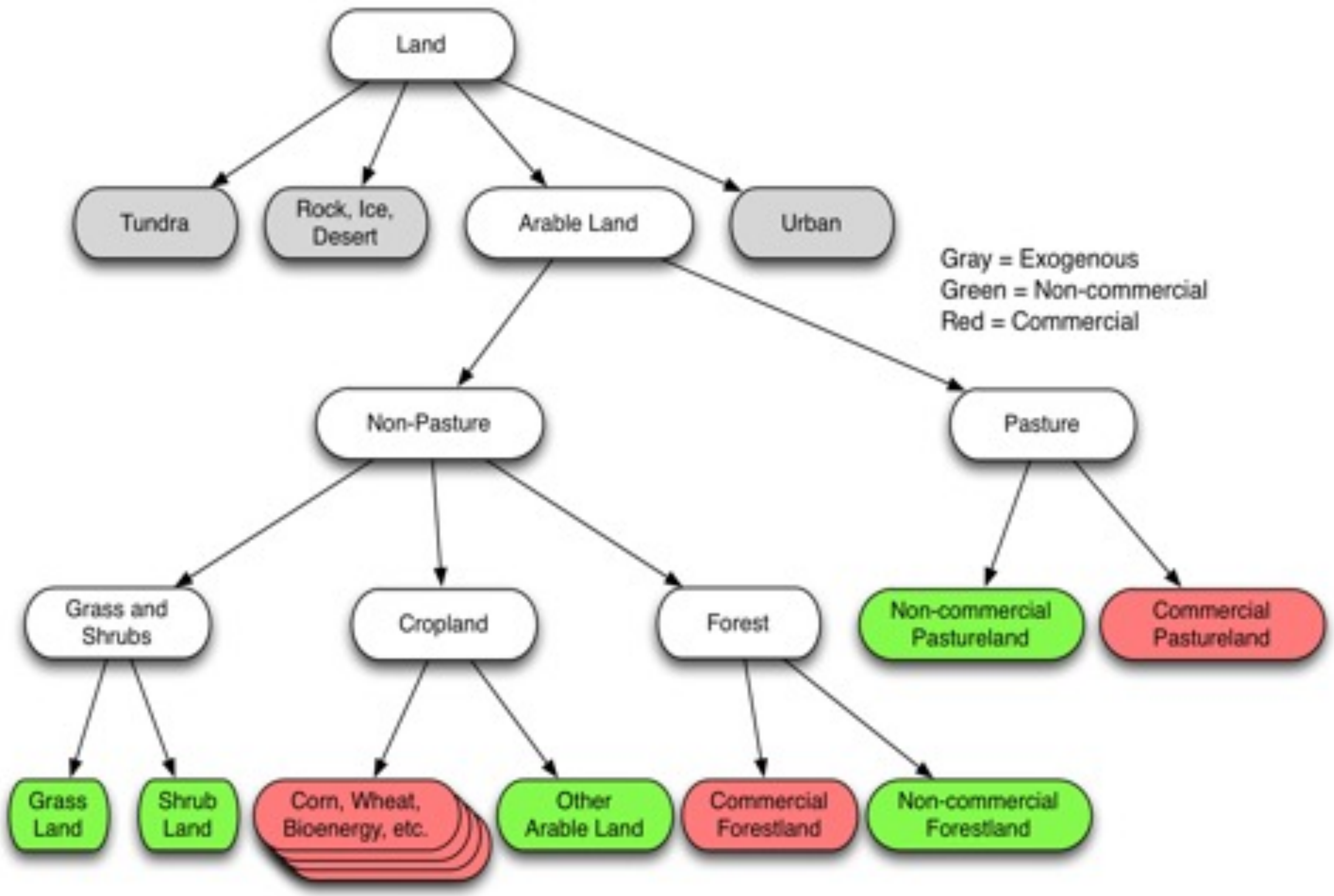


- GCAM solves each period by finding the set of prices so that all modeled markets are "cleared".
  - Prices are solved such that supply equals demand for each market.
- Equilibrium in regional and global energy, agriculture, land, water, fertilizer, and emissions markets.
  - International trade in energy, crops, and forest products is determined as part of the market equilibrium.
  - Approach sometimes called "partial" rather than "general" equilibrium as all sectors of economy aren't modeled.
- This approach is sometimes referred to a "recursive dynamic" to distinguish it from an "intertemporal optimal" approach.

GCAM Results are a function of scenario input assumptions



GCAM Land Use Categories (within each land use region)



- All land cover and use, including all commercial land uses as well as non-commercial natural lands, are represented in GCAM.
- These land categories are represented in each of the 384 land regions (where applicable) and calibrated to match a historical base year.
- Economics drive future changes in cropland, pasture, forest, and other land uses.

GCAM Ag/Forest/Land Modeling: Inputs and Outputs

Inputs

- Harvested area in historic period
- Land cover in historic period
- Production in historic period
- Consumption in historic period
- Cost of production
- Fertilizer application rates
- Water coefficients
- Carbon density, mature age
- Emissions factors
- Income elasticity of demand
- Price elasticity of demand
- Technical change
- Logit parameters
- FAO bilateral trade matrix

GCAM

Outputs

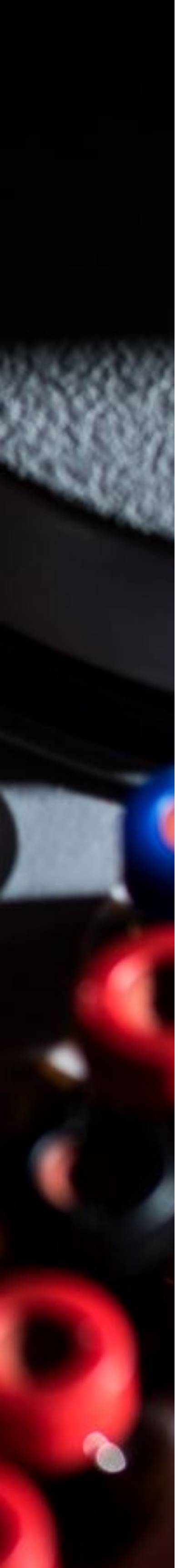
- Production
- Consumption
- International Trade
- Land use, land cover
- Yield
- Crop Prices
- Fertilizer use
- Water withdrawals
- Water consumption
- Land use change emissions
- Other land emissions

Responses to Previous Reviewers' Comments

- The main comment from reviewers in 2021 was to demonstrate coordination with other types of bioenergy models and to communicate the differences/similarities of our approach with other multi-sector economic models.
  - We completed a study coordinating bioenergy technology parameters and modeling scenarios with the NREL Biomass Scenario Modeling (BSM) team and have a manuscript in review at *Environmental Research Letters*
  - We are working in coordination with NREL partners on coordinating biogeochemical modeling of crop yields and terrestrial carbon for GCAM modeling of terrestrial carbon banking.
- Through efforts outside of BETO, (including EMF-37 and work for OTAQ), we compare out results other larger economic models.
  - Complements GTAP modeling of near-term economic and trade impacts by focusing on long-term technology development and physical system details.

Publications, Patents, Presentations, Awards, and Commercialization (Current Period)

- Presentations
  - Lamers, P., M.A. Weber, M.A. Wise, Y. Wang, G. Avery. “Terrestrial Carbon Drawdown ”. USDA Carbon Sinks Modeler Forum, September 2022.
  - Lamers, P., M.A. Wise, M. Bergero, M.A. Weber, Y. Wang, G. Avery, K. Morris, and J. Edmonds. “The potential scale and impacts of enhancing the terrestrial carbon sink via changing agricultural practices in long-run climate scenarios.” Integrated Assessment Modeling Consortium, November 2022.
  - Weber, M.A., M.A. Wise, Y. Wang, P. Lamers, K. Morris. G. Avery, and J. Edmonds. “Implications of Converting Conventional Tillage to No-Till Agriculture on Emissions, Land, and Water Usage.” American Geophysical Union Fall Meeting, December 2022
- BETO-funded Manuscript Papers in Review
  - Bergero, CM, MA Wise, P Lamers, Y. Wang, M.A. Weber. “Biochar as a carbon dioxide removal strategy in integrated long-run climate scenarios.” 2022. in review at Nature Communications and Earth Systems.
  - Vimmerstedt, L, S Antoorkar, C Bergero, M wise, et al. “Deep Decarbonization and U.S. Biofuels Production: A Coordinated Analysis With a Detailed Structural Model and an Integrated Multisectoral Model.” 2022. in revision at Environmental Research Letters.
- PNNL non-BETO published study using BETO-funded GCAM Biochar capability
  - Fuhrman J.G., H.C. McJeon, A.F. Clarens, W. Shobe, S. Doney, S. Monteith, and F. Wang, et al. 2022. "A comprehensive suite of carbon dioxide removal approaches reduces energy-water-land tradeoffs of meeting the 1.5 °C goal." Nature Climate Change



Earlier GCAM Bioenergy-Related Papers

- Rose, Steven K, Nico Bauer, Alexander Popp, John Weyant, Shinichiro Fujimori, Petr Havlik, Marshall Wise, Detlef P van Vuuren (2020). “An overview of the Energy Modeling Forum 33rd study: assessing large-scale global bioenergy deployment for managing climate change.” *Climatic Change*, https://doi.org/10.1007/s10584-020-02945-6.
- Bauer, Nico, Steven K. Rose, Shinichiro Fujimori, Detlef P. van Vuuren, John Weyant, Marshall Wise, Yiyun Cui, Vassilis Daioglou, Matthew J. Gidden, Etsushi Kato, Alban Kitous, Florian Leblanc, Ronald Sands, Fuminori Sano, Jessica Strefler, Junichi Tsutsui, Ruben Bibas, Oliver Fricko, Tomoko Hasegawa, David Klein, Atsushi Kurosawa, Silvana Mima, and Matteo Muratori (2018). “Global energy sector emission reductions and bioenergy use: overview of the bioenergy demand phase of the EMF-33 model comparison.”, *Climatic Change*. July 2018. https://link.springer.com/article/10.1007/s10584-018-2226-y
- Wise, M., M. Muratori, P. Kyle (2017). “Biojet Fuels and Emissions Mitigation in Aviation: an Integrated Assessment Modeling Analysis.” *Transportation Research Part D: Transport and Environment*, 52, pp 244-253. May 2017. http://dx.doi.org/10.1016/j.trd.2017.03.006
- Calvin, K., M. Wise, P. Luckow, P. Kyle, L. Clarke and J. Edmonds (2016). "Implications of uncertain future fossil energy resources on bioenergy use and terrestrial carbon emissions." *Climatic Change* 136(1): 57-68.
- Muratori, M., K. Calvin, M. Wise, P. Kyle and J. Edmonds (2016). "Global economic consequences of deploying bioenergy with carbon capture and storage (BECCS)." *Environmental Research Letters* 11(9): 095004.
- J. Gao, A. Zhang, S.K. Lam, X. Zhang, A. Thomson, E. Lin, K. Jiang, L. Clarke, L. Edmonds, G.P. Kyle, S. Yu , Y. Zhou, and S. Zhou (2016). “An integrated assessment of the potential of agricultural and forestry residues for energy production in China.” *GCB Bioenergy (2016) 8*, pp. 880–893.

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Thank you