Development under Spatial Equilibrium for the Great Lakes Region

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Development under Spatial Equilibrium for the Great Lakes Region

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INTRODUCTION

This study established an integrated energy- environmental-economic dynamic recursive computable general equilibrium model. Using this spatial computable general equilibrium (CGE) model, we show how to analyze environmental sustainability and individual well-being resulting from changes in the Great Lakes region's complex economic and environmental systems. Our general equilibrium framework models interactions between human (economic, behavioral, social) and environment.

OBJECTIVE

1. Captures the interactions between local, regional, national, and global systems across space.
2. Understand linkages between economics agents and different sectors for the policymakers.
3. Assess the climate change risks that may impact agriculture, energy, and manufacturing sectors
4. Devise a related policy to maximize the welfare of policy maker's citizens and sustainably develop economies.

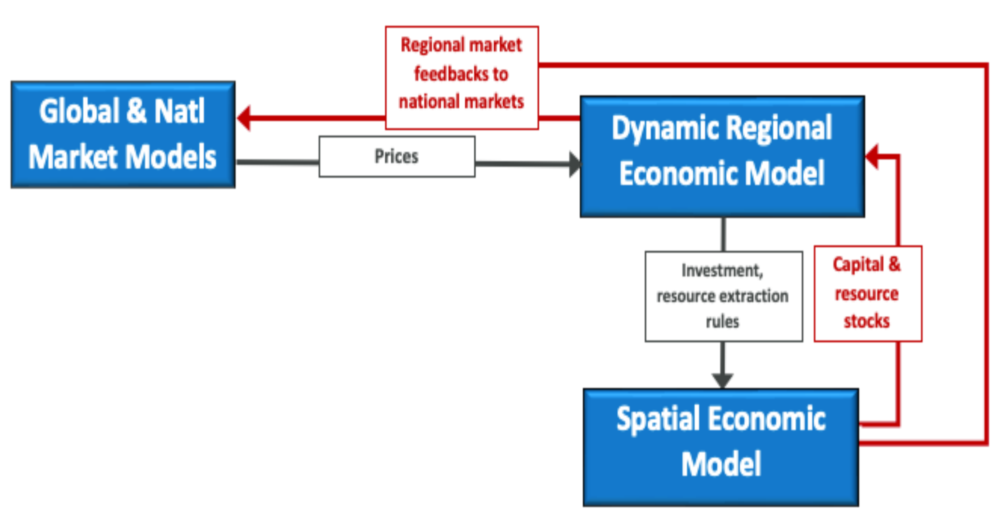

Figure 1 Model Structure

METHODS

This study has established a recursive dynamic CGE model incorporating agriculture, energy, food, ecosystem, and transportation to assess the economic impact of local economies under climate change.

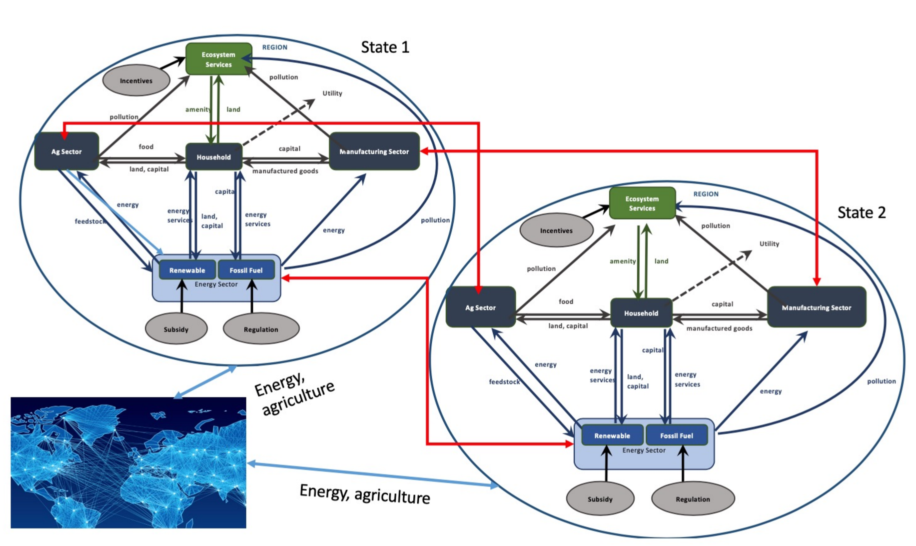

Figure 2 Model Framework

Our model is based on a recursive dynamic mechanism. During the recursive dynamic process, economic growth is mainly driven by the increment of investments and production factors.

1. The dynamic economic model will provide intertemporal decisions which are investment rules and resource extraction rules to the spatial CGE model.
2. Spatial CGE model will output the capital and resource stocks, production, and consumption which provide feedbacks to dynamic economic model

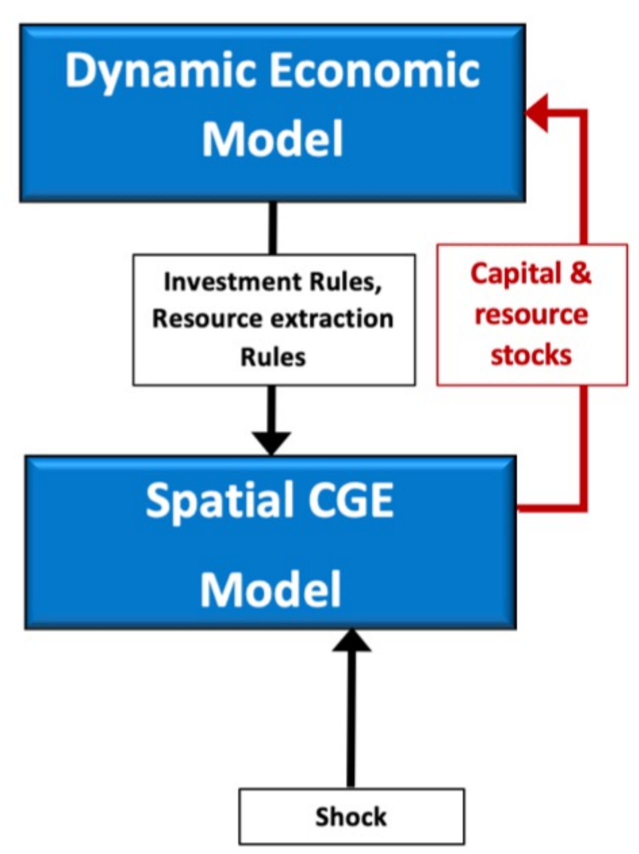

Figure 3 Recursive Process

RESULTS

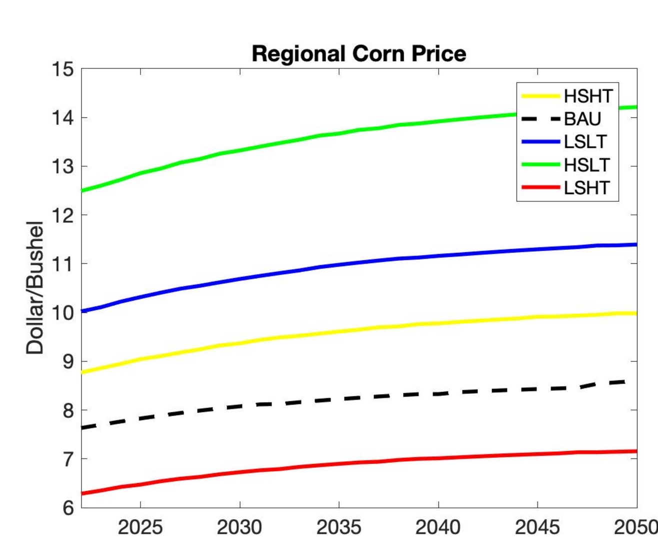

Figure 4 Regional Corn Price

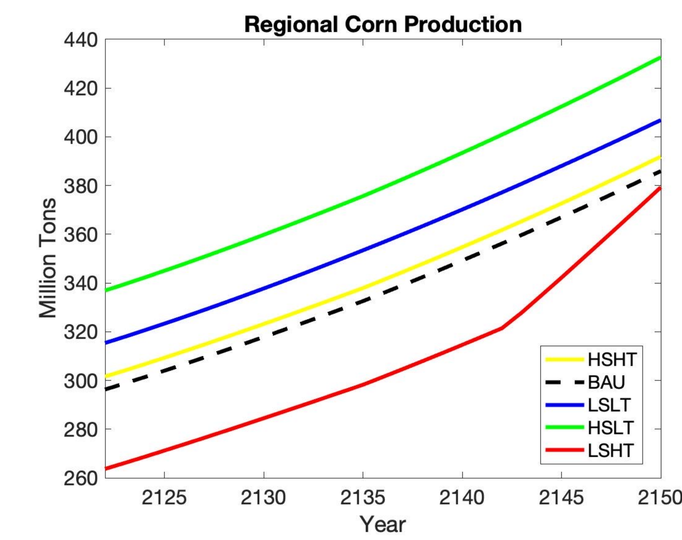

Figure 5 Regional Corn Production

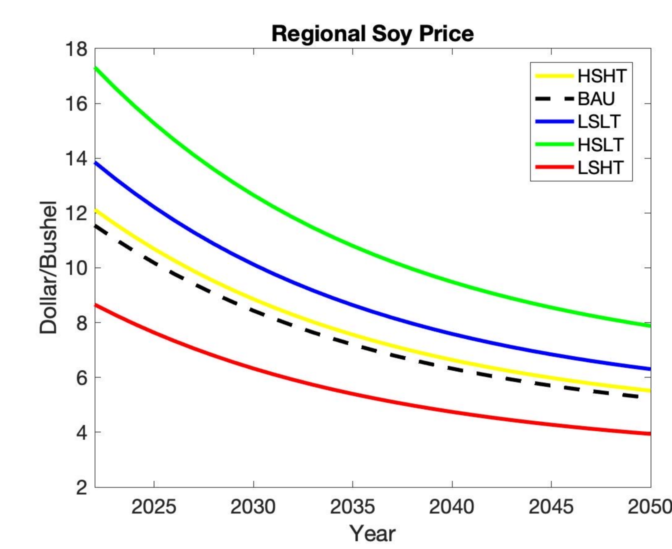

Figure 6 Regional Soy Price

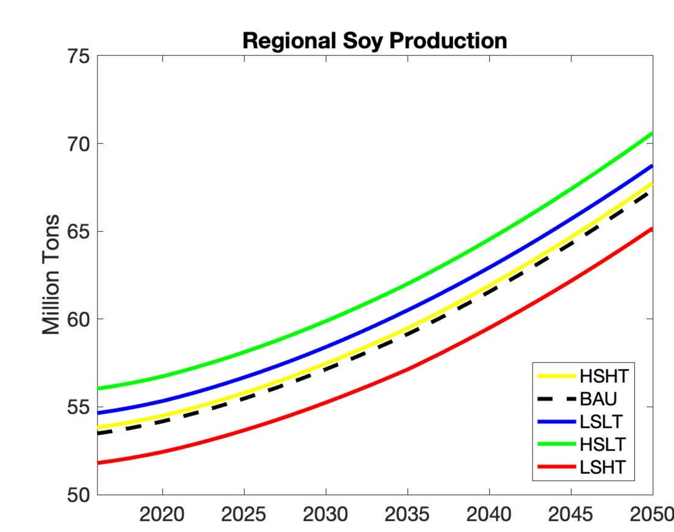

Figure 7 Regional Soy Production

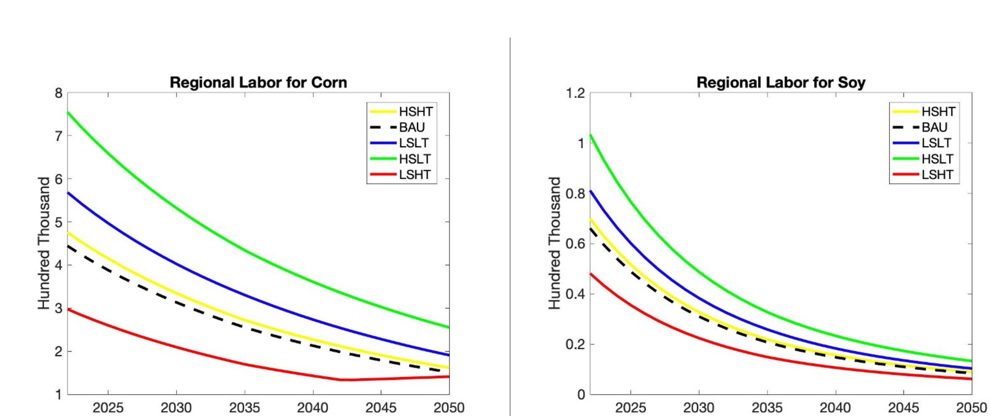

Figure 8 Regional Labor for Corn and Soy

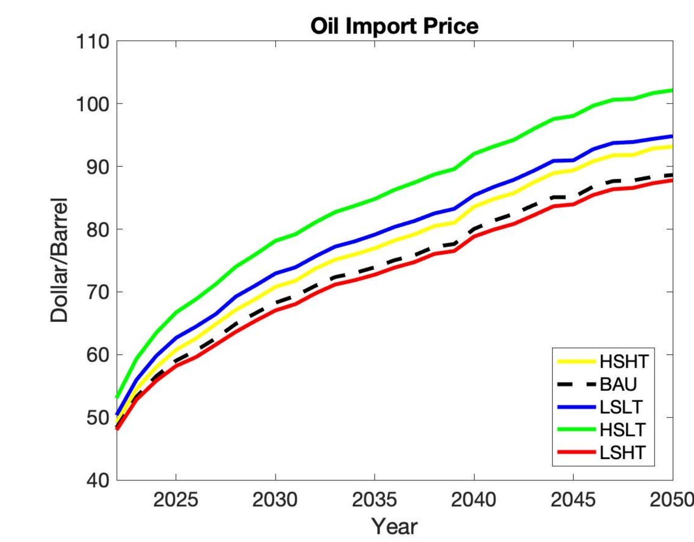

Figure 9 Regional Oil Import Price

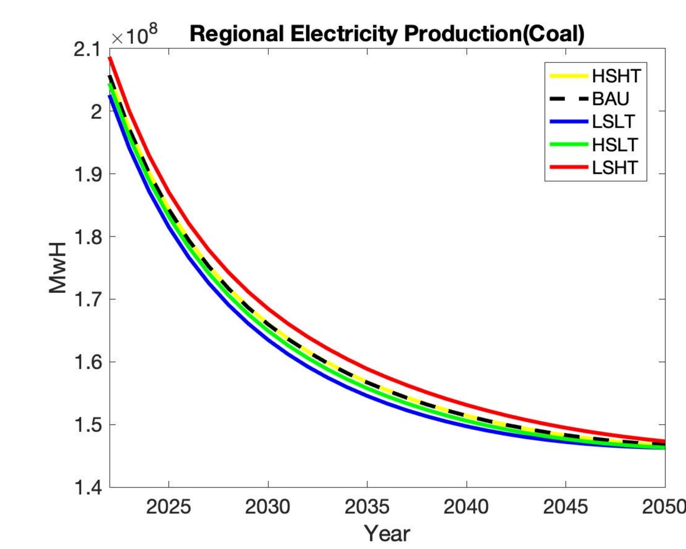

Figure 10 Regional Electricity Generated by Coal

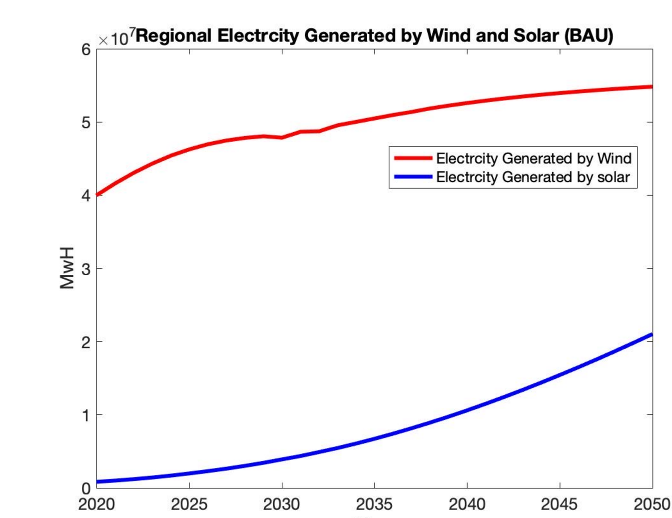

Figure 10 Regional Electricity Generated by Wind and Solar

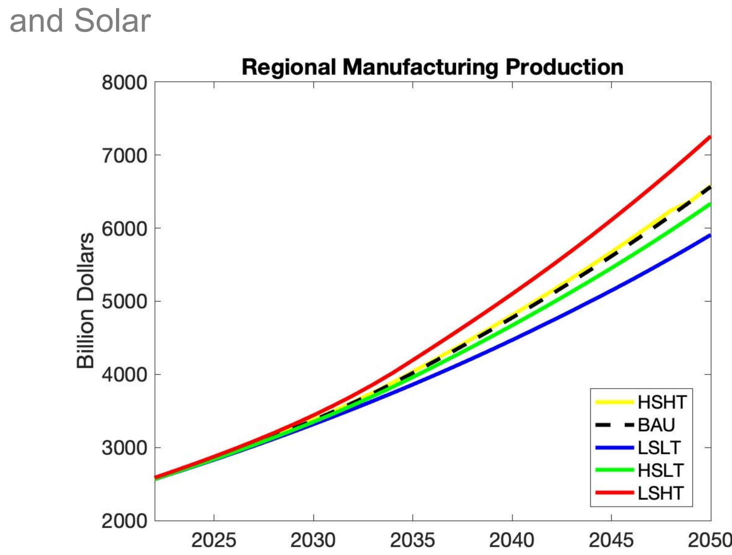

Figure 11 Regional Manufacturing Production

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Development under Spatial Equilibrium for the Great Lakes Region

Abstract

The economic impact of climate change on key economic sectors has been studied for a long time. This study establishes an integrated energy-environmental-economic dynamic recursive computable general equilibrium model. Using this spatial computable general equilibrium (CGE) model, we show how to analyze environmental sustainability and individual well-being resulting from changes in the Great Lakes region's complex economic and environmental systems. Our general equilibrium framework models interactions between human (economic, behavioral, social) and environment. It also captures the interactions between local, regional, national, and global systems across space. This paper provides a tool to understand these linkages between economics agents and different sectors for the policymakers. So, they could use our work to assess the climate change risks that may impact agriculture, energy, and manufacturing sectors under climate change and devise a related policy to maximize the welfare of their citizens and sustainably develop economies.

1 Introduction

The economic growth is tightly related to several aspects of structural change. In recent years, as one of the biggest global challenges of the 21st century, climate change has attracted growing awareness among world leaders. Plenty of evidence has proved that the impact of climate change due to human activities will be far-reaching than previously thought. Economists have responded to this challenge through many new studies investigating the impact of climate change on different aspects of society and the economy.

Economic modeling can support understanding the impact of climate change on the local economy under various scenarios and policies. It also becomes a more prominent role in climate policy analysis (Peace and Weyant, 2008). However, the economy and its linkages to other systems, like the environment, are very close. Ignoring these linkages will lead to an unreasonable result. Thus, economists decide to combine all individual models and linking them to a concerted and informed comprehensive model. In creating such a comprehensive model, the Integrated Assessment Model (IAM) comes to our view. The Integrated Assessment Model is an approach for estimating the impact of climate change on both socio-economic and physical effects. It has two essential parts: physical and economic. Intergovernmental Panel on Climate Change (IPCC) shows the IAM as a valuable approach in analyzing the impact of climate change.

Since Nordhaus (1979), IAM model have been developed to study the impact of economic activity on climate change, such as DICE and RICE (Nordhaus 1992, 1996). Computable general equilibrium model, as the economic aspects of many IAM models, is used to research the inter-sectoral linkages in different regional levels. These models are complex models with many sectors and regions and are connected to the environment through the usage of energy and GHG emissions (Ciarli and Savona 2019). Thus, the computable general equilibrium (CGE) model is one of the most essential tools used to analyze the long-term economic implication of a climate change policy based on a top-bottom modeling framework (Wang and Chen, 2006; Peace and Weyant, 2008). CGE model is a computable model with the general equilibrium structure created by Arrow and Debreu (1954). It applies economic data to the numerical and simulation approach to solve the optimal and equilibrium level of demand , supply , and price across a specified set of markets (Sue Wing, 2004).

In previous research, static CGE models are widely used, however, static CGE models are limited in climate change related economic policy analysis. Because decision-makers want to know when different impacts of climate change on the local economy will happen, and they want to prepare responses to related events ahead. Furthermore, they also want to get a multi-year projection of economic growth. Static models without the time dimension assume predictions are expected to be realized immediately. This expectation is unrealistic (Gillespie et al., 2001). On the other hand, the dynamic model could overcome these drawbacks. Partridge and Rickman (2003) demonstrate how these dynamic factors could be helpful for regional economic policy analysis. Pereira and Shoven (1988) build a dynamic CGE county-level model to connect all the equilibriums by the flow in capital stocks determined by savings. Many researchers use different approaches for the dynamic CGE model. Some researchers assume an initial steady-state path and backward-looking expectations including McGregor, Swales, and Yin (1996) and Gillespie et al. (2001). Others take a different approach—Deepak, West, and Spreen (2001) incorporate forward-looking expectations into the dynamic CGE model. With improvements in modern computer's capacity for computation, more forward-looking models are included in recent literature.

Moreover, many regional CGE models only have two parts : one single region and the rest of the world. These models also assume that the region is too small to affect the larger region, such as country and global levels. As a result, these models will be insufficient to capture linkages, which could be interregional flows of goods, labor, and capital in regional economies (Partridge and Rickman, 1998). This is because single region models can miss important interregional feedbacks, which are critical for analyzing a small-region economy (Rickman and Schwer, 1993; Lofgren and Robinson, 2002). Even impacts of interregional interactions may be small because of offsetting effects. (McGregor, Swales, and Yin, 1999). For some regions, the local economy and its growth strongly depend on the trade and in-commuting. A model without these would underestimate the effects by omitting outside region's feedback effects. This is because some people may commute between two different regions and spend money locally especially when this region is a retail center. Alternatively, it would overestimate the increase of the benefits to its residents by assuming local firms and labor would fill all new opportunities, and all wages and profits would remain in the area (Partridge and Rickman, 2010). Alternatively, models with different regions can capture local, regional, national, and global policies' regional effects. (e.g., Kim and Kim, 2002, 2003; Klepper and Peterson, 2006; Madden, 2006).

In recent CGE literature, there is also a rapid growth on the impact of climate and sustainability analysis on regional economy. However, based on our knowledge, no such dynamic CGE model has ever been done for the Great Lakes (GL) region. In this paper, we build a dynamic recursive computable general equilibrium model for the Great Lakes economy. Our model uses a dynamic multi-region forward-looking approach because we want to model factors that represent differences between regional, country, and global economic settings. Our model has many advantages and contributions. First, we provide a way for investigating the complexity of relations between structural change and climate change within an economic modeling framework. Second, we integrate different sectors and trade into a state-level model due to many of these sectors being related. We think this unique effort can lead to a proper estimation of linkages between economic activities and environments. Third, unlike most other

CGE models, we also include some specific features of the Great Lakes region's economy, particularly in its agriculture sector. Because the Great Lakes region economy depends strongly on its agricultural sector, which occupies more than 40 percent of the land and contributes to a large amount of export. Fourth, our general equilibrium framework allows shocks to all sectors in the model. It also can capture linkages among prices, income, supply, and demand in the whole economy. With dynamic factors in the CGE model, we can generate projections of different economic variables under different scenarios for potential shocks over a given period. Thus, we believe this approach provides a better analysis of the potential effects of shocks due to climate change on a wide range of economies than the partial equilibrium or static CGE models. Fifth, with a top-down approach, we also link this model to the dynamic trade model, land use model, and water quality model to assess potential social and environmental outcomes of the future impact of different climate change scenarios at different levels and systems.

Due to the current situation faced by the Great Lakes region under climate change and President Biden's goal on net zero-emission, this work aims to implement a sustainable analysis based on the link between human and environmental systems across local, regional, national, and global, to assess the economic impact of climate change. Then, decision-makers can use this work to devise related policies. The methodology used in this work is based on a recursive dynamic CGE model incorporating agricultural, food, manufacture, transportation, and energy sectors in the Great Lakes region's economy. Here, our study region includes Illinois, Indiana, Michigan, Ohio, and Wisconsin.

In the remaining part of this article, Section 2 briefly describes the CGE model used in this article, and then shows the entire model; Section 3 concludes the main results of this work; Section 4 provides the potential extending and future research of this work.

2 Description of the Model

This study has established a recursive dynamic CGE model incorporating agriculture, energy, food, ecosystem, and transportation to assess the economic impact of local economies under climate change.

Our CGE model contains five states. Figure 1 shows the schematic of the CGE model with only two states for illustration. In the model, there are a representative household and eight sectors for each state: farming, livestock, food production, manufacturing, fossil fuel extraction, energy, and trading.

Each sector in each state has a connection to the other sectors in the model. For example, the agriculture sector could provide food for the household. Also, the household can allocate the land and other resources like fertilizer to the agriculture sector. Furthermore, all sectors are connected to the ecosystem through carbon emissions. And, the policy maker could provide subsidy or impose the carbon tax to the energy sector.

2.1 Production Process

The production process consists of seven sectors. We assume that each sector produces one type of good. Moreover, all sectors make production decisions based on constant returns to scale and maximize their profits at each time period t. For the production function, we use the nested constant elasticity of substitution (CES) function. Different sectors have different CES production functions due to the difference in required input factors in these sectors. Besides, we differentiate between two capital stocks: manufacturing and renewable capi-

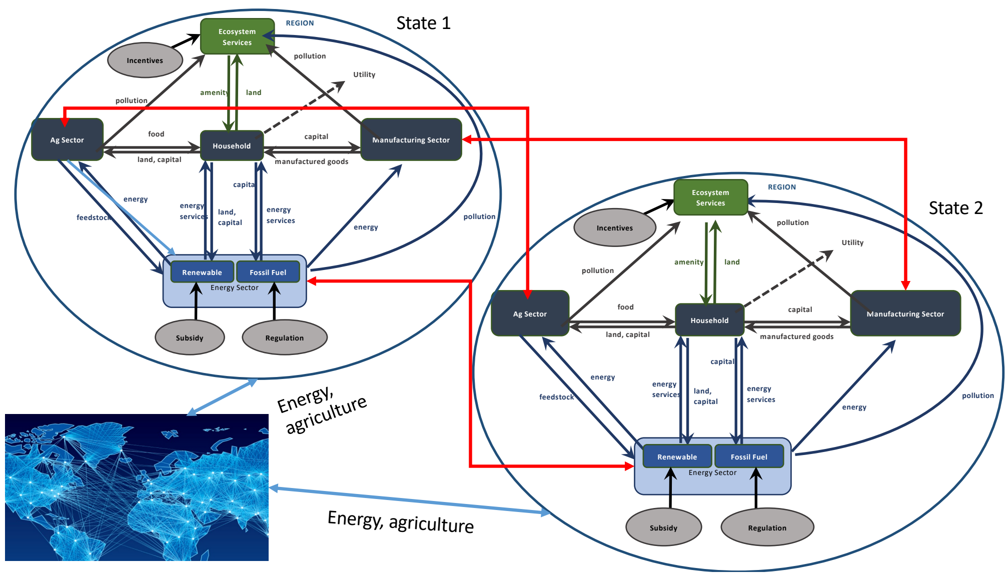

Figure 1: CGE Model with Two States

tal. In the electricity generation sector, we also separate it into fossil-fuel-based energy and renewable energy. Technical change is modeled for each input individually, modifying the composition of inputs and as a change in Total Factor Productivity (TFP).

2.2 The Dynamic Process

The dynamic process in our model is based on a recursive dynamic mechanism. During the recursive dynamic process, economic growth is mainly driven by the increment of investments and production factors. Unlike a static model, a dynamic model means that time variant where capital stocks available for use in year $t+1$ are shaped by investment in year t and before. In the dynamic model, the household and firms are assumed to be forward-looking, and stock accumulation interactions are explicitly considered. Our recursive dynamic CGE model is used for multi-period analyses. In each period, we obtain solution for each successive year, and then we use the equilibrium result obtained in year t as baseline year for consecutive year $t+1$. As shown in Figure 2, the dynamic economic model provides intertemporal decisions which are investment rules and resource extraction rules to the spatial CGE model. Then the spatial CGE model will output the capital and resource information like how much investment or fossil fuel will be in the next year to the dynamic economic model. And, it will repeat this recursive process to obtain the result for each period. With this dynamic recursive approach, it would be easier for us to add the stochasticity into the model . For example, if we have a 50 period stochastic model without the setting above, we will need to estimate 50 expectations for each stochastic variable at one time. Now, since the stochastic shock or event happens at the end period of the spatial CGE model, we only need to do one expectation for each stochastic variable in each time. This could help us reduce the related

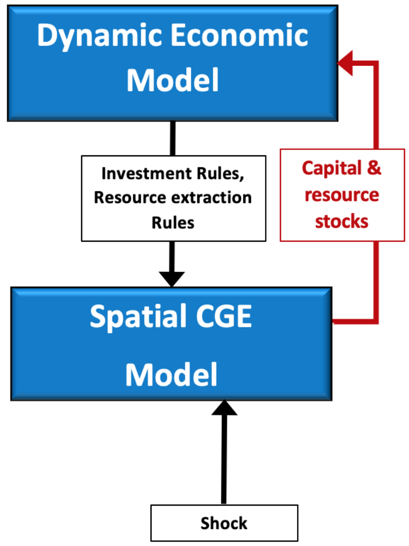

Figure 2: The Dynamic Process

computation. Besides, it also helps us have a finer spatial resolution.

We assume that there is a representative household in each state. The household owns the land, share of trading firms, farming firms, food production firms, manufacturing firms, fossil fuel and renewable energy firms, and transportation energy firms. At each period, the household receives profits from these firms in each state j. Firms maximize profits, subject to the available capital stock and technology, using labour, capital, intermediate inputs, and energy sources. The full model will be as follow.

2.3 Representative Household

In the model, we are interested in the behavior of the representative household in each state j whose object is to maximize the current utility U^j from a vector of consumptions from Pop_t^j the population in state j, $\mathbf{y}_t^j = (y_t^{food,j}, y_t^{energy,j}, y_t^{manu,j})$, which includes food consumption $y_t^{food,j}$, energy service $y_t^{energy,j}$, and consumption in manufacturing goods $y_t^{manu,j}$

$$\max U^j(\mathbf{y}_t^j)$$

where

$$U^j(\mathbf{y}_t^j, L_t^{eco,j}) = \frac{\left(c^j(\mathbf{y}_t^j)\right)^{1-\gamma_c}}{1-\gamma_c} Pop_t^j$$

where γ is the inter-temporal elasticity of substitution and $c^j(\mathbf{y}_t^j)$ is the consumption bundle

$$c^j(\mathbf{y}_t^j) = (y_t^{food,j})^{\alpha_1} \cdot (y_t^{energy,j})^{\alpha_2} \cdot (y_t^{manu,j})^{1-\alpha_1-\alpha_2}$$

where α_1 and α_2 are elasticities of different consumptions.

The representative household will consume energy service in three ways: electricity $y_t^{energy,Elec,j}$, transportation $y_t^{energy,trans,j}$, and heat from natural gas $D_t^{ng,heat,j}$:

$$\begin{aligned} y_t^{energy,j} = & [\phi_1^{energy}(y_t^{energy,Elec,j})^{\rho_e} + \phi_2^{energy}(y_t^{energy,trans,j})^{\rho_e} \\ & +(1-\phi_1^{energy}-\phi_2^{energy})(D_t^{ng,heat,j})^{\rho_e}]^{1/\rho_e} \end{aligned}$$

where ϕ_1^{energy} and ϕ_2^{energy} denote proportions of energy service in electricity and transportation respectively, and ρ^e is a parameter.

The representative household will buy goods from different industries. Its budget constraint is determined by its wage via the labor market equilibrium, profits from the firms, taxes, and subsidy. So, the representative household will face the following budget constraint:

$$\Pi_t^j + \sum_{ff} \tau^{ff,j} D_t^{ff,j} + w_t^j N_t^{lb,j} + \sum_{crop} P_t^{L,j} L_t^{crop,j} + \tau^{eco,j} L_t^{eco,j}$$
$$= Pop_t^j (p_t^{food,j} y_t^{food,j} + p_t^{elec,j} y_t^{energy,Elec,j} + p_t^{trans,j} y_t^{energy,trans,j} + p_t^{ng,j} D_t^{ng,heat,j}$$
$$+ y_t^{manu,j}) + I_t^{manu,j} + I_t^{wind,j} + I_t^{solar,j}$$

On the left-hand side of the budget constraint, the representative household will receive a total profit Π_t^j from all firms, a tax $\tau^{ff,j}$ from the extraction of fossil fuel $D_t^{ff,j}$ (for $ff = coal, oil, ng$), the wage w_t^j from labor $N_t^{lb,j}$ (for $lb =$ corn, soy, wheat, specialty, food, manufacturing, livestock, electricity, and transportation), the rent from the cropland $L_t^{crop,j}$ with a price $P_t^{L,j}$ (for $crop = corn, soy, wheat, specialty$), and the subsidy of the ecosystem land $L_t^{eco,j}$ with a rate $\tau^{eco,j}$. Furthermore, on the right-hand side of the equation, Pop_t^j is the population in state j, the representative household will have to pay for consumptions include food $y_t^{food,j}$ with a price $p_t^{food,j}$, electricity $y_t^{energy,Elec,j}$ with a price $p_t^{elec,j}$, transportation $y_t^{energy,trans,j}$ with a price $p_t^{trans,j}$, natural gas $D_t^{ng,heat,j}$ for heating with a price $p_t^{ng,j}$, and manufacturing goods $y_t^{manu,j}$ (as the numeraire good with a price 1). The representative household will also invest in manufacturing $I_t^{manu,j}$, wind turbine$I_t^{renew,j}$ and solar panel $I_t^{solar,j}$.

The capital stock held by the household will face a transition law that the capital in the next period equals the sum of depreciated capital and the investment in the current period:

$$\begin{aligned}
K_{t+1}^{manu,j} &= (1 - \delta^{manu}) K_t^{manu,j} + I_t^{manu,j} \\
K_{t+1}^{wind,j} &= (1 - \delta^{wind}) K_t^{wind,j} + I_t^{wind,j} / c_t^{wind} \\
K_{t+1}^{solar,j} &= (1 - \delta^{Renew}) K_t^{solar,j} + I_t^{solar,j} / c_t^{solar}
\end{aligned}$$

where δ is the capital depreciation rate. Here, capitals for wind $K_t^{wind,j}$ and solar $K_t^{solar,j}$ are in capacity. So, we will need to divide investment by the capital cost for wind c_t^{wind} and c_t^{solar} to calculate capitals for them.

As for the total profit, since we assume that household owns land and share of all firms, the household will receive profits from agricultural trading firms $\Pi_t^{trading,crop,j}$ (for $crop = corn, soy, wheat, specialty$), livestock trading firms $\Pi_t^{trading,livestock,j}$, natural gas trading firms $\Pi_t^{trading,ng,j}$, coal trading firms $\Pi_t^{trading,coal,j}$, oil trading firms $\Pi_t^{trading,oil,j}$, farming firms $\Pi_t^{farm,j}$, livestock firms $\Pi_t^{livestock,j}$, manufacturing firms $\Pi_t^{manu,j}$, food production firms $\Pi_t^{foodprod,j}$, fossil fuel extraction firms $\Pi_t^{extraction,j}$, fossil fuel based electricity generation firms with $\Pi_t^{ElecFF,j}$, renewable energy firms $\Pi_t^{Elec,renew,j}$, and transportation service firms $\Pi_t^{trans,j}$ in each state j at each period t. The total profit is

$$\begin{aligned}
\Pi_t^j \quad = \quad & \Pi_t^{trading,crop,j} + \Pi_t^{trading,livestock,j} + \Pi_t^{trading,ng,j} \\
& + \Pi_t^{trading,coal,j} + \Pi_t^{trading,oil,j} + \Pi_t^{farm,j} \\
& + \Pi_t^{livestock,j} + \Pi_t^{manu,j} + \Pi_t^{foodprod,j} + \Pi_t^{extraction,j} \\
& + \Pi_t^{ElecFF,j} + \Pi_t^{Elec,renew,j} + \Pi_t^{trans,j}
\end{aligned}$$

2.4 Trading Firms

Each state has different productivity because of land, natural resource stock, and capital. If a state produces more goods than they consume, it will export some goods to other regions. On the contrary, if a state cannot produce enough goods, it will buy some goods from other regions. So, flows between the Great Lakes (GL) region and outside the GL region or global systems affect and are affected by these regional economic interactions. Thus, we assume each state has some trading firms to trade agricultural and energy products with other region. In the model, trading firms will not aim to maximize their profits because the household should make trading decisions. We assume all trade within a state will have to go through trading firms where importing price and exporting price are exogenous.

The profit for crop trading firms in state j will be the profit from selling the crops to other regions less than the purchasing from other regions. We denote the exogenous exporting prices for corn, soy, and wheat as $p_t^{corn,export}$, $p_t^{soy,export}$, and $p_t^{wheat,trade}$ respectively. Denote $\Delta_t^{corn,j-}$, $\Delta_t^{soy,j-}$, and $\Delta_t^{wheat,j-}$ as amounts of corn, soy, and wheat that state j sells to other regions. Denote $\Delta_t^{corn,j+}$, $\Delta_t^{soy,j+}$, and $\Delta_t^{wheat,j+}$ as amounts of corn, soy, and wheat that state j buys from other regions. Thus, we have:

$$\begin{aligned}\Pi_t^{trading,corn,j} &= [(1-TC^{trans,corn,j})p_t^{corn,export} - p_t^{corn,j}]\Delta_t^{corn,j-} + \\ &\quad [p_t^{corn,j} - (1+TC^{trans,corn,j})p_t^{corn,export}]\Delta_t^{corn,j+}\end{aligned}$$

$$\begin{aligned}\Pi_t^{trading,soy,j} &= [(1-TC^{trans,soy,j})p_t^{soy,export} - p_t^{soy,j}]\Delta_t^{soy,j-} + \\ &\quad [p_t^{soy,j} - (1+TC^{trans,soy,j})p_t^{soy,export}]\Delta_t^{soy,j+}\end{aligned}$$

$$\begin{aligned}\Pi_t^{trading,wheat,j} &= [(1-TC^{trans,wheat,j})p_t^{wheat,trade} - p_t^{wheat,j}]\Delta_t^{wheat,j-} + \\ &\quad [p_t^{wheat,j} - (1+TC^{trans,wheat,j})p_t^{wheat,trade}]\Delta_t^{wheat,j+}\end{aligned}$$

In the same manner, specialty and livestock trading firm in each state will also make their profits from trade:

$$\Pi_t^{trading,specialty,j} = [(1-TC^{trans,specialty,j})p_t^{specialty,import} - p_t^{specialty,j}]\Delta_t^{wheat,j-} + [p_t^{specialty,j} - (1+TC^{trans,specialty,j})p_t^{specialty,import}]\Delta_t^{specialty,j+}$$

$$\Pi_t^{trading,livestock,j} = [(1-TC^{trans,livestock,j})p_t^{livestock,export} - p_t^{livestock,j}]\Delta_t^{livestock,j-} + [p_t^{livestock,j} - (1+TC^{trans,livestock,j})p_t^{livestock,export}]\Delta_t^{livestock,j+}$$

The natural gas trading firm in state j will either buy $\Delta_t^{ng,j-}$ or sell $\Delta_t^{ng,j+}$ amount of natural gas to other regions with a exporting price $p_t^{ng,export}$. The total profit of the natural gas trading firm $\Pi_t^{trading,gas,j}$ will be the difference between them:

$$\Pi_t^{trading,ng,j} = [(1-TC^{trans,ng,j})p_t^{ng,export} - p_t^{ng,j}]\Delta_t^{ng,j-} + [p_t^{ng,j} - (1+TC^{trans,ngj})p_t^{ng,export}]\Delta_t^{ng,j+}$$

The coal trading firm follows the same way:

$$\Pi_t^{trading,coal,j} = [(1-TC^{trans,coal,j})p_t^{coal,trade} - p_t^{coal,j}]\Delta_t^{coal,j-} + [p_t^{coal,j} - (1+TC^{trans,coal,j})p_t^{coal,trade}]\Delta_t^{trade,j+}$$

Since, we assume the GL region will only import the oil, so the profit for oil trade firm will be:

$$\Pi_t^{trading,oil,j} = [p_t^{oil,j} - (1 + TC^{trans,oil,j})p_t^{oil,import}]D_t^{oil,import,j}$$

2.5 Crop Farming Firms

Crop farming firms use labor $N_t^{crop,j}$, fertilizer $F_t^{crop,j}$ and land $L_t^{crop,j}$ at price $p_t^{F,crop,j}$ and $p_t^{L,j}$ respectively as the input to produce $Q_t^{crop,j}$ amount of crops (including corn, soy, wheat , and specialty) and sell at the price $p_t^{crop,j}$. The crop farming firm maximizes the profit $\Pi_t^{farm,j}$:

$$\max \Pi_t^{farm,j}$$

with

$$\Pi_t^{farm,j} = \sum_{crop} \left[p_t^{crop,j} Q_t^{crop,j} - p_t^{L,j} L_t^{crop,j} - p_t^{F,crop,j} F_t^{crop,j} - w_t^j N_t^{crop,j} \right]$$

with r_t the interest rate. We assume that fertilizer usage is linear to land area, i.e., $F_t^{crop,j} = \phi_t^{crop,j} L_t^{crop,j}$. For simplicity, we assume $\phi_t^{crop,j} \equiv F_0^{crop,j}/L_0^{crop,j}$, where $F_0^{crop,j}$ and $L_0^{crop,j}$ are initial values of total fertilizer usage and land for each crop type. The crop production function is :

$$\frac{Q_t^{crop,j}}{Q_0^{crop,j}} = A_t^{crop,j} \left(\frac{L_t^{crop,j}}{L_0^{crop,j}} \right)^{\alpha_{crop}} \left(\frac{N_t^{crop,j}}{N_0^{crop,j}} \right)^{\beta_{crop}}$$

where $A_t^{crop,j}$ is the productivity for crop in state j, α_{crop} and β_{crop} are elasticity parameters, for each $crop = corn, soy, wheat, specialty$. And, $L_0^{crop,j}$ and $N_0^{crop,j}$ are initial values for land and labor in the state j . We use the initial values as denominators in the production function for the scaling issue.

2.6 Livestock Firms

Livestock firms choose labor $N_t^{livestock,j}$, pasture land $L_t^{pasture,j}$, corn $Q_t^{corn,feed,j}$ and soybean $Q_t^{soy,feed,j}$ to feed livestock with input being priced at $p_t^{livestock,j}$ and $p_t^{corn,j}$ respectively, and then produce $Q_t^{livestock,j}$ amount of livestock, and sell them at price $p_t^{livestock,j}$. The livestock firm maximizes the profit $\Pi_t^{livestock,j}$:

$$\max \Pi_t^{livestock,j}$$

with

$$\Pi_t^{livestock,j} = p_t^{livestock,j} Q_t^{livestock,j} - p_t^{corn,j} Q_t^{corn,feed,j} - p_t^{soy,j} Q_t^{soy,feed,j} - w_t^j N_t^{livestock,j}$$

The livestock production function is:

$$\frac{Q_t^{livestock,j}}{Q_0^{livestock,j}} = A_t^{livestock,j} \left(\frac{Q_t^{corn,feed,j}}{Q_0^{corn,feed,j}} \right)^{\alpha_l} \left(\frac{Q_t^{soy,feed,j}}{Q_0^{soy,feed,j}} \right)^{\beta_l} \left(\frac{L_t^{pasture,j}}{L_0^{pasture,j}} \right)^{\gamma_l} \left(\frac{N_t^{livestock,j}}{N_0^{livestock,j}} \right)^{\eta_l}$$

where $A_t^{livestock,j}$ is the productivity for livestock, and α_l, β_l, γ_l, and η_l are elasticity parameters. Here, $Q_0^{livestock,j}$, $Q_0^{corn,feed,j}$ and $Q_0^{soy,feed,j}$ are initial values for the livestock production and the usage of corn and soy to feed the livestock in the state j.

2.7 Food Production Firms

Food production firms use labor $N_t^{food,j}$, and $Q_t^{corn,food,j}$, $Q_t^{soy,food,j}$, $Q_t^{wheat,food,j}$, $Q_t^{livestock,food,j}$, and $Q_t^{specialty,food,j}$ of corn, soy, wheat, livestock, and specialty with prices at $p_t^{corn,j}$, $p_t^{soy,j}$, $p_t^{wheat,j}$, $p_t^{livestock,j}$, and $p_t^{specialty,j}$ respectively to produce $Y_t^{food,j}$ amount of food in the state j. The firms sell the food at price

$p_t^{food,j}$. The food production firm maximizes the profit $\Pi_t^{food,j}$:

$$\max \Pi_t^{food,j}$$

with

$$\begin{aligned}\Pi_t^{food,j} &= p_t^{food,j} Y_t^{food,j} - p_t^{corn,j} Q_t^{corn,food,j} - p_t^{soy,j} Q_t^{soy,food,j} - p_t^{wheat,j} Q_t^{wheat,j} \\ &\quad - p_t^{livestock,j} Q_t^{livestock.food,j} - p_t^{specialty,j} Q_t^{specialty,food,j} - w_t^j N_t^{food,j}\end{aligned}$$

The food production function is:

$$\begin{aligned}\frac{Y_t^{food,j}}{Y_0^{food,j}} &= \left[w_{f1} \left(\frac{Q_t^{corn,food,j}}{Q_0^{corn,food,j}} \right)^{\alpha_f} + w_{f2} \left(\frac{Q_t^{soy,food,j}}{Q_0^{soy,food,j}} \right)^{\alpha_f} + w_{f3} \left(\frac{Q_t^{wheat,j}}{Q_0^{wheat,j}} \right)^{\alpha_f} + \right. \\ &\quad \left. w_{f4} \left(\frac{Q_t^{Specialty,food,j}}{Q_0^{Specialty,food,j}} \right)^{\alpha_f} + w_{f5} \left(\frac{Q_t^{livestock,food,j}}{Q_0^{livestock,food,j}} \right)^{\alpha_f} \right]^{\beta_f/\alpha_f} \left(\frac{N_t^{food,j}}{N_0^{food,j}} \right)^{1-\beta_f}\end{aligned}$$

where w_{f1}, w_{f2}, w_{f3}, w_{f4}, and w_{f5} are shares for corn, soy, wheat, specialty, and livestock respectively, and α_f and β_f are parameters.

2.8 Manufacturing Firms

Manufacturing firms use capital $K_t^{manu,j}$, labor $N_t^{manu,j}$, electricity $E_t^{manu,elec,j}$ and transportation energy $E_t^{manu,tr,j}$ to produce manufacturing goods $Y_t^{manu,j}$. We choose the manufacturing goods as the numeraire so its price is set to one. The manufacturing firm maximizes the profit $\Pi_t^{manu,j}$:

$$\max \Pi_t^{manu,j}$$

with

$$\Pi_t^{manu,j} = Y_t^{manu,j} - r_t K_t^{manu,j} - p_t^{elec} E_t^{manu,elec,j} - p_t^{trans,j} E_t^{manu,tr,j} - w_t^j N_t^{manu,j}$$

We choose the manufactured goods as the numeraire so its price is set to one. The production function of manufactured goods is:

$$\frac{Y_t^{manu,j}}{Y_0^{manu,j}} = A_t^{manu,j} \left(\frac{K_t^{manu,j}}{K_0^{manu,j}}\right)^{\alpha_m} \left(\frac{E_t^{manu,j}}{E_0^{manu,j}}\right)^{\beta_m} \left(\frac{N_t^{manu,j}}{N_0^{manu,j}}\right)^{1-\alpha_m-\beta_m}$$

where $A_t^{manu,j}$ is the productivity for manufacturing, α_m and β_m are parameters. The production for electricity $E_t^{manu,elec,j}$ is :

$$E_t^{manu,j} = E_0^{manu,j} \left[\phi_m \left(\frac{E_t^{manu,elec,j}}{E_0^{manu,elec,j}}\right)^{\rho_m} + (1-\phi_m)\left(\frac{E_t^{manu,tr,j}}{E_0^{manu,tr,j}}\right)^{\rho_m}\right]^{1/\rho_m}$$

where ϕ_m is the share of electricity used in the production process, and ρ_m is a parameter.

2.9 Fossil Fuel Extraction Firms

Fossil fuel extraction firms extract fossil fuel $D_t^{ff,j}$ (for $ff = coal, ng$) with cost $G_t^{ff,j}$ and labor $N_t^{ff,j}$, and then sell them at prices $p_t^{ff,j}$. The fossil fuel extraction firm maximizes the profit $\Pi_t^{extraction,j}$:

$$\max \Pi_t^{extraction,j}$$

with

$$\Pi_t^{extraction,j} = \sum_{ff} (p_t^{ff,j} D_t^{ff,j} - G_t^{ff,j} - w_t^j N_t^{ff,j})$$

The production function is :

$$D_t^{ff,j} = A_t^{ff,j}\left(N_t^{ff,j}\right)^{\alpha_{ff}}$$

where $A_t^{ff,j}$ is productivity and α_{ff} is elasticity. We assume the fossil fuel are extracted from finite reserves and the stock remaining at time t is $R_t^{ff,j}$. The resource stock $R_t^{ff,j}$ satisfies the following transition law :

$$R_{t+1}^{ff,j} = R_t^{ff,j} - D_t^{ff,j}$$

The extraction costs of coal and natural gas are :

$$\begin{aligned} G_t^{coal,j} &= \theta_{1,coal}(D_t^{coal,j}/R_t^{coal,j})^{\theta_{2,coal}} \\ G_t^{ng,j} &= B_t^{ng,j}\left(D_t^{ng,j}/R_t^{ng,j}\right)^{\theta_{ng}} \end{aligned}$$

where $\theta_{1,coal}$, $\theta_{2,coal}$, and θ_{ng} are parameters, and $B_t^{ng,j}$ is an exogenous declining path over time for representing the technology improvement in reducing extraction costs. We omit oil extraction in the region as the regional oil extraction (and oil stock) is small.

2.10 Fossil Fuel Electricity Generation Firms

Fossil fuel electricity generation firms are fossil fuel based power plants. They produce electricity from coal $E_t^{elec,coal,j}$ and natural gas $E_t^{elec,ng,j}$, from labor $N_t^{elec,coal,j}$ and $N_t^{elec,ng,j}$, coal $D_t^{coal,j}$ and natural gas $D_t^{ng,elec,j}$, with these inputs being priced at $p_t^{coal,j}$ and $p_t^{ng,j}$ respectively. And, they sell their outputs at price $p_t^{elec,j}$. The fossil fuel electricity generation firm maximizes the profit $\Pi_t^{elec,FF,j}$:

$$\max \Pi_t^{elec,FF,j}$$

with

$$\Pi_t^{elec,FF,j} = p_t^{elec,j} E_t^{elec,FF,j} - p_t^{coal,j} D_t^{coal,j} - p_t^{ng,j} D_t^{ng,elec,j} - w_t^j (N_t^{elec,coal,j} + N^{elec,ng,j})$$

Electricity production functions for coal and natural gas are :

$$\begin{aligned}
\frac{E_t^{elec,coal,j}}{E_0^{elec,coal,j}} &= A_t^{elec,coal,j} \left(\frac{D_t^{coal,elec,j}}{D_0^{coal,elec,j}} \right)^{\alpha_{elec,coal}} \left(\frac{N_t^{elec,coal,j}}{N_0^{elec,coal,j}} \right)^{\beta_{elec,coal}} \\
\frac{E_t^{elec,ng,j}}{E_0^{elec,ng,j}} &= A_t^{elec,ng,j} \left(\frac{D_t^{coal,ng,j}}{D_0^{coal,ng,j}} \right)^{\alpha_{elec,ng}} \left(\frac{N_t^{elec,ng,j}}{N_0^{elec,ng,j}} \right)^{\beta_{elec,ng}}
\end{aligned}$$

where $A_t^{elec,coal,j}$ and $A_t^{elec,gas,j}$ are the productivity for coal and natural gas based electricity.

2.11 Renewable Electricity Generation Firms

Renewable electricity generation firms produce electricity from wind $E_t^{elec,wind,j}$ and solar $E_t^{elec,solar,j}$ with labor wind $N_t^{wind,j}$, labor solar $N_t^{solar,j}$, and capital. They sell their outputs at price p_t^{elec}. The renewable electricity generation firm maximizes the profit $\Pi_t^{elec,renew,j}$:

$$\max \Pi_t^{elec,renew,j}$$

with

$$\Pi_t^{elec,renew,j} = p_t^{elec} (E_t^{elec,wind,j} + E_t^{elec,solar,j} + E_t^{Other,j}) - w_t (N_t^{wind,j} + N_t^{solar,j})$$

where E_t^{Other} is exogenous electricity generated from other sources including nuclear and hydropower.

The production function of wind and solar electricity is :

$$\frac{E_t^{elec,wind,j}}{E_0^{elec,wind,j}} = A_t^{wind,j}\left(\frac{K_t^{wind,j}}{K_0^{renew,j}}\right)^{\alpha_{wind}}\left(\frac{N_t^{wind,j}}{N_0^{wind,j}}\right)^{\beta_{wind}}$$

$$\frac{E_t^{elec,solar,j}}{E_0^{elec,solar,j}} = A_t^{solar,j}\left(\frac{K_t^{solar,j}}{K_0^{solar,j}}\right)^{\alpha_{solar}}\left(\frac{N_t^{solar,j}}{N_0^{solar,j}}\right)^{\beta_{solar}}$$

where $A_t^{wind,j}$ and $A_t^{solar,j}$ are the productivity for wind and solar based electricity, α and β are parameters.

2.12 Transportation Energy Firms

Transportation energy firms produce energy $E_t^{tr,j}$ from labor $N_t^{tr,j}$, diesel $D_t^{diesl,j}$ and gasoline $D_t^{gasoline,j}$ at price p_t^{oil}, as well as biofuel $q_t^{corn,trans,j}$ at price p_t^{corn} and electricity $E_t^{elec,trans,j}$ at price p_t^{elec} for electric vehicles. They sell their outputs at price p_t^{tr}. The transportation energy firm maximizes profit $\Pi_t^{tr,j}$:

$$\max \Pi_t^{tr,j}$$

$$\Pi_t^{tr,j} = p_t^{tr}E_t^{tr,j} - p_t^{oil}(D_t^{diesel,j} + D_t^{gasoline,j}) - p_t^{corn,j}Q_t^{corn,tr,j} - w_t^j N_t^{tr,j} - p_t^{elec}E_t^{elec,trans,j}$$

The transportation energy production function is :

$$\begin{aligned}\frac{E_t^{tr,j}}{E_0^{tr,j}} \quad = \quad & A_t^{tr,j}\Bigg[\omega_{tr}\left(\frac{D_t^{diesel,j}}{D_0^{diesel,j}}\right)^{\alpha_{tr}} + \\ & (1-\omega_{tr})\left(\frac{D_t^{gasoline,j}}{D_0^{gasoline,j}}\right)^{\alpha_{tr}\beta_{tr1}}\left(\frac{q_t^{corn,trans,j}}{q_0^{corn,trans,j}}\right)^{\alpha_{tr}\beta_{tr2}}\left(\frac{E_t^{elec,trans,j}}{E_0^{elec,trans,j}}\right)^{\alpha_{tr}(1-\beta_{tr1}-\beta_{tr2})}\Bigg]^{\gamma_{tr}/\alpha_{tr}} \\ & \left(\frac{N_t^{tr,j}}{N_0^{tr,j}}\right)^{\eta_{tr}}\end{aligned}$$

where $A_t^{tr,j}$ is the productivity for transportation energy, ω_{tr} is the proportion of the diesel used in the production process, and α_{tr}, β_{tr}, γ_{tr} and η_{tr} are parameters.

2.13 Market Clearing Conditions

In this subsection, we show market clearing conditions in the model. The left-hand side of equations represent the produced/imported amounts, and the right-hand side of equations represent consumed/exported amounts. The population N_t^j are allocated among sectors:

$$\begin{aligned} N_t^j &= \sum_{crop} N_t^{crop,j} + N_t^{livestock,j} + N_t^{food,j} + N_t^{manu,j} \\ &\quad + \sum_{ff} N_t^{ff,j} + N_t^{elec,coal,j} + N_t^{elec,ng,j} + N_t^{wind,j} + N_t^{elec,solar,j} + N_t^{tr,j} \end{aligned}$$

2.13.1 Agricultural Sector

Corn :

$$Q_t^{corn,j} + \Delta_t^{corn,j+} = Q_t^{corn,food,j} + Q_t^{corn,feed,j} + Q_t^{corn,tr,j} + \Delta_t^{corn,j-}$$

Soy :

$$Q_t^{soy,j} + \Delta_t^{soy,j+} = Q_t^{soy,food,j} + Q_t^{soy,feed,j} + Q_t^{soy,ex,j} + \Delta_t^{soy,j-}$$

Specialty :

$$Q_t^{specialty,j} + \Delta_t^{specialty,j+} = Q_t^{specialty,food,j} + \Delta_t^{specialty,j-}$$

Livestock :

$$Q_t^{livestock,j} + \Delta_t^{livestock,j+} \quad = \quad Q_t^{livestock,food,j} + \Delta_t^{livestock,j-}$$

We assume that all produced food is consumed by the household:

$$Y_t^{food,j} \quad = \quad y_t^{food,j} N_t^j$$

We assume that the total land available for planting crops and ecosystem services is:

$$L_t^j = \sum_{crop} L_t^{crop,j} + L_t^{pasture,j} + L_t^{eco,j}$$

and L_t^j is exogenous.

2.13.2 Energy

The total production of electricity from fossil fuel, renewable capital and other resource equal the electricity used in manufacturing firms plus the electricity used by the household :

$$E_t^{elec,coal,j} + E_t^{elec,ng,j} + E_t^{elec,wind,j} + E_t^{elec,solar,j} + E_t^{Other,j} = E_t^{manu,elec,j} + y_t^{energy,elec,j} N_t^j + E_t^{elec,trans,j}$$

The total produced transportation energy is consumed by the manufacturing firms and the household:

$$E_t^{tr,j} = E_t^{manu,tr,j} + y_t^{energy,tr,j} N_t^j$$

Gas:

$$D_t^{ng,j} + \Delta_t^{ng,j+} = D_t^{ng,elec,j} + d_t^{ng,heat,j} N_t^j + \Delta_t^{ng,j-}$$

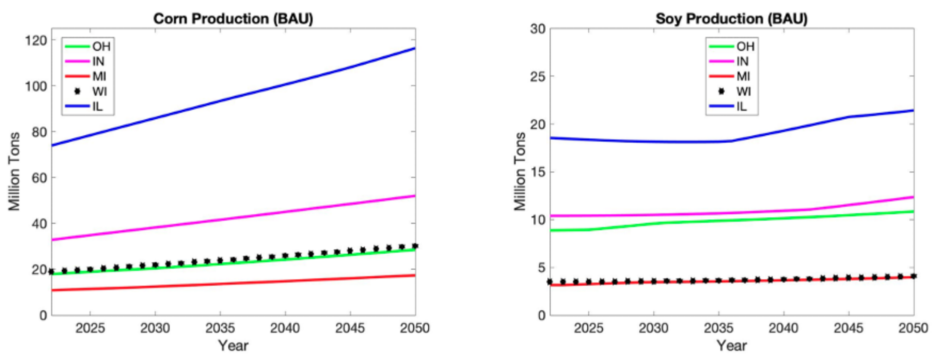

Figure 3: Crop Production

The total amount of imported oil equal the total amount of diesel and gasoline used in the transportation energy firms:

$$D_t^{oil,import,j} = D_t^{diesel,j} + D_t^{gasoline,j}$$

3 Result and Discussion

In this part, we will show the result of our model. We will also show what key factors will change under the different scenarios. [1]

As shown in Figure 3, we find that Illinois has the highest production for corn, followed by Indiana, Ohio,Wisconsin, and Michigan. And, we can conclude from the trend that the production of corn will increase as time goes. This is because we will use more ethanol in the future as part of renewable energy, which makes the demand for corn higher. As for the soy, Illinois has the highest production for soy, followed by Indiana, Ohio, Wisconsin, and Michigan. The trend of soy production is relatively flat.

[1] In this paper, we will adapt the Shared Socioeconomic Pathways (SSPs) scenarios.

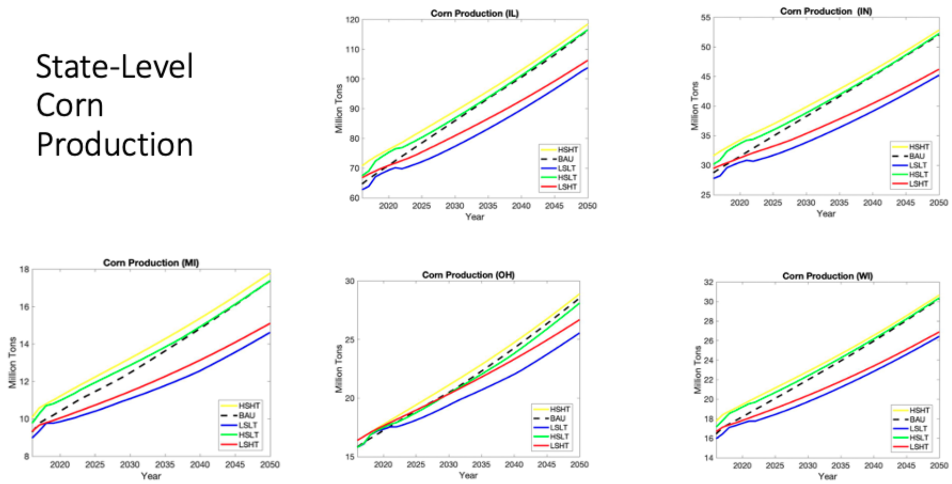

Figure 4: Corn Production Scenario Analysis

The Figure 4 shows the corn production under different scenarios in each state.[2] The red line (LSHT) and the blue line (LSLT) show higher trade will lead to higher corn production. This result is very straightforward. Because higher trade means higher demand which will lead to a higher supply. Moreover, both blue (LSLT) and green (HSLT) lines have a small jump from 2018 until 2022 on corn production. This jump is because China, which purchases most of the soy in the world, will impose a high tariff on US soy production during the trade war, leading to lower soy production. As a result, some of the resource and capital for the soy production will be allocated to the corn production. Thus, corn production will have a jump in the Great Lakes region during the trade war.

From the blue (LSLT) and green (HSLT), we can find higher sustainability will lead to higher corn production. This result makes sense. We will generally

[2]HS and LS stand for high and low sustainability. HT represents the high trade and globalization. LT means low trade and de-globalization. In a low trade scenario, we assume there will be a trade war between the US and China from 2018 to 2022. A high tariff will be imposed on the US soy production by China.

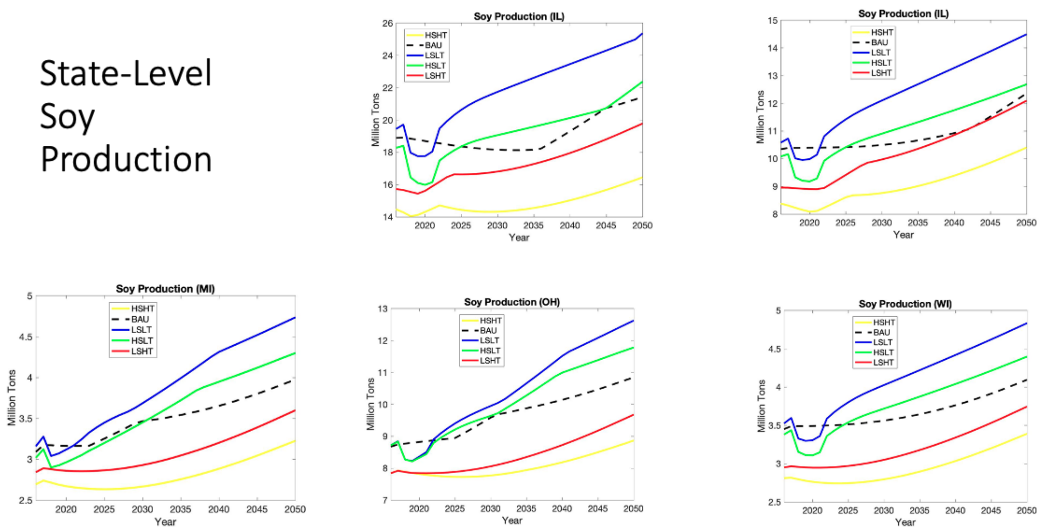

Figure 5: Soy Production Scenario Analysis

think higher sustainability will lead to higher corn production since we will use more renewable energy, like ethanol. As the demand for corn goes higher, the production of corn will also be higher.

Figure 5 shows soy production under different scenarios. By comparing the red line (LSHT) and the yellow line (HSHT), we can see that lower sustainability will lead to lower soy production. Because corn demand is higher in the high sustainability scenario, so that, producing corn is more profitable than soy. Therefore, farmers will allocate more resources and capital to corn production, leading to lower soy production.

By comparing the red line (LSHT) and the blue line (LSLT), we can conclude higher trade will lead to lower soy production in the Great Lakes region. This result is counterintuitive. We generally think higher trade will increase the demand for the soy, leading to higher soy production. However, we believe the logic behind this result is as follows. First, the international soy trade market

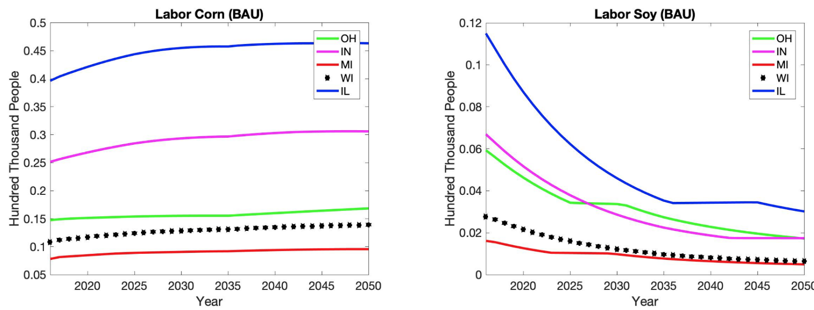

Figure 6: Labor

is unique. On the one hand, China is the only major buyer in the soy trade market. And, most of the soy trade in China is controlled by one national-owned company. On the other hand, there are a lot of major sellers on the market, like the US, Brazil, and Argentina. Besides, China has a relatively stable demand for soy each year. With higher trade and globalization, US soy producers will face more competition from other soy producers for the Chinese soy market worldwide. As a result, the soy supply will be higher than the soy demand from China in the global soy market. Thus, the soy price will be lower. So, farmers in the Great Lakes region will allocate the resource and land to other agricultural products, like corn.

As shown in Figure 6 , we find that Illinois has the most labor for corn, followed by Indiana, Ohio, Wisconsin, and Michigan.This result matches the corn production order in Figure 3. However, the growth rate for labor corn is smaller than the production of corn. We think the intuition behind this result is technology change. Agriculture technology will become more advanced than before as time goes, making productivity higher. We will need less labor for producing the same amount of corn than before. And, we can find this, obviously, with the labor for soy. In the Figure 3, soy production has a flat

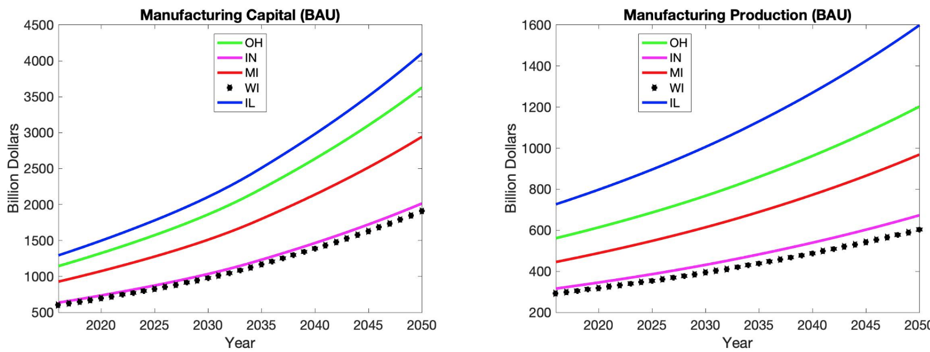

Figure 7: Manufacturing Sector

trend. Given the small soy production growth each year, the labor for soy will have a downward trend. Also, some of the labor in soy production will switch to corn production.

Figure 7 shows Illinois, Ohio, Michigan, Indiana, and Wisconsin have the highest to lowest manufacturing capital, which matches the data. It is easy to conclude that the manufacturing production will have the same order as the rank of the manufacturing capital. Because capital is one of the essential factors in the manufacturing sector. The right side of the Figure 7 confirms this conclusion.

From the left side of Figure 8, we can find that production for electricity from wind will grow fast first, and then the curve is relatively flat. The logic behind it could be that decision-makers will install more and more wind turbines in the near future due to the lower cost. However, wind turbines could only use a limited amount of land to generate electricity because of the nature of the wind. So, the growth of the electricity generated by wind will increase slower when the available land reach its limit.

From the right side of Figure 8, we can find that electricity generated by solar grows fast, different from the wind. Because solar panels have less land

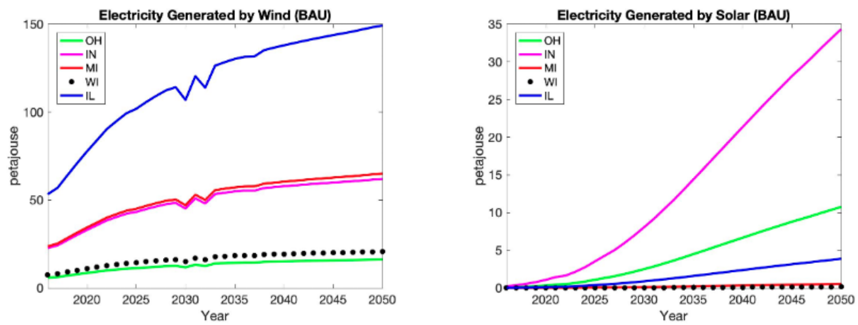

Figure 8: Regional Electricity Generate by Renewable Energy

restriction than a wind turbine, as long as there is sunshine, we can install solar panels.

From the Figure 9, we find Illinois has the highest oil import, and Wisconsin has the lowest oil import. Oil import has a fast growth in Illinois, Ohio, and Indiana. This is a very interesting result. Because, we do not expect a large growth of fossil fuel since we will use more renewable energy.

However, Figure 9 contradicts this expectation. We believe there are two potential reasons behind it. First, the increasing usage of renewable energy can not catch the increase of the total demand for energy. Second, there exists a Green Paradox effect. As it is known to us, environmental regulation will become more strict in the future. To maximize the current profits, firms tend to use fossil fuels as much as they can before they are not able to.

4 Limitation and Future Research

This model is not perfect and has several obvious limitations. Future research could overcome these limitations by extensions of the work described here. First, we will recalibrate the parameters to match real-world data better. Second, we

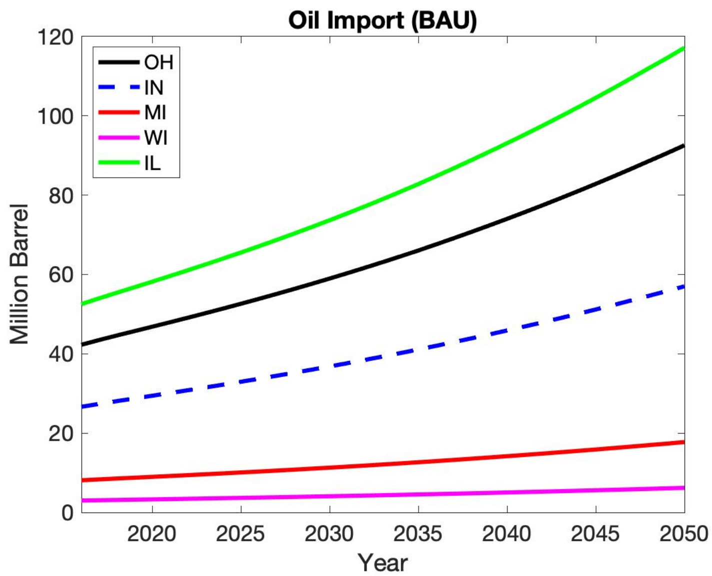

Figure 9: Oil Import

will improve the trade model, especially the transaction cost. Third, we will add risk and shock, like the global pandemic into the model. Last but least, we will work on downscaling the model to the county level.

References

[1] Arrow, K. J.; Debreu, G. (1954). "Existence of an equilibrium for a competitive economy". Econometrica. 22 (3): 265–290. doi:10.2307/1907353. JSTOR 1907353.

[2] Ciarli, T and Savona, M, 2019. "Modelling the Evolution of Economic Structure and Climate Change: A Review (January 2019)". SWPS 2019-01, Available at SSRN: https://ssrn.com/abstract=3319852 or http://dx.doi.org/10.2139/ssrn.3319852

[3] Deepak, M.S., Carol Taylor West, and Thomas H. Spreen, 2001. "Local Government Portfolios and Regional Growth: Some Combined Dynamic CGE/Optimal Control Results," Journal of Regional Science 41, 219-254.

[4] Gillespie, Gary, Peter G. McGregor, J. Kim Swales, and Ya Ping Yin, 2001. "The Displacement and Multiplier Effects of Regional Selective Assistance: A Computable General Equilibrium Analysis," Regional Studies 35, 125-139.

[5] Hewings, M. Sonis, M. Madden and Y. Koimura eds.1999 Understanding and Interpreting Economic Structure, Berlin: Springer.

[6] IPCC, 2007. Climate Change 2007: Mitigation of Climate Change, Contribution of Working Group III to the Fourth Assessment Report. Cambridge University Press, Cambridge.

[7] Kim, Euijune and Kabsung Kim, 2002. "Impacts of the Development of Large Cities on Economic Growth and Income Distribution in Korea: A Multiregional CGE Model," Papers in Regional Science 82, 101-122.

[8] Kim, Euijune and Kabsung Kim, 2003. "Impacts of Regional Development Strategies on Growth and Equity of Korea: A Multiregional Model," The Annals of Regional Science 36, 165-180.

[9] Klepper, Gernot, and Sonja Peterson, 2006. "Emissions Trading, CDJM, JI, and More: The Climate Strategy of the EU," Energy Journal 27(2), 1-26.

[10] Lofgren, Hans, and Sherman Robinson, 2002. "Spatial-Network, General Equilibrium Model with a Stylized Application," Regional Science and Urban Economics 32, 651-671.

[11] Madden, John R., 2006. "Economic and Fiscal Impacts of Mega Sporting Events: A General Equilibrium Assessment," Public Finance and Management 8(3), 346-394.

[12] McGregor, Peter G., J. Kim Swales, and Ya Ping Yin, 1996. "A Long-run Interpretation of Regional Input-Output Analysis," Journal of Regional Science 36, 479-500.

[13] McGregor, Peter G., J. Kim Swales, and Ya Ping Yin, 1999. "Spillover and Feedback Effects in General Equilibrium Interregional Models of the National Economy: A Requiem for Interregional Input-Output," in G.J.D.

[14] Nordhaus, William D., 1979. Efficient Use of Energy Resources. Yale University Press, New Haven, CT (jan).

[15] Nordhaus, William D., 1992. An optimal transition path for controlling greenhouse gases. Science 258 (5086), 1315–1319 (nov).

[16] Nordhaus, William D. and Yang, 1996. "A Regional Dynamic General-Equilibrium Model of Alternative Climate-Change Strategies." The American Economic Review Vol. 86, No. 4 (Sep., 1996), pp. 741-765 (25 pages)

[17] Partridge, Mark and Dan S. Rickman, 1998. "Regional Computable General Equilibrium Modeling: A Survey and Critical Appraisal," International Regional Science Review, 21, 205-248.

[18] Partridge, Mark and Dan S. Rickman, 2003. "Do We Know Economic Development When We See It?" The Review of Regional Studies 33, 17-39.

[19] Partridge, Mark and Dan S. Rickman, 2010. "Computable General Equilibrium (CGE) Modelling for Regional Economic Development Analysis", Regional Studies, 44 (10) (2010), pp. 1311-1328

[20] Peace, J., Weyant, J., 2008. Insights not numbers: the appropriate use of economic models. White paper of Pew Center on Global Climate Change.

[21] Pereira, Alfredo and John B. Shoven, 1988. "Survey of Dynamic Computational General Equilibrium Models for Tax Policy Evaluation," Journal of Policy Modeling 10, 401-36.

[22] Rickman, Dan S. and R. Keith Schwer, 1993. "Regional Definition in Regional Economic Impact Models: The Case of the REMI Model and Clark County, Nevada," Economic Systems Research 5(4), 419-432.

[23] Sue Wing, I., 2004. Computable general equilibrium models and their use in economy-wide policy analysis. Technical Note No. 6, MIT Joint Program on the Science and Policy of Global Change.

[24] Wang, C., Chen, J., 2006. Parameter uncertainty in CGE modeling of the macroeconomic impacts of carbon reduction in China. Tsinghua Science and Technology 11 (5), 617–624.