Preliminary and incomplete

Comparing Economic and Crop Models: The Case of Climatic and Agricultural Impacts of Nuclear War

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Abstract

In this paper, we simulate the economic effects of a regional nuclear event between India and Pakistan that results in 5 Tg of soot. The effects derived under the economic model are compared to those of the gridded crop model. Our analysis suggests that agro-economic models aiming to inform the agricultural and development policy debate require analysis on both economic behavior and biophysical drivers. More specifically, policy lessons derived from a crop model can be significantly nuanced when coupled with economic feedback derived from economic models. On the other hand, the aggregation to regions masks the heterogeneity of the shocks across space and may significantly reduce its negative effect on production.

The conclusions of this work emphasize the importance of estimating demand and supply parameters of major agricultural and energy commodities, and of updating these estimates over time; as well as the importance of aggregation across space. With respect to policy, the analysis suggests that preserving the world trading system is key to preventing widespread famine and suffering – a thriving world trading system minimizes the costs born from disruptions to climate.

Keywords: *Climate Models; CLM5; CMIP5; Computable General Equilibrium Model; Crop Models; ENVISAGE; Nuclear winter*

I. Introduction

Natural and anthropogenic clouds in the upper atmosphere can have profound impacts on agriculture, world food trade, and ultimately can produce famine. A scenario where human disruptions affect climate may result in serious ramifications to economic activity, especially agriculture. While focusing on a nuclear event between India and Pakistan, as an example, previous work showed that using less than 1% of global nuclear arsenal could create climate disruption with significant ramifications. Crop models predict that this scenario will lead to reductions of agricultural production by 20% to 40% in the first 5 years. Even after the 9th year, agricultural production continues falling, with the accumulated production dropping by 56% and 59% respectively for corn and soybeans globally [CITE]. However, what happens when the economic models are introduced?

To answer this question we work through climate, crop, and economic models to quantify the economic effects caused by the nuclear event. We discuss the implications of climatic impact of nuclear event for the general public and the poor, and within and between nations. The analysis quantifies the socioeconomic outcomes through a multimarket model. The outcomes of the multimarket model are contrasted with a computable general equilibrium model, an extension of the Environmental Impact and Sustainability Applied General Equilibrium (ENVISAGE) model [van der Mensbrugghe, 2018], coined the ENVISAGE Nuclear Winter model (ENVISAGE-NW). We use this comparison to better understand the implications of a nuclear event, with differences between the multimarket and the ENVISAGE-NW attributed to economy-wide spillover effects. Next, we compare the outcomes of the economic models with the Community Land Model version 5 (CLM5) crop model and show the importance of aggregation across space – comparing outcomes under alternative aggregation schemes: the first uses economic and spatial parameters, while the second uses biophysical parameters. We also simulate the following scenarios, one at a time, using the ENVISAGE- NW: (i) total collapse of the world trading system; and (ii) model sensitivity with respect to key elasticities to capture short- as opposed to long-run economic activity.

The analysis shows the socioeconomic impacts of a nuclear event, and that agro-economic models aiming to inform the agricultural and development policy debate require analysis on both the economic behavior and biophysical drivers. The analysis focuses on two key outcomes: a) policy lessons derived from a crop model can be significantly nuanced when coupled with economic feedbacks derived from economic models; and b) that aggregation of countries into regions may significantly reduce the negative impact of the nuclear event on the global food system. Aggregation masks the heterogeneity of the shocks across space and reduces its negative effect on production. The parametrization of the economic model is also an important factor impacting outcomes. There are significant differences between short- and long-run scenarios.

The conclusions of this work emphasize the importance of estimating demand and supply parameters of major agricultural and energy commodities, and of updating these estimates over time; and shows the importance of aggregation across space. With respect to policy, the analysis suggests that preserving the world trading system is key to preventing widespread famine and suffering – a thriving world trading system minimizes the costs born from disruptions to climate, from volcanic eruptions through nuclear war to climate change.

Our approach to modeling of the nuclear event is described in section II. Section III depicts the main results derived via the economic models and shows the differences across models. The reasons for the differences across models are conceptually explored in Section IV. Section V offers discussion and concluding remarks.

II. The approach

The analysis links the climate and crop models with an economic model, whereby the effect of nuclear winter on household income and welfare is quantified, and its effect on the food supply systems and food security investigated. The three facets of the analysis are the (i) climate model, (ii) gridded crop model, and (iii) economic model, which we describe in turn below while focusing on the economic model.

2.1 Climate models:

The climate output is based on past climate scenarios using the Coupled Model Intercomparison Project Phase 5 (CMIP5) [Taylor et al., 2012]. In particular, the climate simulations for 1980-2011 (Historical Runs, forced by observed radiative forcing) are used to generate baseline data that is then used to generate 31 control years for the gridded crop model below. Because Earth only goes through one realization of weather and climate, we use three ensemble members from multiple models to obtain a data series of possible climates in the past to examine the robustness of the results. All output from all the climate models is available on the Earth System Grid Federation website (http://esgf.llnl.gov).

The climate model focuses on a scenario simulating a nuclear war between India and Pakistan. In this event, the two countries use 50 nuclear weapons, each the size of the nuclear weapon used on Hiroshima (i.e., 15 kt). This scenario will yield 5 Tg of black carbon injection into the stratosphere (Toon et al., 2007). Although current estimates of black carbon injection from a nuclear event between India and Pakistan may lead up to 25 Tg, accounting for larger arsenals, weapons, and targets (Toon et al. 2018, GC33B-12: Rapid Expansion of Nuclear Arsenals by Pakistan and India Threatens Regional and Global Catastrophes), we elected to focus on the 5 Tg case. Even though the 5 Tg case is very small compared to the global nuclear arsenal, this work shows that this relatively small event will still result in significant ramifications to the global food systems.

Figure 1 depicts the simulated effect of a 5 Tg nuclear event that results in the cooling of the Earth and in significant ramifications to the Earth climate system. These ramifications subside only after a quarter of a century, which led the analysis to calculate shocks for the 26 years following the nuclear event.

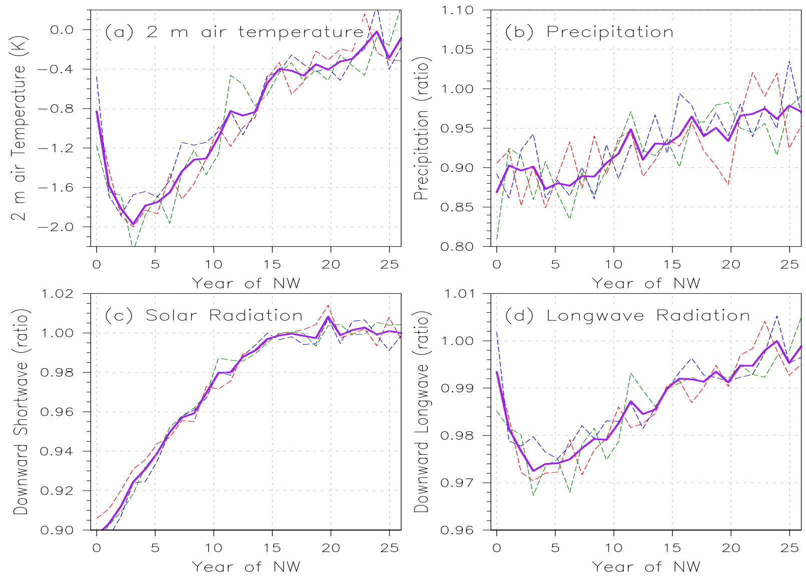

Figure 1. The simulated effect of a 5 Tg black carbon injection into the stratosphere using the CMIP5 climate model (CITE SOURCE).

2.2 Gridded crop model:

Anthropogenic climate change affects factors key to crop production [Robock, 2010]. By 2100, the atmospheric CO_2 concentration may reach 750-1300 ppm and the increase in global temperature may reach 7.8°C, depending on global emission scenarios [IPCC, 2014]. Those climate changes are likely to have strong negative impacts on agriculture production, particularly in tropical and sub-tropical regions [Rosenzweig and Parry, 1994; Rosenzweig et al., 2014].

Previous studies estimated climate impacts on agriculture by methods including field experiments [e.g., Long et al., 2006], empirical statistical models [e.g., Lobell et al., 2011; Pongratz et al., 2012], and dynamical crop models [e.g., Parry et al., 2004; Rosenzweig et al., 2014]. Dynamical crop models are appealing for analyzing the effects of climate change and agriculture practice change on crop yields, because they calculate the actual processes involved in plant growth and allow for simulating the impacts of different management practices and climate scenarios. Earlier work on predicting future global warming impacts on agriculture showed that warmer temperatures or drier growing seasons would cause crop yields to decline [Terjung et al., 1984]. Later studies [e.g., Rosenzweig, 1985; Lal et al., 1998] supported this result but found that many decreases in yield would be largely offset by positive impacts on plant growth associated with higher levels of atmospheric CO_2 concentration.

To force global crop models and produce yield shocks used in the ENVISAGE-NW model to simulate the economic impact of 5 Tg soot on agriculture production and food security, climate input of daily maximum temperature, daily minimum temperature, daily precipitation, and daily solar radiation were used. For example, reduction of temperature, precipitation, and solar radiation would significantly affect agriculture production in the Midwest US and China [Özdoğan et al., 2012; Xia and Robock, 2013; Xia et al., 2015].

The crop model, the CLM5.0 land model developed by CESM,[1] uses knowledge and understanding of land surface processes, mechanistically treats these processes, and supplies an explicit representation of land use and land-cover change. The model uses biophysical and biochemical processes to simulate for each subgrid land unit, column, and plant functional type, the effect of the climate forcing. It assumes that all subgrids within a grid-cell are the same. The crop model used 1-degree by 1-degree grid cells. Perturbations to the observed climate from 31 years, 1980-2011, were used to generate 31 control years. Assuming multiple ensembles and scenarios, with the same soil profile and agriculture practice distributed by GGCMI [CITE – spell the acronym], the crop model assessed the robustness of the results across regions. Specifically, three different ensemble members differentiated by initial input values where used together with the 31 alternative control years. That analysis focused on 6 crops:

1. Corn
2. Cotton
3. Rice
4. Sugarcane
5. Soybean
6. Wheat

The crop model simulated the effect of the nuclear event on yield for each of the 1-degree by 1-degree cells. That data was aggregated to the country level and used by the economic model. The

[1] CLM5 documentation is available at http://www.cesm.ucar.edu/models/cesm2/land/

data supplied by the crop model to the economic model included 237 countries, 6 crops, and yield shocks for 26 post-event years.

Figure 2 depicts the outcome of the shocks simulated under the three ensembles, as well as the average of the three ensembles, for corn. Whereas Figure 2a depicts the global shocks, Figure 2b depicts the regional shock for a selected number of regions. The first-year global shock for each of the 6 crops is presented in Table 1. When simulating the results of the crop model, the nuclear event is assumed to start in 2020 where the post-event outcomes are calculated for 2021 till 2046.

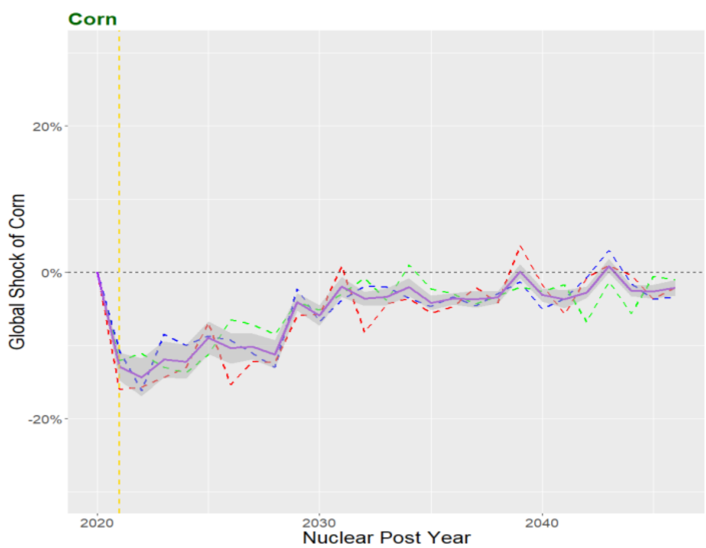

Figure 2a. Global change in production post nuclear event

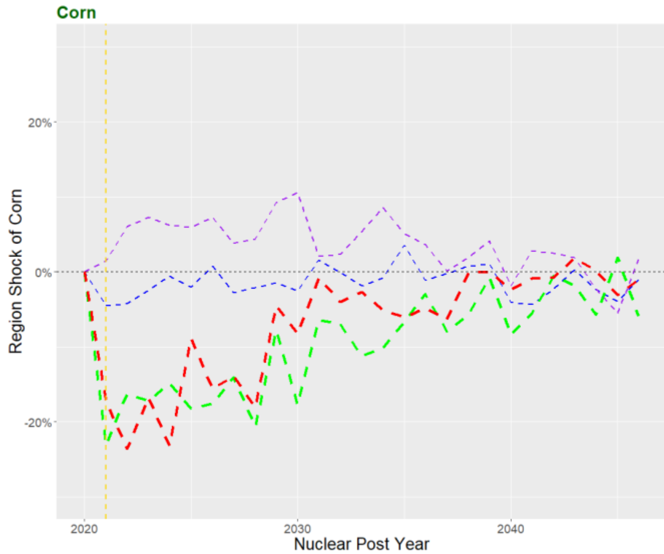

Figure 2b. Regional change in production post nuclear event

Figure 2. The gridded crop model's outcomes (CITE SOURCE)

Table 1 depicts the one-year post nuclear event outcome and the global effect of the event on the production of the six crops.

Table 1: Weighted average of global production change under CLM5.0

	Yield shocks in the first year post nuclear event, globally
Corn	-12.9%
Cotton	5.8%
Rice	-5.6%
Soybeans	-14.7%

Sugarcane	3.1%
Spring Wheat	3.7%

2.3 The economic impact of a nuclear event

Changes in crop production affect the world food trade system, where the direction and extent of the nuclear event varies across regions. The economic model attempts to better understand how the global food system will respond to the climatic effect of a regional nuclear event between India and Pakistan. Two alternative frameworks are employed: a simple multi-market framework, and a computable general equilibrium framework ENVISAGE-NW.

2.3a A simple multimarket model

Suppose we have a system of supply and demand curves for the 6 commodities; each curve is a function of the prices of the other commodities. So, we have:

$$\begin{aligned} \text{Supply:} \quad & Q_{s,i} = \alpha_{s,i} + \beta_{s,i,1}P_1 + \ldots + \beta_{s,i,n}P_n \\ \text{Demand:} \quad & Q_{d,i} = \alpha_{d,i} + \beta_{d,i,1}P_1 + \ldots + \beta_{d,i,n}P_n \end{aligned}$$

This system is in equilibrium at time $t = 0$ where P_0 and Q_0 are vectors representing the equilibrium price and quantity. We then introduce a predefined shock, $\alpha_{shock,i}$, to each supply curve and define $\alpha_{s,i}' = \alpha_{s,i} + \alpha_{shock,i}$. This shock occurs at time $t = 1$; at this moment, the price and quantity are not in equilibrium, but can find the new equilibrium price and quantity by solving:

$$\alpha_{s,i}' + \beta_{s,i,1}P_1 + \ldots + \beta_{s,i,n}P_n = \alpha_{d,i} + \beta_{d,i,1}P_1 + \ldots + \beta_{d,i,n}P_n$$

For simplicity, we introduce the following notation:

$$\alpha = \begin{bmatrix} \alpha_{s,1}' & -\alpha_{d,1} \\ & \vdots \\ \alpha_{s,n}' & -\alpha_{d,n} \end{bmatrix}, \quad \beta = \begin{bmatrix} \beta_{d,1,1} - \beta_{s,1,1} & \cdots & \beta_{d,1,n} - \beta_{s,1,n} \\ \vdots & \ddots & \vdots \\ \beta_{d,n,1} - \beta_{s,n,1} & \cdots & \beta_{d,n,n} - \beta_{s,n,n} \end{bmatrix}, \quad P = \begin{bmatrix} P_1 \\ \vdots \\ P_n \end{bmatrix}, \quad Q = \begin{bmatrix} Q_1 \\ \vdots \\ Q_n \end{bmatrix}$$

We can then simplify the former equation into $\beta P = \alpha$ and solve to give us the equilibrium price; the equilibrium quantity then follows from a substitution into the demand or supply.

In the analysis below, assume the shock is the CLM5.0 yield shock and that this shock is commissioned for each of the 26 years.

2.3b The CGE model ENVISAGE-NW:

The changes in yield calculated under the alternative scenarios in the crop model affects productivity in the economic model that simulate global economic outcomes under the various ensemble/scenarios up to 2050. Changes in yields affect the world food trade system, influence markets, and dramatically change the global food supply chain. The estimated changes in yields affect the intensive margin, specifically the amount produced within a given cultivated land [Hertel, 2010; Cohn et al., 2011]. The estimated changes in yields, however, will also affect the extensive margins, that is, total amount of land allocated for production of a crop.

We model economic changes using a multi-sector recursive dynamic computable general equilibrium (CGE) model, the ENVISAGE model [van der Mensbrugghe, 2018], which is supported by a rich database (GTAP) that includes 140 regions and 57 sectors. The economy is disaggregated into the following sectors (Table 2).

Table 2. The economy's sectors

Food & Feed sectors	Other sectors
1. Rice	1. Minim & Extraction
2. Wheat	2. Light manufacturing
3. Corn	3. Heavy manufacturing
4. Soybean	4. Utility & Construction

5. Sugarcane	5. Transport & Communication
6. Fruit vegetables	6. Other services
7. Cotton	
8. Processed food	
9. Livestock	

The dynamic CGE model is divided into 15 aggregate sectors, where the production structure is represented using a nested structure of constant elasticity of substitution production functions [Hertel, 1997, van der Mensbrugghe, 2018]. The representative household maximizes utility, producers maximize profits, and government revenues are collected via taxes and tariffs. To simplify the analysis, total government expenditure is assumed as a fixed share of nominal gross domestic product, where the allocation of government expenditures follows the same relative distribution as that of the base year 2011.

2.4 Aggregating over space

We use GTAP dataset version 9.0 with base year 2011. This dataset divides the world into 140 countries and regions. Because of numerical and algorithmic constraints, we need to aggregate this data. We employ two alternative aggregation schemes: The first uses economic activity and spatial location. Countries and regions with similar economic activities and spatial location are aggregated together. For example, Europe becomes one aggregate region and South America becomes a second region. Countries with known nuclear arsenal are not aggregated into a region but left as individual countries. This aggregation led to the following 19 regions (Table 3):

Table 3. The list of regions when aggregating the data uses economic and spatial location

Regions	Regions (continue)

China	Oceania
Korea	High income, East Asia countries
USA	Low to medium income East Asia countries
India	South East Asia
Pakistan	South Asia
Brazil	Canada & Mexico
Argentina	Latin America
EU 28	Rest of the world
Middle-East & North Africa	
Middle & South Africa	

The second aggregation scheme uses biophysical parameters. Here, we use the CLM5.0 gridded crop model; we use planting days and soil water availability to cluster countries into regions. We use two alternative techniques to determine the natural grouping of the countries: *kmeans cluster analysis* and an *agglomerative hierarchical clustering*. Technically, each country is defined using two biophysical parameters: planting days and soil water availability. For the kmeans clustering we limit the total number of clusters to XX clusters. The alternative technique, the Hierarchical clustering, follows Kaufman and Rosseeuw (1990) and uses average linkage methods. The outcomes of the two alternatives clustering techniques are depicted in Table 4.

Table 4. Aggregation using biophysical parameters.

Kmeans clustering		***Hierarchical clustering***	

The gridded crop model generated yield shocks. We use these shocks to modify productivity through the technology parameters. Modifying the technology affected relative input prices. The analysis below shows that aggregation is important for the analysis since aggregation smooths extreme values. For instance, aggregating two countries, one with a 5% increase in yield and the other with a 5% decrease in yield results in 0% shock for the region as a whole. Aggregation can mask a change in production and result in a smaller impact than otherwise.

We show below that different aggregation schemes yield significantly different impacts. When developing the model and its aggregation, we evaluate the benefits from using biophysical parameters, as opposed to economic and spatial parameters in the aggregation. Using biophysical parameters results in more uniform shocks within regions than otherwise, and this is significant when the analysis focuses on the agricultural food supply system.

2.5 The elasticity parameters

The calibration of the economic model starts with the default parameters of the ENVISAGE model. We, then, simulate the outcome of a nuclear event between India and Pakistan assuming four alternative set of parameters, one at a time:

1. We use existing ENVISAGE parameters.
2. We assume Leontief production structure, where the nested CES crop production structure has elasticities of substitution of 0.01 throughout.
3. We assume crop supply chain, from farm to fork, is inelastic with elasticities of 0.01 throughout.
4. After the nuclear event, we introduce barriers to trade among all regions for a few years.

III. Quantifying the economic effects of a nuclear event **(TBA at a later date)**

1. Outcomes of the simple multimarket model (DONE)
    a. Long-run outcome (using existing ENVISAGE elasticities)
    b. Crop production is inelastic
2. Outcomes under ENVISAGE-NW
    a. Elasticity values (Under original aggregation): DONE
        i. Long-run outcome (using existing ENVISAGE elasticities)
        ii. Crop production inelastic
    b. Elasticity values (Under alternative aggregation and clustering schemes – FAO & CLM5.0):
        i. Long-run outcome (using existing ENVISAGE elasticities)
        ii. Crop production inelastic
    c. Simulating the collapse of trade (comparing the outcome under the two alternative clusters)

IV. The challenge in aggregating the data (TBA at a later date)

V. Discussion and concluding remarks (TBA at a later date)

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