Economic incentives modify agricultural impacts of a regional nuclear war concerning food insecurity and famine

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Abstract

A nuclear war using less than 1% of the current global nuclear arsenal could produce climate change unprecedented in recorded human history and large impacts on agricultural productivity. These effects would be most severe for the first five years after the nuclear war and may last for more than a decade. This paper calculates how the price and availability of food worldwide would change by employing the Environmental Impact and Sustainability Applied General Equilibrium model. It evaluates how results depend on assumptions about how free trade would continue in a post-war economic environment. The results suggest that preserving the world trading system is key to preventing widespread food shortages as a thriving world trading system minimizes the costs born from disruptions to climate. The analysis shows that the regional nuclear war scenario would affect regional food supply systems, especially in high latitude regions. Although the global average impact on wheat is only a few percentage points, the regional nuclear war leads wheat production in EU 28 countries to plumed, on average, by more than 15%. The model also suggests that regional impacts may result in a plausible domino effect with substantial negative ramifications for local food supplies.

Keywords: *Climate Models; Crop models; Computable General Equilibrium Model; Envisage; Partial equilibrium; Simulated regional nuclear war*

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1 Introduction

Natural and anthropogenic aerosols in the stratosphere can have profound impacts on agriculture and world food trade through its effects on climate, and ultimately may produce famine. While major volcanic eruptions cause natural aerosol layers, anthropogenic aerosols may be the outcome of fires caused by a nuclear war. Previous work showed that a nuclear war between India and Pakistan, using less than 1% of the global nuclear arsenal, could create climate disruption with significant effects (Toon et al., 2019). Crop models project that this scenario could lead to reductions of agricultural production of maize, wheat, rice, and soybean by 13 (±1)%, 11 (±8)%, 3 (±5)%, and 17 (±2)% over 5 years (Jägermeyr et al., 2020). However, changes of agricultural productivity would be modified by economic activity, including adaptation by farmers and trade, affecting the ultimate availability of food and the possibility of regional famine.

We use economic models to show the impacts of a nuclear war on food availability and food insecurity, both within and between different regions. Initially, we start with a partial equilibrium model as an example. This approach results in crop production adjusting to the effects borne from the nuclear war through explicit adjustments of the individual food-crop prices. Taking this model one step further, Jägermeyr et al. (2020) introduced storage and a global trade network into the analysis while using trade data from 2007-2008 (a period when trade in food commodities was already strained). However, both approaches simplify more detailed potential economic responses to the food production shock and here we highlight the importance of modeling the economy in its entirety in this regard

The alternative model, the computable general equilibrium (CGE) model, is an extension of the Environmental Impact and Sustainability Applied General Equilibrium (Envisage) model (van der Mensbrugghe, 2018), which we call the Envisage Nuclear Winter model (Envisage-NW). In the Envisage-NW model, crop producers adjust management by switching to different crops in response to changed crop productivity, available prices of resources, goods and services, and international trade.

In general equilibrium analyses, explicit factors used for production (e.g., capital, labor and land) become important. The difficulty of these models, however, lies in the fact that hypothetical scenarios induce changes in factor prices and technology; both are fixed in partial equilibrium analysis but allowed to vary under the general equilibrium analysis. These changes in factor prices and technology create different composition effects than in partial equilibrium. We assume yield shocks calculated under the crop models are interpreted as changes to land productivity under the Envisage-NW model. The climatic change, which affects surface biophysical parameters of relevance to agriculture production through the crop models, significantly impacts land productivity. Thus, under the Envisage-NW model, regional nuclear war causes a shock that changes output through changes in land productivity, all else remaining equal. The Envisage-NW enables the use of a more comprehensive approach to modeling the effects of a regional nuclear war on the agriculture supply systems than that used for the partial equilibrium model.

In the Envisage-NW model, we use crop productivity responses to climate perturbations after the injection of 5 Tg of soot into the upper troposphere derived from seven individual global gridded crop models and simulate the economic ramifications of a regional nuclear war (Robock et al., 2007; Mills et al., 2014; Toon et al., 2019). Simulations from six of the crop models are from the AgMIP's Global Gridded Crop Model Intercomparison Project (GGCMI) (Jägermeyr et al., 2020; Müller et al., 2017) – see Table 1. The seventh model is the Community Land Model version 5.0 (CLM5.0) (Lombardozzi et al., 2019). While the models participating in GGCMI simulated rice, corn, soybean and wheat (spring and winter wheat separately), CLM5.0 simulated rice, corn, and soybean, as well as spring wheat (no winter wheat), cotton, and sugarcane/sugar-beet.

To simulate changes in the system's ability to adapt to adverse crop productivity responses, we distinguish between economic behavior in the near future (i.e., the short-run defined as two to five years), and the far future (i.e., the long-run – more than 5 years). We also simulate a partial collapse of the world trading system using Envisage-NW, to illustrate the importance of trade.

Our approach to modeling the nuclear war is described in section II. Section III depicts the outcome under the partial equilibrium analysis. The main results are derived using the Envisage-NW model (section IV). Section IV also sheds new light on the implications from the variability of impacts across regions. Section V offers discussion and concluding remarks.

2 Modeling the Nuclear War Shocks

The analysis links the climate and crop models with an economic model, whereby the effect of climate changes from nuclear war on household income and welfare is quantified, and its effect on the food supply systems and food security is investigated. The three facets of the analysis are the climate model, the gridded crop models, and the economic models, which we describe below, while focusing on the economic model.

Table 1. The crop models used in the study

Project	**Acronym**	**Crop Model**	**Reference**
Global Gridded Crop Model Intercomparison Project (GGCMI)	EPIC-BOKU	Environmental Policy Integrated Climate Universität für Bodenkultur Wien	Balkovic et al., 2013
	GEPIC	GIS-based Environmental Policy Integrated Climate	Folberth et al., 2012
	LPJmL	Lund-Potsdam-Jena with managed Land	Von Bloh et al., 2018
	pDSSAT	pSIMS platform Decision Support System for Agrotechnology Transfer	Elliott et al., 2014
	PEPIC	Python-based Environmental Policy Integrated Climate	Liu et al., 2016
	PROMET	Processes of Mass and Energy Transfer	Mauser et al., 2015; Hank et al., 2015
Other	CLM5.0	Community Land Model version 5.0	Lombardozzi et al., 2019

2.1 Climate model

The climate model simulation we use focuses on a scenario of 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 would yield 5 Tg of black carbon injection into the upper troposphere and stratosphere (Toon et al., 2007), and produce global climate change

(Robock et al., 2007). We use the results from a recent simulation of the same scenario by Mills et al. (2014), which uses the Community Earth System Model, a state-of-the-art, fully coupled, global climate model, configured with fully interactive ocean, land, sea ice, and atmospheric components (Hurrell et al., 2013). The atmospheric component is represented by the Whole Atmosphere Community Climate Model, version 4 (WACCM4). WACCM is a high-top chemistry-climate model that extends from the surface to 5.1 x 10^{-6} hPa (˜140 km). It has 66 vertical levels and horizontal resolution of 1.9° latitude x 2.5° longitude. WACCM includes interactive chemistry that is fully integrated into the model's dynamics and physics[1]. Although current estimates of black carbon injection from a nuclear war between India and Pakistan may lead up to 46 Tg, accounting for larger arsenals, weapons, and targets (Toon et al., 2019), 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 relatively small nuclear war could still result in significant ramifications to the global food systems. Because of the natural variability of climate, we used six ensemble members, three each from runs with different versions of WACCM by Mills et al. (2014) (henceforth, denoted scenarios M1, M2 & M3) and Toon et al. (2019) (henceforth, denoted scenarios T1, T2 & T3), which produced crop responses from the six models in Table1.[2] In addition, we used the three ensemble members from Toon et al. (2019) to produce crop output from CLM5.0. Ensemble members are produced by starting with different initial conditions in each model run, to investigate the impacts of random, chaotic weather variations. Because of the large forcing, more ensemble-members were not needed (Mills et al., 2014).

Figure 1 depicts the three-ensemble members produced by Mills et al. (2014). The simulated effect of a 5 Tg soot injection that results in the cooling of the Earth and in significant impacts to Earth's climate system. These impacts subside only after a quarter of a century. Similar results are observed when plotting the three-ensemble members generated by Toon et al. (2019).

2.2 Gridded crop models

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). Dynamic or process-based 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. Future global warming is projected to have adverse impacts on agriculture productivity mainly due to higher temperatures and shifted precipitation patterns where drier growing seasons would cause crop yields to decline (Terjung et al., 1984; Rosenzweig et al. 2014). Under global warming, the decrease in yield would to some extent be offset by positive impacts on plant growth associated with higher levels of atmospheric CO_2 concentration (e.g., Rosenzweig, 1985; Lal et al., 1998), an effect that is missing under global cooling. A regional nuclear war can affect factors key to crop production (Robock, 2010; Jägermeyr et al. 2020).

We use output of the gridded crop models to project the effect of a 5 Tg regional war on global food production: CLM5.0, EPIC-BOKU, GEPIC, LPJmL, pDSSAT, PEPIC, and PROMET (Table 1). These models are forced with climate input of daily maximum temperature, daily minimum temperature, daily precipitation, and daily solar radiation from the Community Earth System Model (Mills et al., 2014; Jägermeyr et al., 2020). We use the term "land productivity

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[1] Description available at https://www2.acom.ucar.edu/gcm/waccm [Viewed: May 18, 2020]

[2] Scenarios M1, M2 and M3 denote scenarios 003, 006, and 006 from Mills et al. (2014), scenarios T1, T2, and T3 denote scenarios 01, 01m02, and 01m03 from Toon et al. (2019).

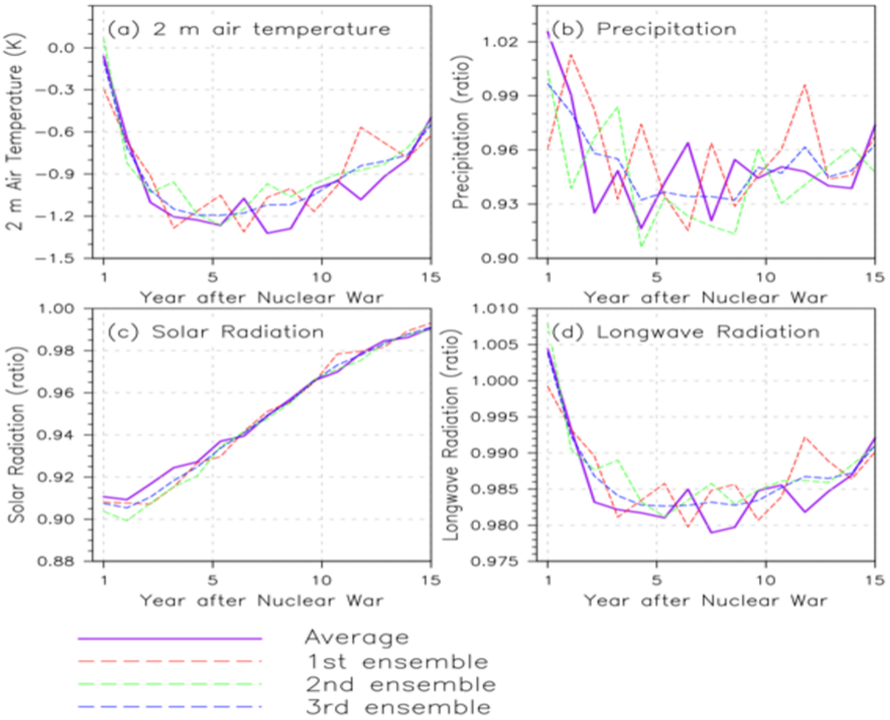

Figure 1. The simulated global average effects of a 5 Tg black carbon injection into the stratosphere (Mills et al., 2014).

shocks" to describe the changes of crop production per unit area while holding all prices constant, and this serves as input to the Envisage-NW model to simulate the economic impact of 5 Tg soot on agriculture production and food security. Previous work examined how the 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 work presented here takes advantage of new global crop model simulations. These crop models use biophysical and biochemical processes to simulate for each grid cell, and crop, the effect of the climate forcing. The crop model simulations employed from Jägermeyr et al. (2020) use a delta-correction approach to perturb the weather dataset (1980-2011), to improve crop yield simulations by maintain natural variability. Each post-conflict year is simulated by 31 years of historical weather to account for uncertainty associated with general weather patterns during the spot injection. The CLM5.0 simulations added in this study follow the same climate input protocol. Table 2 depict the crop models' global shocks for each of the crops (see also Figure 5a). When simulating the results of the crop model, the nuclear war is assumed to start in 2020 where the post-event outcomes are calculated for 2021 through 2035. The table suggests large shocks to soybean, corn, and wheat, with much smaller shocks to spring wheat. In addition, the table also suggests that, on average, cotton and sugarcane growers may benefit from the cooling of the Earth.

2.3 Defining land using FAO's Agro-Ecological Zones

The crop models simulate the effects of the nuclear war on yield for each of the 1°x1° cells. These data were aggregated to the Food and Agricultural Organization (FAO) Agro-Ecological

Zones (AEZ) (known as the Global Agro-Ecological Zones, GAEZ)[3] at the country level and used by the economic model. The data supplied by the crop models to the economic model cover 18 AEZ zones, 237 countries, 4 (or 6) crops, and yield shocks for 15 post-event years.

Table 2. The change in global production-weighted mean yield using the girded crop models.

Year	Corn	Soybean	Rice	Wheat	Spring Wheat	Cotton	Sugar
2021	-13% (6.8%)	-19% (6.4%)	-4% (7.8%)	-6% (9.5%)	-4% (1.6%)	-1% (2.2%)	-2% (3.4%)
2022	-15% (6.7%)	-18% (6.7%)	-4% (5.8%)	-11% (9.3%)	-5% (2.8%)	2% (3.8%)	1% (5.3%)
2023	-15% (6.2%)	-17% (6.3%)	-3% (6.2%)	-11% (9.2%)	-4% (0.9%)	5% (0.3%)	1% (2.3%)
2024	-15% (6.2%)	-19% (7.1%)	-4% (6.1%)	-13% (8.7%)	-5% (1.6%)	1% (5.0%)	0% (4.9%)
2025	-11% (4.5%)	-14% (3.5%)	-4% (5.4%)	-9% (7.9%)	-4% (1.2%)	1% (2.8%)	-1% (3.1%)

Note: (i) The corn, soybean, and rice yield shocks are averaged over the seven crop models. Wheat is average over the six crop models, other than CLM5.0. And spring wheat, cotton, and sugarcane are averaged only over the CLM5.0 crop model.
(ii) In online supplementary SA1, we depict the global production-weighted mean yield change from 2021 to 2035.
(iii) Note also that standard deviation is in parenthesis

3 Partial equilibrium as an example

Changes in crop production affect the world food system, where the direction and extent of the impacts of nuclear war vary across regions (Jägermeyr et al., 2020). However, do these yield shocks translate one-to-one to production changes, because of economic interactions? We answer this question below while investigating the economic response of regional and global food systems to the climatic effect of a 5 Tg regional nuclear war between India and Pakistan.

We begin with a partial equilibrium framework and use this framework to shed light on the importance of using general equilibrium models. The partial equilibrium framework uses the Envisage-NW parameters to model the crop markets of interest, using corn and soybeans as examples and assuming a supply curve and a demand curve for each of the crops. The supply curve describes the total amount of crop available at different prices, and the demand curve models the inverse relation between price and quantity demanded of the crop.

3.1 The partial equilibrium model

Formally, let superscript s denote supply and superscript d denote demand, where $Q^d_{c,s,t}$ and $Q^s_{c,s,t}$ denote quantity demanded and supplied, respectively, of crop c in country s at time t. For simplicity and brevity, we assume that the demand captures all sources of demand for the crop

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[3] This methodology was developed over the last 30 plus years and is used to assess agricultural resources and their potential. The GAEZ uses agronomy to quantify land productivity, among other uses.

(i.e., it is aggregated), and similarly that the supply captures all sources of supply for the crop. We will assume a system of supply and demand curves for 2 crops (corn and soybean); each curve is a function of the crop's own price as well as the price of the other crop; and for simplicity and brevity, assume linear curves where α and β are parameters. So, we have:

$$\text{Supply: } Q^s_{c,s,t} = \alpha^s_{c,s} + \beta^s_{c,s} \cdot P_{c,s,t} + \beta^s_{j,s} \cdot P_{j,c,t} \tag{1a}$$

$$\text{Demand: } Q^d_{c,s,t} = \alpha^d_{c,s} + \beta^d_{c,s} \cdot P_{c,s,t} + \beta^d_{j,c} \cdot P_{j,c,t} \tag{1b}$$

where $P_{c,s,t}$ is the price of crop c in country s at time t, and assume $c \neq j$. The parameter $\beta^s_{c,s}$ models the effect of a change in the price of crop c, i.e., $P_{c,s,t}$, on the amount of crop c supplied, i.e., $Q^s_{c,s,t}$, capturing, for example, the effect of a decline in the price of soybean on the amount of corn supplied, ceteris paribus. For example, if the price of soybeans declines, farmers substitute away from soybeans and grow more corn – the change in the price of soybeans would result in corn becoming relatively more profitable to farmers than soybeans. On the other hand, the parameter $\beta^d_{c,s}$ models the effect of a change in the price of crop c, i.e., $P_{c,s,t}$, on the quantity demanded of crop i, i.e., $Q^d_{c,s,t}$, thus capturing, for example, consumers' substitution away from corn and into soybeans (e.g., using more soybeans than corn for feed). The parameters are calibrated using existing estimates, which are region specific.

This system starts in a business-as-usual (BaU) equilibrium, which is denoted with superscript $(^0)$ (i.e., in equilibrium $Q^0_{c,s,t} \equiv Q^{s,0}_{c,s,t} = Q^{d,0}_{c,s,t}$). We then introduce a predefined shock to each supply curve which shifts the supply and thus results in a simulated equilibrium outcome. Technically, the average yield shock of the 7 crop models, $\varepsilon_{c,s}$, modifies the intercept $\alpha^s_{c,s}$ and results in a new supply intercept, $(1+\varepsilon_{c,s}) \cdot \alpha^s_{c,s}$, where if the shock is negative ($i.e.,\ \varepsilon_{c,s} < 0$) then $(1+\varepsilon_{c,s}) \cdot \alpha^s_{c,s} < \alpha^s_{c,s}$. The simulated outcome is denoted with superscript $(^1)$ (i.e., $Q^1_{c,s,t}$ denotes the simulated equilibrium). The new outcome models the effect of the yield shock generated by the crop model on crop market c through the explicit shifting of the supply curve. The difference between the simulated equilibrium and the BaU one is the product of the nuclear war and the climatic change it caused.

We distinguish between two alternative economic scenarios: one assumes no cross-price effects, i.e., $\beta^s_{j,s} = \beta^d_{j,s} = 0$ (henceforth single-market partial equilibrium or SM-PE) and another assumes cross-price effects, i.e., either $\beta^s_{j,s} \neq 0$ or$\beta^d_{j,s} \neq 0$ (henceforth multimarket partial equilibrium or MM-PE). While the SM-PE model assumes markets are independent of each other, the MM-PE model assumes the crop markets depend on each other. The MM-PE model links different crop markets with each other and allows substitution on either the consumption side or the production side, while maintaining the assumption of no trade between countries.

3.2 The outcome of the partial equilibrium analysis

Starting with a 5 Tg nuclear war between India and Pakistan and assuming the SM-PE model, we derive the effect of the regional nuclear war on corn and soybeans. Figure 3 depicts the change in quantity in three key countries: United States, China, and Brazil.[4] The figure depicts the outcome of the simulation given the parameters used in the Envisage-NW analysis. That is, we use the Envisage-NW parameters to calculate β in Eq. (1), and then use β together with price and quantity data from 2020 to calculate α. The change between the BaU and the simulated outcome is reported on the y-axis, i.e., $\frac{(Q^1_{c,s,t} - Q^0_{c,s,t})}{Q^0_{c,s,t}}$, with the x-axis depicting the number of years following the nuclear war. We also assess the sensitivity of the results to the parameters. We start with

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[4] The explicit shocks calculated for the various countries are presented in supplementary material SA1.

the own price elasticity of demand ($\eta^d_{c,s} = \beta^d_{c,s}\frac{P^0_{c,s,t}}{Q^0_{c,s,t}}$) and of supply (i.e., $\eta^s_{c,s} = \beta^s_{c,s}\frac{P^0_{c,s,t}}{Q^0_{c,s,t}}$), where the elasticity measures the sensitivity of the quantity demanded or supplied to a 1% change in price. This definition of the elasticity is used to calibrate the parameters $\beta^d_{c,s}$ and $\beta^s_{c,s}$ in Eq. (1) – recall that quantity and price are taken from the data and the own-price elasticity is estimated in the literature and is location specific. To this end, we used own price elasticity, a parameter that relates the percent quantity change of crop to percent change in the own crop's price. An own price elasticity is defined for the demand and another for the supply. We increased or decreased the elasticity modeling the sensitivity of quantity to prices by 20%, one parameter at a time. We then used the new elasticity value to calculate the revised β parameter and repeat the analysis that generated the shock to production. The outcome of the sensitivity analysis suggests the results are robust to the various values (Fig. 2). In terms of Fig. 2a, changing the demand or supply parameters, one at a time, results in similar adjustments to production and thus in the cyan and red colors mostly overlapping thus resulting in a purple shade. When comparing the economic outcome to the input yield shocks from the crop models (the green line in Fig. 2a), we do observe some differences. For example, while the weighted average of the first-year yield shock in the US for corn is -21.9%, the SM-PE model projected corn production in the US will decline by -18.2%. All else equal, the yield shock resulted in the farmer producing less than before the nuclear war. However, because consumers want more crops and are willing to pay higher prices, the farmer elects to use more resources to produce crops (e.g., land, water, fertilizer). The increase in the resources allocated to production of crops reduces the impact of nuclear war on food production. The partial equilibrium model does not explicitly model the resources needed to produce the crops. but this is implied by the upward sloping supply function; that is, it is implied by the curve modeling the cost of production — when building this curve, it is assumed that more production results in higher costs per bushel of soybeans produced.

Next, the effects using the MM-PE model are derived assuming cross-price effects where price of one crop is affecting the other, i.e., either $\beta^s_{j,s} \neq 0$ *or* $\beta^d_{j,s} \neq 0$ but not both are assumed. These effects are also shown in Fig. 2a where the data used to construct these figures are presented in supplementary material SA2. The outcome of this analysis is depicted in Fig. 2a using either the dots when cross supply effects are assumed ($\beta^s_{j,s} \neq 0$) and dashes when cross demand effects are assumed ($\beta^d_{j,s} \neq 0$). Although the MM-PE model relaxes the assumption of no cross-price effects and that prices of one crop may affect another, the effect of a nuclear war over time on Brazil, China, or the US is still similar to that of the SM-PE model and thus the crop models' projections. Because the nuclear war affects corn and soybean, similarly, linking these markets through prices did not change the results substantially. Some differences, however, do exist. For example, the cross-price effects resulted in the shocks to Brazil's corn and soybean production increasing less than projected under the crop models. We suspect the reason of this outcome is that the cross-price effects through the demand curves dominate the impacts of the shock borne from the regional nuclear war; the spike in the corn (soybean) price amplifies the effect of the simulated nuclear war on soybean (corn) beyond what was projected under the crop models.

What are the implications of these results? We answer this question through Fig. 2b, which shows the calorie uptake in the three key countries. To combine corn and soybean, we first convert the quantity of each crop into calories using data from the USDA nutrition database.[5] For soybeans, we use the entry on "Soybeans, green, raw," while for corn we use the entry on "Corn, sweet, yellow, frozen, kernels on cob, unprepared." Then, once the units are converted to a common measure (kcal), we calculate the change in calories consumption by each country for each shock and sum these values across all countries. Fig. 2b summarizes these calculations and reports the

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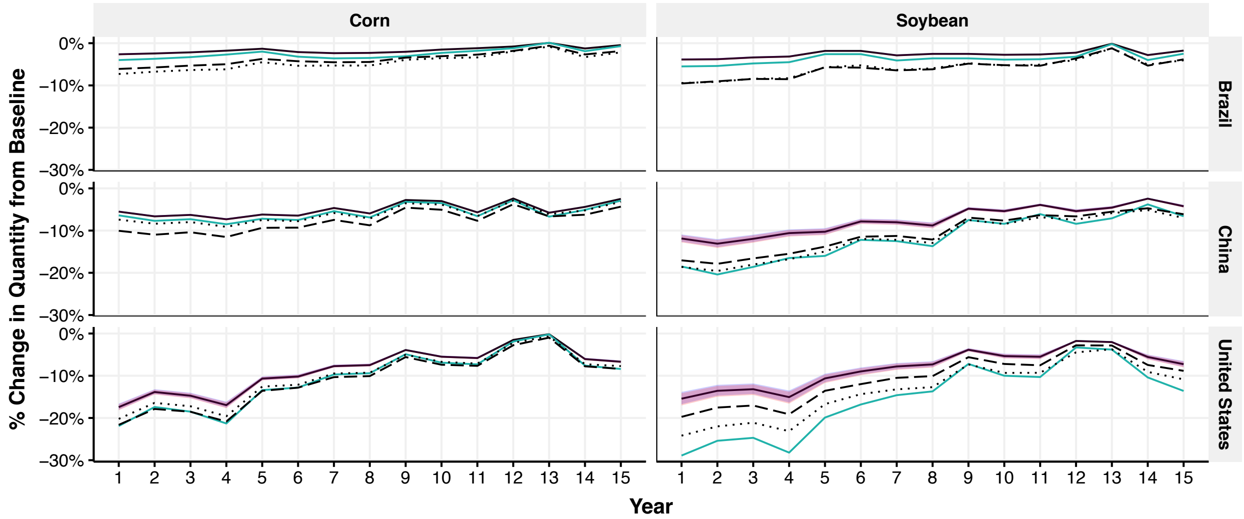
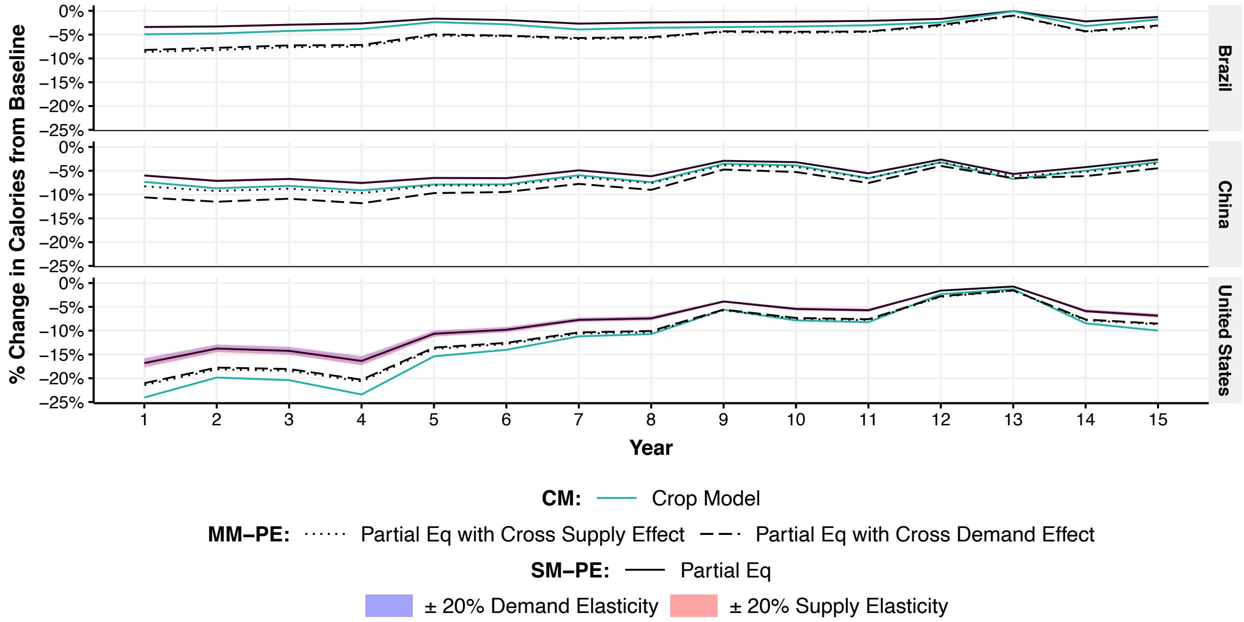
[5] Data and documentation are available at https://ndb.nal.usda.gov/ndb/

(a) Percent change in corn and soybean production for Brazil, China, and the U.S.



(b) Percent change in calories over time from corn and soybeans.



Note: (i) The output shocks are calculated under the crop model (averaged across all seven models) with the outcome of the SM-PE and MM-PE models.
(ii) ***SM-PE scenarios:*** 20% Demand elasticity, namely, $\eta^d_{c,s}$: denotes a simulated scenario where own price demand elasticity increases or decreases by 20% with $\beta^d_{C,S} = \eta^d_{c,s} \cdot Q^0_{c,s,t}/P^0_{c,s,t}$; 20% Own Supply, namely, $\eta^s_{c,s}$: denotes a simulated scenario where own price supply elasticity increases or decreases by 20% with $\beta^s_{c,s} = \eta^s_{c,s} \cdot Q^0_{c,s,t}/P^0_{c,s,t}$.
(iii) ***MM-PE scenarios:*** With Cross Supply Effect (cyan): denotes a simulated scenario where $\beta^s_{j,c} \neq 0$, while With Cross Demand Effect (red): denotes a simulated scenario where $\beta^d_{j,c} \neq 0$.

Figure 2. Percent change over time from corn and soybeans.

relative caloric change relative to the baseline amount of equilibrium calories consumed prior to introduction of the shock (the data used to produce the graph are summarized in supplementary material SA2). A 10%-12% reduction in caloric intake is significant. Starting with the average 2,000 and 2,500 calories consumed by women and men, respectively, daily, a reduction of 500 calories a day (25% and 20% for women and men, respectively) result in these individuals losing half a kilogram (1 pound) a week.[6] These rough calculations suggest that starting with the average daily calories per person, a regional nuclear war can result in significant impact on food security. This concern is amplified several fold when we consider that in many developing world countries, stunting (i.e., "the impaired growth and development that children experience from poor nutrition. Children are defined as stunted if their height-for-age is more than two standard deviations below the World Health Organization Child Growth Standard median" (World Health Organization – viewed: February 15, 2020) and famine is already prevalent.[7]

So far, economics does not result in substantial impact differences, globally, from the projections of the crop models albeit we do observe differences when regional impacts are compared. The effects are similar in magnitude, as is the spatial allocation of the shocks and their impact on food production. The 5 Tg soot affected the climate, but the effect is not uniform as the Figs. 3 and 4 illustrate. Some countries are negatively affected by the war, because of their spatial location on Earth and because of their crops' response to the change in the climate. To this end, the negative ramifications from a 5 Tg regional nuclear war between India and Pakistan are magnified further with the introduction of international trade when the BaU uses data from 2007-2008 when the global trading system was already constrained (Jägermeyr et al., 2020).

4 The economic impact of a nuclear war: Envisage-NW model

We assume changes in yield calculated under alternative scenarios in the crop models affect the productivity of land in the general equilibrium model and use these changes to simulate the economic effect of a regional nuclear war globally.

4.1 The Envisage-NW model

The economic changes computed below are modeled using the Envisage model (van der Mensbrugghe, 2018), which is supported by a rich database (Global Trade Analysis Project, version 9 – GTAP V9) that covers 141 regions and 57 sectors. Building on this dataset, we aggregate the economy into the following sectors (Table 3).

The production structure of the Envisage-NW model is divided into 15 aggregate sectors, of which nine sectors belong to the Food & Feed sectors and the other six sectors do not (Table 3). This production structure is represented using a nested structure of constant elasticity of substitution (CES) production functions (Hertel, 1997, van der Mensbrugghe, 2018). This CES production function combines two inputs to calculate an output bundle, assuming the following: proportional change of the ratio of two inputs with respect to the ratio of the extra output gained via increasing the input by one unit (i.e., marginal productivity) is constant. The nested CES structure modifies the CES production function, assuming two or more CES functions nested within each other, where the outcomes of lower level CES functions are used as inputs in higher level CES functions. The nested structure allows different substitution possibilities between factors of production and

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[6] Data available at https://www.healthline.com/nutrition/how-many-calories-per-day [viewed: February 15, 2020]

[7] Data and description available at https://www.who.int/nutrition/healthygrowthproj_stunted_videos/en/ [viewed: February 15, 2020]. Stunting is prevalent in many parts of the world – see https://en.wikipedia.org/wiki/Stunted_growth#/media/File:Stunting_1995-2007.png [viewed: February 15, 2020].

Table 3. Economy Sectors in the Envisage-NW Model.

Food & Feed sectors (9 total)	**Other sectors (6 total)**
Rice	Mining & Extraction
Wheat	Light Manufacturing
Corn	Heavy Manufacturing
Oil seeds (henceforth, soybean)	Utility & Construction
Sugarcane & sugar beet (henceforth, sugarcane)	Transport & Communication
Fruit & vegetables	Other Services
Plant-based fiber (henceforth, cotton)	
Processed food	
Livestock	

categories within them. For example, in Figure 3 we assume land and labor used in production of a crop. In this example, σ_{AEZ} denotes the lower-level CES of the various AEZs and σ_{crop} denotes the higher-level CES of the production nest. The two can be different, thus yielding different substitution (for the Envisage crop production structure, which includes the land bundle nest among other nests, see van der Mensbrugghe [2018]). The production function, in this case, first uses σ_{AEZ} to calculate the land bundle and then uses σ_{crop} to calculate crop output while using land and labor bundles.

For instance, the nested CES production function uses land bundle (defined as an index of total land used; an index that aggregates land of various AEZs into one number) as an input in the production of a crop. Put differently, the production function of a crop nests lower level CES functions that are used to calculate various input bundles, such as land bundles. The higher level CES functions, then, calculate crop outputs. When calculating land bundles, we start with biophysical parameters that spatially disaggregate land within a region. We employ GAEZ data and calculate land share of each of the AEZs in each of the regions (Baldos, 2017). We then assume land of one type of AEZ is an imperfect substitute to other AEZs; that is, we assume that a crop can be planted on different AEZs – however, yield per acre varies across AEZs with some AEZs exhibiting significantly higher yield per acre than others.

We also assume the representative household maximizes utility that measures the household's satisfaction from consuming goods and services (such as the usefulness of satisfying the household's need for food), 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. The allocation of government expenditures follows the same relative distribution as that of the base year 2011.

We use the GTAP V9 with base year 2011. Because of the numerical and algorithmic limitations of the solver, it is necessary to aggregate the data, where the aggregation needs to balance between two effects (Britz & van der Mensbrugghe, 2016): the numerical and algorithmic constraints born from the use of numerical tools, and the smoothing of yield shocks introduced through aggregation. Thus, we focus on 14 regions throughout the analysis while disaggregating each of these regions to the various AEZs. Fig. 4 shows the locations of the various regions.

The analysis below focuses on two alternatives, which aim to capture short-run and long-run scenarios. While the short-run captures the years two to five post regional nuclear war, the long-run is modeling the effect of the regional nuclear war beyond half a decade (i.e., five year after the nuclear war). For the short-run, we assume inelastic parameters that limit the farmer's ability to adapt, while for the long-run we assume the farmer has more flexibility to adapt to the climatic changes brought by the nuclear war. In all runs, we assume one alternative set of elasticity parameters at a time. Even though the interpretation of short-run and long-run are ad-hoc, we feel they capture the agricultural sector ability to adapt over time to the changes brought upon the industry through a regional nuclear war. While short-run encompass more reactive adjustments (e.g., adjusting planting season), the long-run is a more intentional and planned adaptation response that results in significant shifts of management practices (e.g., changing crops planted).

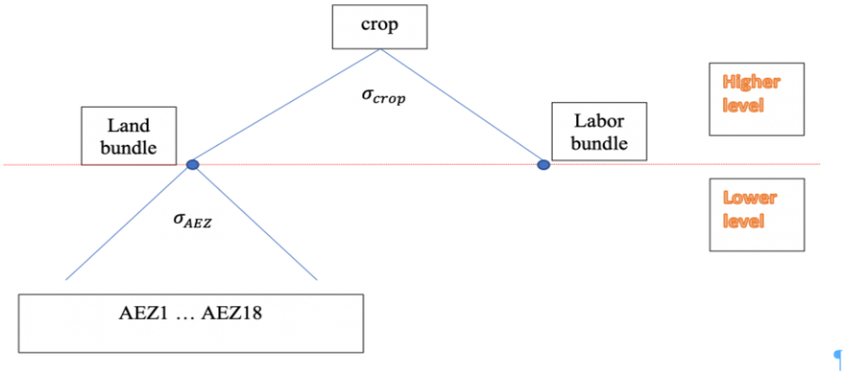
The calculations below do not account for the physical devastation created by the nuclear war.

4.2 Quantifying the economic effects of a nuclear war: Envisage-NW

Now, we are ready to employ the Envisage-NW model, and calculate the economic impacts of a regional nuclear war between India and Pakistan that injects 5 Tg of black carbon into the stratosphere.

4.2.1 Nuclear war shocks and their effects on food supplies: global versus regional

The Envisage-NW is defined using annual time steps. It is limited in its ability to predict immediate to short-run outcomes of war and cannot be used to understand the implications of a nuclear war on global food supply and food security in the months following the conflict. The outcomes from the war start after existing crops are harvested and new ones are planted. Within the first year the production of staple crops has little if any room to adapt to the changing climate – even though shocks in some regions exceed -50% (Jägermeyr et al., 2020), thus leading to significant ramifications to regional supply chains. We assume that not much adaptation is possible during the first year following the war, and thus use the Envisage-NW model to only analyze the second year post nuclear war and onward. The production process modeled via the Envisage-NW introduces mathematical expressions that link physical units of inputs with those of output. It describes the boundary or frontier representing the limit of output obtainable from the feasible combination of inputs. Introducing a more comprehensive approach to modeling of the shocks, while explicitly describing the effect of the shock on land productivity, suggests that under the Envisage-NW, less



Note: σ_{AEZ} denotes the lower-level CES of the various AEZs and σ_{crop} denotes the higher-level CES of the production nest, which combines labor and land.

Figure 3. The land bundle (i.e., the land input aggregated across all AEZs) and the CES of land.

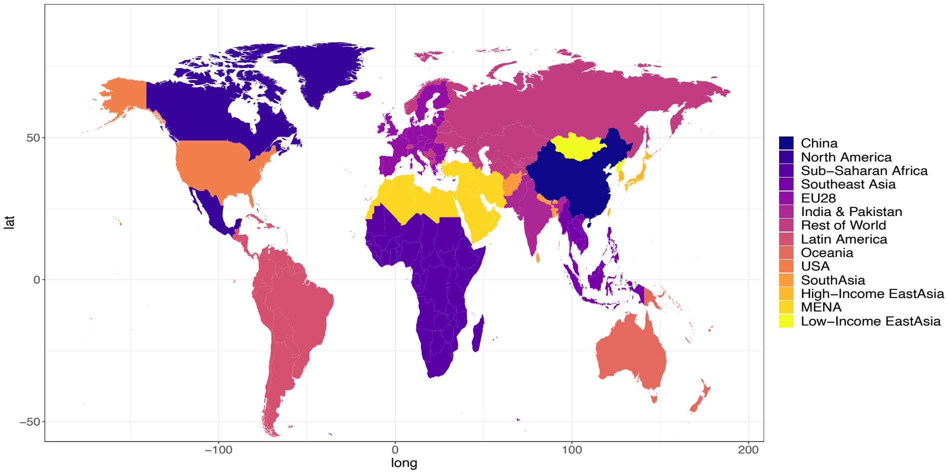


Figure 4. Map of the 14 regions.

than 20% of the yield shocks passes through the production process and affects output (Figure 5b). Changes in land productivity result in profit-maximizing farmers changing their production decisions and the allocation of resources that support that production. To that end, estimates in the literature suggest that the cost of land in crop production is only 16% of total cost globally (Hertel & de Lima, 2020). Thus, when yield shocks affect output only through land productivity, the production process implies that farmers can shift inputs among production activities and reduce the effect of the initial shock on output. However, because the ability of farmers to shift among inputs improves with time, we distinguish between the nuclear war's effects during the first five years and those that persist over longer time-periods.

We summarize in Table 4 key facets of the various models. In contrast to partial equilibrium models, which focus only on one section of the economy, the Envisage-NW looks at the entire economy and takes into account the interactions among the economy's different segments. An analysis under the Envisage-NW can therefore shed light on the wider economic impact of regional nuclear war and reveal its indirect or unintended effects. In addition, and unlike the input-output models that focus only on the demand side and assume no capacity constraints, the Envisage-NW incorporates both the demand side and the supply side, and hence allows for price movements. These price movements however simplify reality because these changes in prices lead profit-maximizing farmers to switch among crops and reallocate resources among alternative production activities, instantaneously and at no additional cost. In addition, seeds, knowledge, and any management or infrastructure needed to support changes in production are available with no time delays. Thus, to restrict farmers ability to switch among crops and reallocate resources among alternatives, the Envisage-NW is used to assess impacts only from the second year following the nuclear war and onward. In addition, the Envisage-NW distinguishes between short- and long-run. The Envisage-NW assumes that farmers ability to respond to the climatic changes brought by the regional nuclear war during the first five years are limited, when compared to farmers ability to respond over longer time periods.

On the other hand, gridded crop models are a formal way to present quantitative knowledge about how crops grow in interaction with surface biophysical parameters. The crop models are mathematical algorithms that capture quantitative information and use this information to explain and predict crop growth and development. However, the crop models are mute with respect to the farmer's ability to adapt to the new realm of altered agronomical and physiological parameters.

Table 5. Technological change and production factors across models

Model	**Key assumptions**	**Sectoral differences**	**Regions**	**Shock directly impacts**
Global Gridded Crop Model Inter-comparison Project (GGCMI) (Table 1)	1) Crop yield is an outcome of mechanistic process representation affected by climatic variables, the availability of water and nitrogen, soil properties, management, etc. 2) The various crop models differ with respect to the assumptions and use of the representation and parameterization of processes 3) Crop yield is calculated per crop, with no interactions across crops; 4) Mathematical algorithms quantify the above information and calculate the projected crop yield; 5) Calculations are done at 0.5° x 0.5° grid cells, globally.	Corn, rice, soybeans, spring wheat, winter wheat	Global	Yield
CLM5.0	Same as for GGCMI	Corn, rice, soybeans, spring wheat, sugarcane, and cotton	Global	Yield
SM-PE	1) For each country, a supply and demand curves for both corn and soybeans are assumed; 2) Does not explicitly model the resources needed to produce the crop, although it is implied by the curve modeling the cost of production; 3) **No cross-price effects**; 4) The yield shock calculated by the crop model is used to revise output productivity and shift the supply curve.	Corn or soybeans	Brazil, China, India, USA	Production
MM-PE	1) Per crop/country supply and demand curves are assumed; 2) Does not explicitly model the resources needed to produce the crop, although it is implied by the curve modeling the cost of production; 3) **Cross-price effects**; 4) The yield shock calculated by the crop model is used to revise output productivity and shift the supply curve.		Brazil, China, India, USA	Production

Table 5. Technological change and production factors across models

Model	**Key assumptions**	**Sectoral differences**	**Regions**	**Shock directly impacts**
Envisage-NW	1) Population, labor force growth, and investment targets are specified; 2) Capital dynamics rely on motion equations that equate current capital stock to sum of last period's depreciated stock of capital and current period investment; 3) Exogenous productivity factors (e.g., technology) affect sectors (e.g., crop yield), final demand, international trade and transport. 4) Land productivity factor is AEZ dependent. This parameter is modified through the yield shock generated by the various crop model scenarios. 5) Under each scenario, yield shocks modify land productivity, and the model solves for a new equilibrium through adjustments of the crops grown in the region, the resources a region allocates to those crops, and international trade.	See Table 3	Global	Land[8]

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[8] In the Envisage-NW model, total land in each region is capped and remains constant through the analysis.

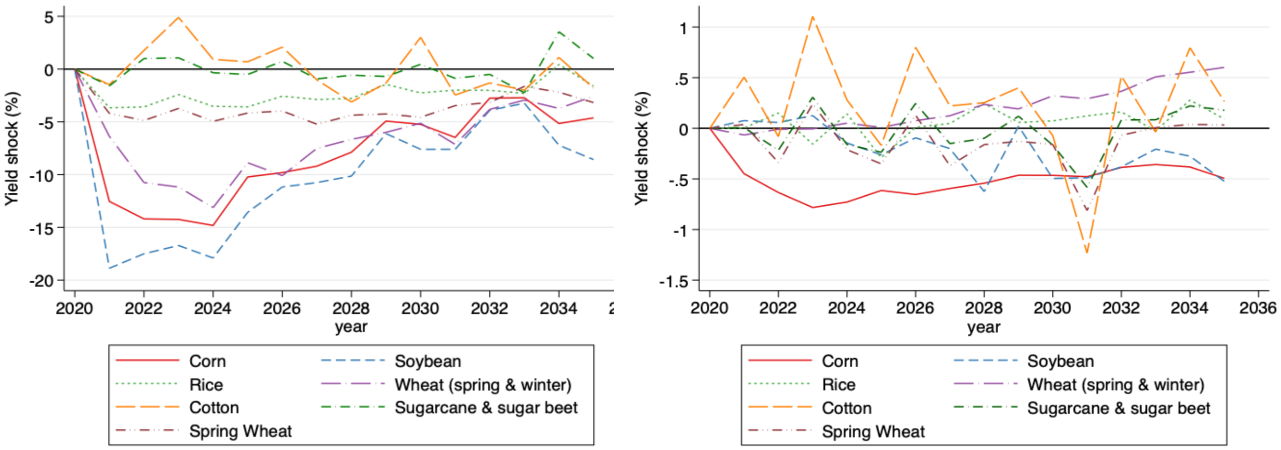
Therefore, in what follows, crop models and the Envisage-NW will be used to define the upper and lower bound on production caused by a 5 Tg regional nuclear war between India and Pakistan. The rigidity of the crop models, especially with respect to farmers' ability to respond to the drastic change to biophysical parameters, makes crop models more reliable predictors for the effect of the regional war during the first few years after the nuclear war. On the other hand, the Envisage-NW outcomes are likely a better predictor for the effect caused by a nuclear war over the longer horizon. The Envisage-NW model projects that production shifts because of changes in output prices (output substitution), inputs are redirected to alternative production chains because of changes in input prices (input substitution), and international trade. The Envisage-NW framework models changes to prices caused by the regional nuclear war between India and Pakistan. These price changes incentivize farmers and consumers to adapt to the new realm and modify the effect on food supply and thus regional food shortages.

Starting by comparing the outcome of the crop models for the three main crops, corn, rice, and soybeans, we show that the gridded crop models project that crops in high latitude regions are substantially impacted by the regional nuclear war, while those native to tropical regions marginally benefit from the cooling of the Earth. However, when introducing the Envisage-NW model, the effects of the land productivity shocks shrink drastically.

Markets adjust to the effects of the regional nuclear war, resulting in the yield shocks projected by the gridded crop model decreasing significantly because of the adjustments to crop prices. The gridded crop models' projections for year 1 post nuclear war suggest that the nuclear war results in a decline in global corn (-13%), rice (-4%), and soybean (-19%) production. However, when we allow farmers to adapt to the climatic changes caused by the nuclear war, the effects on production are significantly modified. The results also suggest significant substitution away from other agricultural activities. The Envisage-NW short-run scenario projects global corn production drops by 1% during the years following the nuclear event (e.g., 2022-2025). The substitution away from other agricultural activities and reemphasis on corn, soybean, and rice production, is caused by the increase in the relative price of these commodities relative to other agriculture activities that were not negatively impacted by the simulated climatic changes. Practically, however, the substitution implied by the short-run analysis might be too large, because the shocks projected by the crop model were very substantial and it is not likely they will get completely absorbed within the first few years following the nuclear war.

The economic analysis using the Envisage-NW model suggests that changes in prices result in the global agricultural system shifting resources toward crops most impacted by large negative land productivity shocks. To this end, the land shocks generated by the crop models resulted in prices of the crops negatively impacted by the nuclear war to spike. The spike in the relative price of the crops leads farmers to shift resources toward the production of those crops. These resources, however, needed to come from other activities. For example, while focusing on the short-run economic scenario, we observe vegetables and fruits contracting more than corn, even though crop models did not shock vegetable and fruits and when simulating the various scenarios, we did not modify vegetables and fruits land productivity parameters. After the regional nuclear war between India and Pakistan, production in the United States shifted away from vegetables and fruits while allocating more resources to corn and soybeans. During year two to year five after the nuclear war, the decline in vegetable and fruit production is larger than that predicted for corn. Farmers respond to the change in prices and shift resources so as to maximize their individual profits.

Another example where markets adjust to the effects of the regional nuclear war, resulting in the yield shocks projected by the gridded crop model decreasing substantially through the adjustment of crop prices is cotton and sugarcane, which were analyzed in the CLM5.0 crop model, but not the other six models. The CLM 5.0 gridded crop model's projections for year 1 post nuclear war suggest



(a) Crop model average

(b) Envisage-NW: Data until 2025 is from the short run scenario while data for 2026 to 2035 is from the long-run scenario

Figure 5. A 5 Tg nuclear war between India and Pakistan and its effect on global agricultural production

that the nuclear war results in an increase in global cotton (+5.8%) and sugarcane/beet (+3.1%) production. However, the nuclear war negatively impacts corn (-12.9%) and soybeans (-14.7%). CLM 5.0 also predicts a decrease in rice production (-5.6%), while spring wheat increases (+3.7%). However, when we allow farmers to adapt to the climatic changes caused by the nuclear war, the effects on production are significantly modified. The results suggest significant substitution away from cotton and sugarcane production. Under the short-run scenario (where limited adaptation is assumed), cotton production under the CLM5.0 scenario drops by -3.5% in 2022 and by -0.21% in 2025. The short-run scenario projects global cotton production drops, which is in stark contrast to the CLM 5.0 gridded crop model's projection of an 8.4% increase in cotton production. The Envisage-NW projects this drop in cotton production continues through 2031, with cotton production dropping by -1.2% in 2031. The substitution away from cotton is caused by the drop in the relative price of cotton than corn and soybean. However, these global impacts mask great heterogeneity among regions, as will be discussed below.

The shock in corn prices in 2007-2008 resulted in food crop prices spiking during the months following the shock, the staple crop industry adjusted accordingly, and food crop prices returned to their long-run averages within a few years (Hochman et al., 2018). Although the analysis predicts similar patterns after a nuclear war, a nuclear war shock is likely to have a more significant and immediate impact on agriculture supply chains that will last for more than a few years. Even when we introduce the ability to adapt to the climatic changes, some of the regional supply chains contracted significantly under some scenarios, while under other scenarios we could not reject the hypothesis that the global food system collapses following a small regional nuclear war (see Online Supplementary SA5).

In the following paragraphs we identify limitations of the global community's ability to adapt and thus highlight regions where famine and food insecurity will prevail over time. The global averages mask heterogeneous outcomes with some regions being much more severely impacted than others. Similar to projections of the crop model, the largest negative variation in production is observed in high latitude regions, which include Russia and North Korea, Canada, and Europe. While soybean production in North America (i.e., Canada)[9] drops by almost 20% annually from 2021 to 2025, corn production drops by about 10% annually, from 2022 to 2024. Conversely, positive shocks are observed in other areas that are closer to the equator, e.g., Brazil.

The regional nuclear war jeopardized regional supply of food from producers to consumers much more than it did the global supply of food. The regional nuclear war results in a likely outcome where some regional food supply chains collapse while others do not (to this end, the crop models suggest yield shocks of -70% and even -100% in some areas). To illustrate the impact of a regional war on regional food supply, two regions were considered as an example: the US and Europe. Starting with the CLM 5.0 crop model, the nuclear war between India and Pakistan moderately affects the United States, where the largest impact on yield is observed in 2025 (similar outcomes are depicted under the alternative crop models – supplementary material SA6). US production drops by less than 10% under all scenarios and both years (2022 and 2025), other than cotton in 2025 where US cotton production drops by about -14%. Europe, on the other hand, faces significant and negative drop in production by 2025. European crop production plummets. Under the short-run scenario spring wheat production in Europe declines by more than 20% in 2025, and during the same year soybean production drops by almost 20%.

How does production in regions located in high latitude areas respond to the regional nuclear war between India and Pakistan? Figure 6 (and the online supplementary SA3) suggest the following: The GEPIC crop model results in large impacts on winter wheat and this results in major impacts to regions located in high latitude area such as Canada and Mexico (North America region excluding the United States) Russia (ROW), and Europe (EU28). The economic imbalance introduced through these scenarios yields major challenges to the economic model, as was discussed above (Figs. 5a and 5b). Figure 6 depicts the production changes implied by the various climate scenarios/crop models for Russia (ROW), where the online supplementary SA3 depicts the production changes for Europe (EU28), and Canada (North America), while focusing on corn, rice, and soybeans. These changes in land productivity also affected total production through the allocation of land among the various activities.

4.2.2 Nuclear war effects on food supplies through input substitution

Changes in output and input prices cause production to shift and land allocation to change (input substitution). Large regional land productivity shocks to key commodities result in major disruptions. Returning to the CLM 5.0, we find that land substitutes away from cotton and into corn and spring wheat (Fig. 7). To better understand how changes in land use impact crop production, we plot the results of the analysis in Figure 7, which plots the outcomes for 2025. In each map, the ratio of land used in production of crop i in region r (henceforth, $l_{i,r}$) is calculated under the nuclear war scenario (denoted with superscript NW) divided by amount of land used under the business-as-usual scenario (denoted with superscript BAU); i.e., ${l_{i,r}}^{\mathrm{NW}}/{l_{i,r}}^{\mathrm{BAU}}$. The short-run economic scenario results in output prices of corn and spring wheat increase substantially, which results in significantly more land allocated to these crops because the return to land used to grow these crops is now higher. The short-run scenario yields larger productivity shocks and more significant price spikes. The increase in prices results in an increase in the value of the marginal productivity of land, leading to land use change in the long-run (where adaptation to the climatic outcome caused by the nuclear war is more likely) and to the allocation of land to food crop production. In the long run, the regional nuclear war scenario yields land converted away from cotton and other agricultural

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[9] Because separating between Mexico and Canada did not affect the results in any substantial way, for simplicity, we decided to combine the two countries into one region, North America.

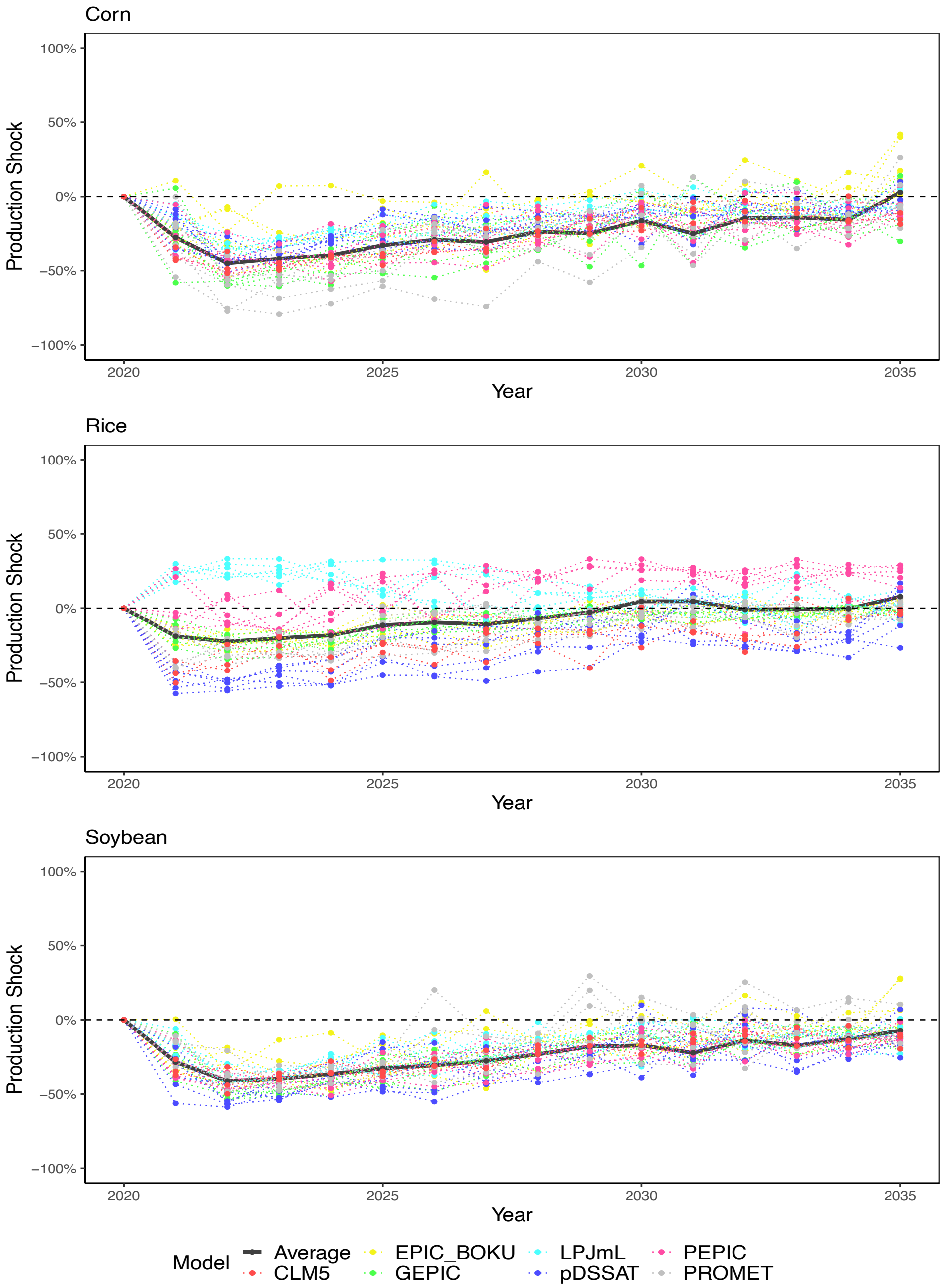


Figure 6. The land productivity shocks introduced to the Envisage-NW model: Rest of the World (Russia)

activities and into key food crops like corn and soybeans (Fig. 10). Because the regional nuclear war negatively impacted land productivity while demand expands over time with population growth, new land needs to be allocated to the production of the crops most impacted by the nuclear war. The regional nuclear war between India and Pakistan resulted in major food insecurity, especially in the short run, with the most significant impacts observed in high latitude regions.

While focusing on the long-run scenario and calculating the amount of land moved into production of the crops impacted by the nuclear war: In 2025, the 5 Tg soot results in 17.6 million

Table 6. Percent of Land Change Allocated to Production of Six Crops in Long-run Scenario.

Year	Corn	Soybean	Rice	Wheat	Spring Wheat	Cotton	Sugar
2021	-13%	-19%	-4%	-6%	-4%	-1%	-2%
	(6.8%)	(6.4%)	(7.8%)	(9.5%)	(1.6%)	(2.2%)	(3.4%)
2022	-15%	-18%	-4%	-11%	-5%	2%	1%
	(6.7%)	(6.7%)	(5.8%)	(9.3%)	(2.8%)	(3.8%)	(5.3%)
2023	-15%	-17%	-3%	-11%	-4%	5%	1%
	(6.2%)	(6.3%)	(6.2%)	(9.2%)	(0.9%)	(0.3%)	(2.3%)
2024	-15%	-19%	-4%	-13%	-5%	1%	0%
	(6.2%)	(7.1%)	(6.1%)	(8.7%)	(1.6%)	(5.0%)	(4.9%)
2025	-11%	-14%	-4%	-9%	-4%	1%	-1%
	(4.5%)	(3.5%)	(5.4%)	(7.9%)	(1.2%)	(2.8%)	(3.1%)

Note: (i) The corn, soybean, and rice yield shocks are averaged over the seven crop models.
(ii) Wheat is average over the six crop models, other than CLM5.0.
(iii) And spring wheat, cotton, and sugarcane are averaged only over the CLM5.0 crop model.
(iv) Note also that the standard deviations are in parenthesis.
(v) In the online supplementary SA6 we depict land changes for all 15 years, i.e., 2021 to 2035.

ha of land use change moving into production of the six crops globally (Table 6). While the most substantial increases in land use are observed for corn and spring wheat, land allocated to both cotton and sugarcane/beet remains stable overtime with only marginal decreases or increases documented globally through the years. In the years to follow the nuclear war, major land shifts to and between agriculture activities is observed. Similar patterns were observed following the spike in food prices caused by corn-ethanol in 2008: the spike in corn prices because of corn-ethanol resulted in a short-run spike in food prices in the months following the shock (Hochman et al., 2018; Carter et al., 2012). Although the Renewable Fuel Standards diverted resources of land away from food and feed, these changes were mostly short run changes that dissipated over time as discussed in the literature on the food commodity spike of 2007/2008 (McPhail and Babcock 2008).

4.2.3 Nuclear war effects and international trade

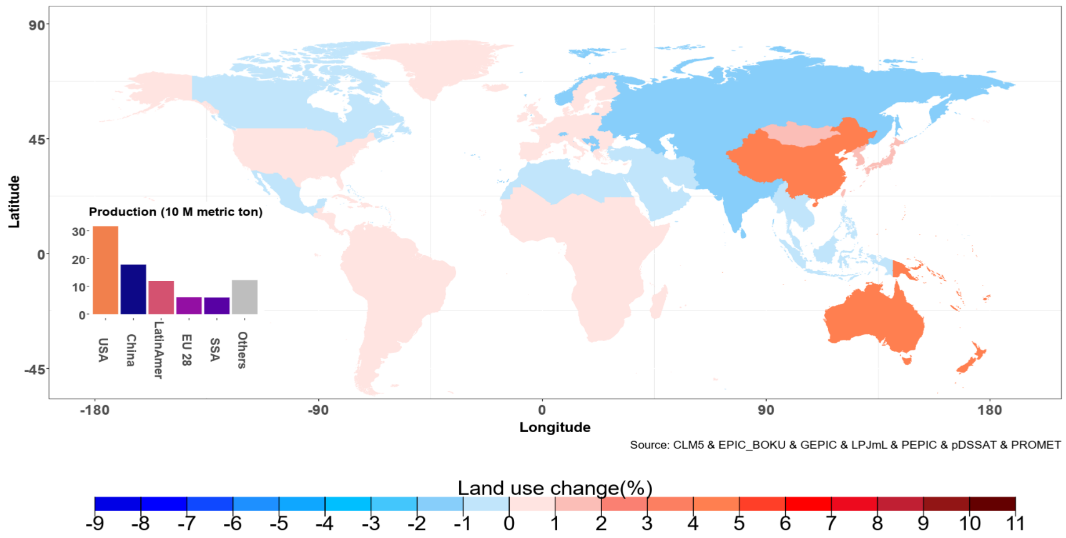
The third channel through which global markets adapt to the changes in land productivity is through international trade. We assume that there is no hoarding and trade proceeds as before the war to maximize profit. The exchange of goods and services among countries plays a vital role in reducing the negative effect of nuclear war on global agriculture supply systems. Through international trade, countries exploit the heterogeneity of the shocks among countries and reduce the negative effect of the nuclear war on agriculture.

With the introduction of changes in land productivity, aggregate trade expands. Under the short-run scenario, for example, trade expands between 2021 and 2025 under CLM 5.0 by 6.5%, globally. The nuclear war has variegated production impacts across regions. Because of difference impacts across regions, international trade reduces the damage to the global supply chain and reduces fluctuations in food consumption.

To show the effects of international trade we assume that the sampling unit is a scenario (climate scenario/gridded crop model/economic scenario) but we do not observe all the trading partners' characteristics. However, assuming the unobservable characteristics are time invariant results in a panel data defined over the trading partners. Then, through the outcomes of the various scenarios we illustrate the effect of the global and regional changes in land productivity on bilateral trade flows (i.e., trade flow of a specific commodity between two trading partners).

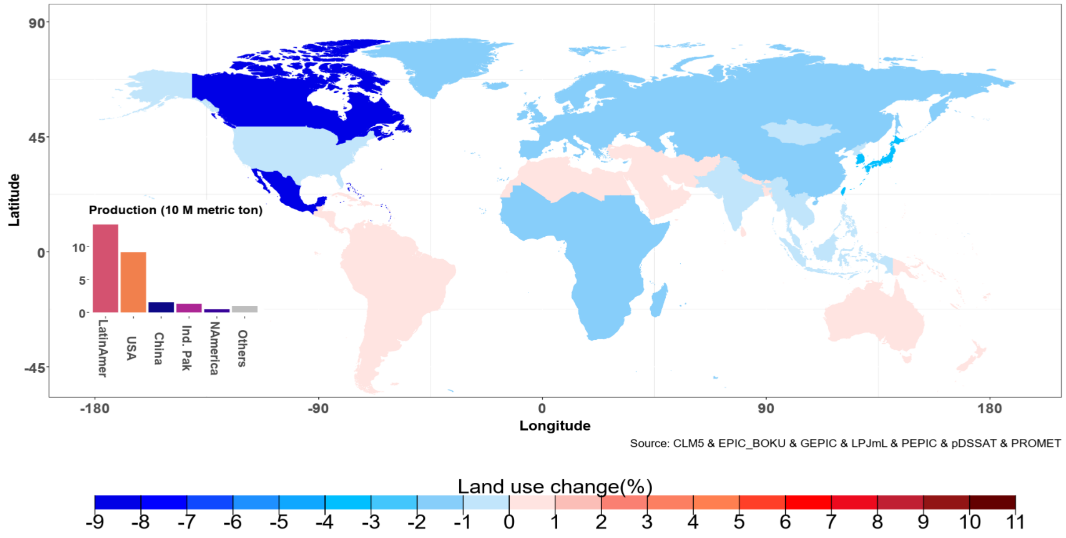
Technically, we start with Gourieroux et al. (1984), who extended the realm of application of

(a) Corn



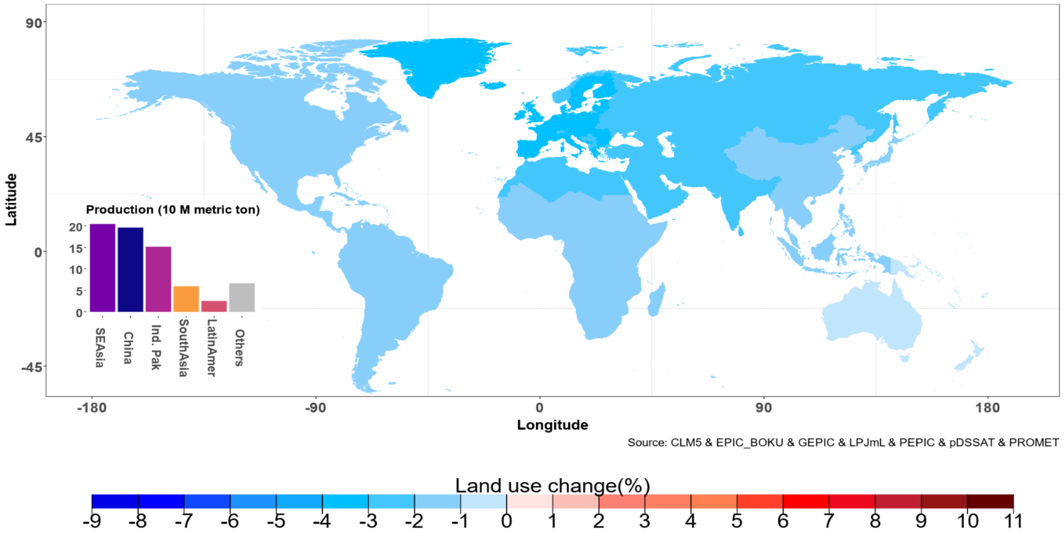
Source: CLM5 & EPIC_BOKU & GEPIC & LPJmL & PEPIC & pDSSAT & PROMET

(b) Soybeans



Source: CLM5 & EPIC_BOKU & GEPIC & LPJmL & PEPIC & pDSSAT & PROMET

(c) Rice



Source: CLM5 & EPIC_BOKU & GEPIC & LPJmL & PEPIC & pDSSAT & PROMET

Note: (i) Note that colors reflect plausible changes to the land used to grow the crops within each of the regions, but that these colors do not imply that a crop is grown throughout the region.
(ii) In online supplementary SA4 we depict the other 4 crops: Wheat (spring and winter), only spring wheat, cotton, and sugarcane/sugar beet.

Figure 7. Changes in land used for production compared to the business-as-usual in 2025 under the short-run scenario.

Poisson regression. That is, we employ the Poisson Pseudo Maximum Likelihood (PPML) methodology, where estimation process identifies and drops regressors that may lead to nonexistence, thus reducing significantly the run-time. The methodology is used to estimate the model depicted in Eq. (2) below, where superscript r denotes regional impacts, while g denotes global impacts; and where subscript s denotes the exporting (source) country and d denotes the importing (destination) country, with t denoting year and c denoting crop; finally, subscript l denotes the land productivity shock taken from the crop models and subscript e denotes the output shocks calculated using the economic model.

Now, let $\beta = (1, \beta_{r,l}, \beta_{g,l}, \beta_{r,e}, \beta_{g,e})$, $\mathbf{x_{s,d,t,c}} = \left(1, x^{r,l}_{s,d,t,c}, x^{g,l}_{s,d,t,c}, x^{r,e}_{s,d,t,c}, x^{g,e}_{s,d,t,c}\right)'$, and let $\mathbf{y_{s,d,t,c}}$ denote the volume of bilateral trade between the export county s and the import country d at time t for crop c. The data are multi-dimensional involving measures over time, with multiple observations for importer-exporter pairs of each of the seven crops investigated by the crop models. The data reflect variation observed among the exporter, importer, and crops. The use of panel data, i.e., longitudinal data where subsets of observations are of the same subjects each time (e.g., same exporter, importer, and crop each time), enables us to exploit these variations and explore the importance of the land productivity and its impact on crop production and thus food insecurity. Using these tools, we estimated Eq. (2) with the categorical variables as fixed effects (representing the subject-specific means that assist in controlling for omitted variable bias due to unobserved heterogeneity that is assume constant over time) in our analysis, i.e., exporter-by-importer ($\alpha_{s,d}$), exporter-by-crop ($\alpha_{s,c}$), and importer-by-crop ($\alpha_{d,c}$) fixed effects.

$$\mathbf{y_{s,d,t,c}} = \exp^{\left(\alpha_{s,d}+\alpha_{s,c}+\alpha_{d,c}+\beta\cdot\mathbf{x_{s,d,t,c}}\right)} \tag{2}$$

Because the application is no longer restricted to count data, PPML can be applied to any dependent variable with nonnegative values without having to explicitly specify a distribution for the dependent variable. Moreover, unlike the log-linear model, PPML regression provides a natural way to deal with zero values on the dependent variable and the literature shows it is "the ideal" estimator for the gravity equation (Correia, et al. 2019 & 2020; Carter & Steinbach, 2020).[10] Thus, we utilize the PPML algorithm to estimate the factors affecting bilateral trade flows (BTF) and to better understand the effect of regional and global change in land productivity on these flows. Technically, bilateral trade flows are the PPML regression's dependent variable, where an observation is defined through origin of BTF, destination of BTF, time and crop. The independent variables in our regression are the regional and global land shocks, as well as the regional and global production shocks. We also assume country of origin, country of destination, and crop fixed effects, and the interactions thereof. That is, our exponential regression model includes exporter-importer, exporter-crop, and importer-crop fixed effects.

The coefficients of interest are then identified by exploiting variation among changes in land productivity over time and space. The outcome of the PPML runs (Table 7) suggests a larger regional negative impact on land productivity results in volume of bilateral trade shrinking, while larger negative global land productivity shock results in an increase in the volume of bilateral trade. The regression is used to identify the following key factors affecting volume of bilateral trade:

1. When the world food system is negatively affected, regions increase trade
2. However, if the negative ramifications of the nuclear war strain the local food system then the region absorbs its exports and reallocates exports for domestic consumption.

A larger negative average global change in land productivity, ceteris paribus, suggests world prices increase and thus the incentive to sell abroad is higher. However, if the change in land productivity affects the region, ceteris paribus, then domestic prices increase and there is a stronger incentive to sell locally.

Although we did not exogenously assume hoarding and that regions limit trade to protect their domestic food systems, our analysis suggests this behavior is endogenous to the analysis and is the outcome of the economic behavior modeled through the Envisage-NW model – a model that assumes producers maximize profits, consumers maximize utility from consumption, and international trade follows the Armington specification which posits that demand for goods is differentiated by region of origin (van der Mensbrugghe, 2018).

In the online supplementary (SA7) we compare scenarios where trade collapses in some regions, but not others and show how trade collapses in all regions, with India and Pakistan's trading partners hurt the most. Because India and Pakistan are directly impacted by the nuclear war, where nuclear radiation as well as other factors contaminate its goods and affect its trade with the rest of the world, we assume trade collapses between the India and Pakistan region and the rest of the world. Specifically, an iceberg trade cost of transporting a good, which equals three-fourths of the good itself rather than other resources, is assumed while focusing on the short-run scenario. This

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[10] Gravity models are used to predict and describe trade flows that mimic gravitational interaction as described in Isaac Newton's law of gravity.

Table 7. Bilateral volume of trade (among the various countries and their trading partners) and the implications from changes to land productivity.

Variables	PPML Model I	PPML Model II
Regional land productivity shock	0.19***	0.19***
	(0.05)	(0.05)
Global average of land productivity shock	-2.33***	-2.35***
	(0.11)	(0.11)
Regional output shock	1.64***	1.87***
	(0.10)	(0.12)
Global output shock		-4.39***
		(0.71)
Wald chi2(4)	945.48	999.35
pseudo R2	0.7186	0.7191
Observations	1,164,000	1,164,000

Note: (i) $***$ denotes $p < 0.01$; Robust standard errors in parentheses.
(ii) For simplicity of exposition, the fixed effect parameters are omitted from the table.

assumption is an analogy to an iceberg floating costless except for the part that melts. The iceberg assumption is due to Samuelson (Samuelson, 1954). See also *Deardorff's Glossary of International Economics*.[11]

5 Implications and policy discussion

A nuclear war between India and Pakistan will lead to climatic changes with major disruptions to regional food supply chains (from farm to fork). However, the magnitude of this disruption depends on farmers' and producers' ability to adapt to the changes. Throughout the analysis, we assume that the substitutability both within and between production processes captures this ability to adapt. Initially, we model substitutability through own-price elasticities, that is, through the sensitivity of the quantity demanded or supplied to a 1% increase in own-price (section III). When no substitution is possible, we use the crop models to capture the negative ramifications of a nuclear war between India and Pakistan. The crop models predict that, on average, global corn production drops by 13% while global soybean production collapses by almost 20% one year after the war (Table 2 – see also Fig. 5a). The global food supply collapses with significant ramifications for nutritional intake. When introducing the partial equilibrium models (both SM-PE and MM-PE), the nuclear war results in the United States calorie intake dropping by 21% in 2021 (Fig. 2b). In the US, the average calorie intake of grains in 2000 amounted to 596 daily calories per person, and it declined to 581 by 2010 (2.5% per capita decline in the caloric intake of grains). In contrast, a 21% decline caused by the simulated nuclear war implies that the daily calorie intake of grains in the US drops to 459. It is also interesting to note that introducing limited output substitution via the SM-PE and MM-PE analysis results in the crop production outcome being similar to that implied by the crop models, suggesting devastating effects on the global food supply during the

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[11] The glossary is available at http://www-personal.umich.edu/~alandear/glossary/

first few years following the regional nuclear war.

How will economic responses change when greater substitutability is introduced into the analysis? To this end, we assume that farmers' and food processors' have greater ability to modify the effects of a regional nuclear war on the supply of food while using a CGE model, namely, the Envisage-NW (section IV). In addition, because over time farmers and food processors can better adapt to the climatic changes brought by the nuclear war, we assume less substitutability in the short run than in the long run. Specifically, we introduce two sets of parameters into the Envisage-NW model:

a. The short run which captures years 2 to 5 following a nuclear war, and

b. The long run which models the effect of a potential regional nuclear war after the initial five years.

Introducing different levels of adaptation helps us better understand the differences over time, as well as the paths the world may take following a regional nuclear war. Naturally, when more substitutability between and within production is introduced, economic behavior yields more adaptation to the climatic shocks and thus significantly reduces the effect of the nuclear war on the global food supply. Global food insecurity is less of a concern if the world can adapt to the significant climatic changes brought about by regional nuclear war. Fig. 5 illustrates this point.

When transitioning from the partial equilibrium to the general equilibrium analysis, not only did we assume greater substitutability, but we also assumed that the climatic shock affects land productivity, which then affects agricultural output. This is in contrast to the partial equilibrium analysis whereby the shock directly affects output. The mechanism through which the regional nuclear war alters the climate and thus food production is explicitly introduced into the CGE modeling. We believe this is key when trying to understand the greater substitutability the Envisage-NW introduces into the analysis. Furthermore, assuming that the crop models' yield shock affects only land productivity may underestimate the true negative effects of the regional nuclear war and detract from other ramifications brought by the nuclear war to the supply and productivity of labor, as well the war's implications for capital flows.

However, even though greater substitutability was introduced into the analysis via the Envisage-NW, some regions still experienced severe impacts and food insecurity following the regional nuclear war; while these regions are not necessarily located close to the war, those most impacted by the war can be located on the other side of the globe. Even though the global ramifications of the war are adsorbed within a few years, ceteris paribus, the effect on high-latitude regions remains extreme for several years after the nuclear war. The magnitude for land productivity for high-latitude regions whose agricultural sectors are extensively hit by the regional war (e.g., Russia, EU 28, and Canada), and the severity of its impact does not diminish when the Envisage-NW model is introduced. For example, five years after the assumed nuclear war between India and Pakistan, both spring wheat and soybean production in the EU-28 drop by about 20% under the CLM5 scenario! See supplementary material SA3, where Russia (ROW) and Canada (North America) are plotted. The nuclear war not only affects the food supply in those regions, but it also destabilizes these economies, with the effects likely to persist for at least half a decade if not longer.

The magnitude of the effects varies across countries, with negative and significant ramifications to some countries, but not to others. The heterogeneity among regions suggests that some regions are much more affected than others, leading to a significant decline in crop production in those regions, which is accompanied by a substantial drop in income in the sectors most impacted by the cooling of the Earth. To support this argument, first, the larger the regional shock, the less likely the Envisage-NW model will support the exogenous population and technological growth assumed under the CGE model (Table 5). Second, the cost to some of the regions being negatively impacted by the nuclear war (e.g., Canada, Europe, and Russia) is large and results in the collapse of their agricultural sectors. Famine is more likely in those regions, and the effect on the poor will be substantially more impactful in these high-latitude regions where daily caloric intake will decline on average by more than 500 calories a day (which is equivalent to running 40 minutes a day while not changing one's diet). For example, while using the crop model with the most extreme case, the short-run economic scenario projects, on average, an accumulated decline in corn production in North America (excluding the US) of -41.5% from 2021 to 2025. Another example is for the Rest of the World, where wheat production is dominated by Russia. In that region, the accumulated decline over a period of five years indicates that wheat production drops, on average, by -44%. Even more alarming is that the worst-case scenario results in wheat yield dropping by -94% following a nuclear war!

However, what are the implications from such variability across countries? What does this heterogeneity suggest to countries located in high-latitude regions? We hypothesize that the Envisage-NW model, and its outcome, suggests that the regional impacts may result in a plausible domino effect with substantial negative ramifications for regional food supplies. We hypothesize that the effect on agricultural production in high-yield regions may result in a chain reaction with negative ramifications to the regional food supply in regions far afield from India and Pakistan. First, some of the countries located in regions most impacted by the nuclear war have a high Fragile States Index (FSI). The FSI measures country vulnerability to conflict or collapse and is based on the following 12 indicators: Security Apparatus; Factionalized Elites; Group Grievance; Economic Decline and Property; Uneven Economic Development; Human Flight and Brain Drain; State Legitimacy; Public Services; Human Rights and Rule of Law; Demographic Pressures; Refugees and Internally Displaced Persons; and External Intervention. Fragility and vulnerability lead to the collapse of nations or to nations resorting to conflict. To this end, many countries with a high FSI index also experience large negative productivity shocks. In Fig. 8, we plot countries facing a negative shock that is lower than -20% (greater than 20% in absolute value) and show that some of the countries hit with large negative shocks also have relatively high FSI; the nuclear war may cause hardship and famine in those countries and this may trigger more unrest in the region. This unrest may significantly amplify and exacerbate the initial effect of the regional nuclear war; the nuclear war may lead to a domino effect with additional conflicts following the original regional war, and such a domino effect may substantially increase the original effect of the nuclear war on food insecurity and famine. Instability in countries with a high FSI has led to armed conflicts in the past. Armed conflicts negatively impact food security and result in ongoing insurgence around food security (Adelaja et al., 2018). For example, the conflict in Nigeria and the Boko Haram insurgency resulted in households facing more limited food varieties in lower portions than otherwise, which led to consumption of less preferred food in smaller amounts (George et al., 2019). Conflict reduces output and productivity and substantially influences agricultural wages and hired labor. The impacts of conflict in Nigeria were augmented by labor shortages, low wages, low income, and less economic opportunity (Adelaja & George, 2019). It is highly likely that a nuclear war would only lead to repeating these patterns with higher intensity since the original hardship is more extreme.

How did the regional nuclear war through the Envisage-NW model bring us to famine and food insecurity that led to further conflict? What brought us to a point where a regional conflict led to a global collapse and massive food insecurity, as well as demand for massive adaptation and modification of existing production technologies and processes? The analysis suggests three channels through which economic behavior responds to the regional nuclear war: production switching where changes in crop prices result in farmers swapping crops with lower profit margins for those with higher margins, input switching whereby the demand for land shifts from production activities with

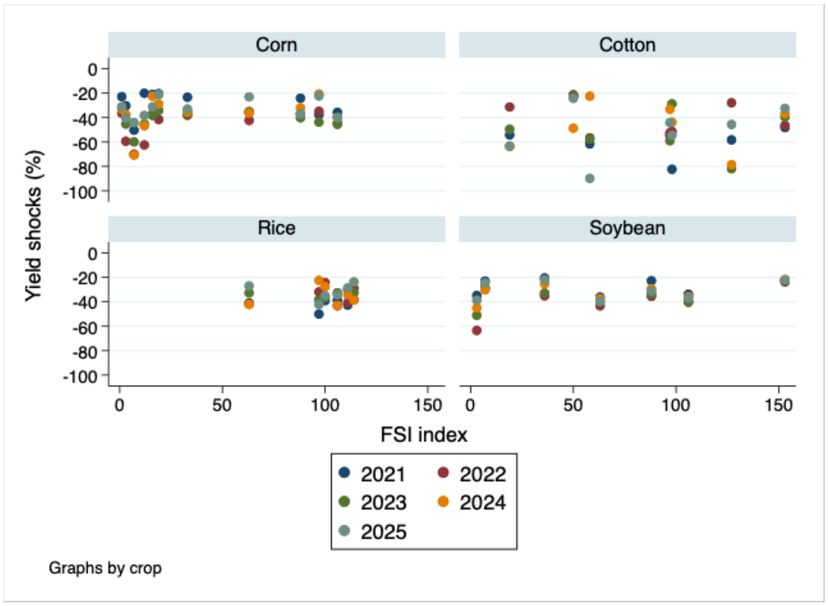

Figure 8. Yield shocks and FSI by crop

lower economic value to those with higher value, and trade which smooths consumption. Output and land prices yield a shift in allocation of land and crop production. One example is the land productivity shock to cotton and how economic behavior responded to the positive shock to cotton (recall that cotton production under the crop model increased by 5% and more, yet under the Envisage-NW model it basically went down or remained constant). Another example is the very large negative land productivity shock to corn and soybeans, which was substantially reduced under the Envisage-NW model (Fig. 5). The change in relative prices results in the spatial distribution of production changing and in the use of input being modified to maximize profits – changing land use as well as the allocation of labor and capital among production alternatives.

The third channel is international trade. Through the statistical analysis (Table 7), as well as the ad hoc example (Fig. 5), we illustrate the importance of the world trading system. If international trade is allowed to buffer local food scarcity and hoarding behavior is not introduced, consumers and farmers substitute one food for another in subsequent years based on changing crop productivity and the market price of their crops, and food scarcity is reduced. The statistical analysis shows that, ceteris paribus, the bigger the negative global land productivity shock, the larger the volume of bilateral trade. However, economic behavior is biased toward hoarding and placing of a higher weight on domestic products. To this end, a large negative regional land productivity shock yields less bilateral trade, ceteris paribus (Table 7). This is because of the Armington specification, which posits that demand for goods is differentiated by region of origin with more weight placed on domestic markets. The Armington specification results in regions reducing export volumes because of domestic shortages, suggesting that regions relying on imports of food will be severely impacted by a regional war of 5 Tg of soot between India and Pakistan (Table 7). Furthermore, these outcomes also depend on assumptions about how freely trade would continue in a post-war economic environment. Our assumptions suggest that regions will bias their response, placing more weight on the domestic economy. Barriers to trade, for example, with India and Pakistan because radiation contaminated the produced goods can severely impact those countries' trading partners as well as the countries themselves.

The findings strongly indicate the need for policies aimed at prevention of conflicts, especially those that may lead to regional nuclear wars. The literature suggests that the post-conflict environment becomes less favorable than otherwise might be expected. Additionally, despite reconstruction and redevelopment in a particular region following a conflict, there may be an add-on effect of substantially more famine and food insecurity in other regions where such problems were already endemic. From a policy standpoint, the short-run food crisis created through the regional nuclear war emphasizes the importance of a proactive inventory-management policy and the need for mechanisms that mitigate the spike in prices (Hochman et al., 2014). Regions without any safety nets will face serious negative ramifications and food insecurity. In addition, investment in outreach and infrastructure that improves the management of food supply distribution and enhances productivity can also go a long way toward alleviating a global food crisis. The analysis also suggests that preserving the world trading system is key to preventing widespread famine and suffering – a thriving world trading system minimizes the costs arising from disruptions to the climate because of nuclear war.

6 Concluding remarks

Economic models aiming to inform the agricultural and development policy debate require analysis of both the economic behavior and biophysical drivers. The key outcomes of the analysis are that (a) policy lessons derived from a crop model can be significantly nuanced when coupled with economic feedbacks derived from economic models; (b) aggregation of countries into regions may significantly mask the negative impact of the nuclear war on the global food system; (c) sensitivity of consumption and production to prices matters; (d) the world trading system is important for countries' abilities to respond to the climatic change from the regional nuclear war; and (e) vulnerability of high latitude regions to the cooling of the planet may yield a domino effect that significantly amplifies the post nuclear-war ramifications documented in this paper.

With regard to policy and the implications of a small regional nuclear war, this work highlights the importance of adaptation and institutionalizing mechanisms that smooth the transition of food supply chains that are severely impacted from a potential regional nuclear war between India and Pakistan and the resulting injection of 5 Tg of soot into the stratosphere. Our results show that nuclear war can significantly disrupt regional supply chains, especially in high latitude areas, and this is a comparatively greater disturbance than that found in the global food supply chain. Climate connects regions globally and a regional nuclear war disrupts the climate in significant ways with far reaching implications to the supply of food. While this paper examines the impacts fo 5 Tg of soot injected into the upper atmosphere after a regional nuclear war, newer analysis (Toon et al., 2019) suggests that much larger injections, and therefore much larger impacts on the global food supply are possible, even for a war between India and Pakistan. A US-Russia nuclear war can produce nuclear winter, with essentially no food production for years and global famine. This suggests the strong need for policies aimed at prevention of conflicts.

On the more technical side of CGE modeling, 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. We also argue that distribution matters and the clustering matters and that aggregation should be minimized and used to filter out small transactions while maintaining data consistency and important economic totals.

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