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To cite this article: Gal Hochman *et al* 2022 *Environ. Res. Lett.* **17** 054003

IOP Publishing Environ. Res. Lett. 17 (2022) 054003 https://doi.org/10.1088/1748-9326/ac61c7

ENVIRONMENTAL RESEARCH
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OPEN ACCESS

RECEIVED
22 July 2021

REVISED
23 March 2022

ACCEPTED FOR PUBLICATION
28 March 2022

PUBLISHED
19 April 2022

LETTER

Economic incentives modify agricultural impacts of nuclear war

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Keywords: climate models, crop models, computable general equilibrium model, Envisage, partial equilibrium, nuclear war, nuclear winter

Supplementary material for this article is available online

Abstract

A nuclear war using less than 1% of the current global nuclear arsenal, which would inject 5 Tg of soot into the stratosphere, could produce climate change unprecedented in recorded human history and significant impacts on agricultural productivity and the economy. 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 food availability would change by employing the Environmental Impact and Sustainability Applied General Equilibrium model. Under a robust world trading system, global food availability would drop by a few percentage points. If the war would destabilize trade, it would magnify by several times the negative ramifications of land productivity shocks on food availability. If exporting countries redirect production to domestic consumption at the expense of importing countries, it would lead to the destabilization of international trade. The analysis suggests that economic models aiming to inform policymakers require both economic behavior analysis and biophysical drivers. Policy lessons derived from a crop model can be significantly nuanced when coupled with economic feedback derived from economic models. Through the impact on yield, farmers could shift production among crops and reallocate land use to maximize profits, showing the importance of general equilibrium effects such as product and input substitution and international trade. Although the global impact on corn and soybean production would be significant when just considering crop production, it could be considerably smaller under the economic model. However, this would be at the expense of other sectors, including livestock. In addition, the costs borne from disruptions to climate would vary significantly across regions, with significant adverse effects in high latitude regions. The severity of the shocks in the high-latitude areas would marginalize the farmers' product and input substitution ability.

1. Introduction

Natural and anthropogenic aerosols in the stratosphere can profoundly impact agriculture and world food trade through their effects on climate, and ultimately may produce famine. While significant 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 a scenario that produced 5 Tg of stratospheric soot could lead to reductions in agricultural production of maize, wheat, rice, and soybean by 13 (±1) %, 11 (±8) %, 3 (±5) %, and 17 (±2) % over five years (Jägermeyr *et al* 2020). However, changes in agricultural productivity would likely be modified by economic activity, including adaptation by farmers and trade, affecting the ultimate availability of food and the possibility of regional famine.

While focusing on the 5 Tg scenario studied extensively in the literature (Robock *et al* 2007a, Toon *et al* 2007a, Stenke *et al* 2013, Mills *et al* 2014), the results here serve as an example to potentially much larger injections and impacts—e.g. a nuclear war between the U.S. and Russia that leads to a nuclear winter, with virtually all agriculture shut down and global famine (Robock *et al* 2007b, Coupe *et al* 2019). However, it is important to analyze the impacts of smaller injections, to understand how catastrophic local nuclear war could be.

As far as we know, this work is the first to use computable general economic (CGE) models to show the impacts of a nuclear war on food availability and food insecurity, both within and between regions. Through the CGE we detail the potential economic responses to the food production shock and highlight the importance of modeling the economy in its entirety. We use a CGE model, the Environmental Impact and Sustainability Applied General Equilibrium (Envisage) model (van der Mensbrugghe 2018). In the Envisage model, crop producers adjust management by switching to different crops according to crop productivity, available prices of resources, goods and services, and international trade. To this end, the farmer uses technology to convert the crop planted into a commodity it sells to generate a profit. The conversion of the inputs into output is through technology, which is captured by the yield the farmer can produce per acre and by the behavioral parameters assumed (which are the standard ones used by the Envisage model) and the factors of production (e.g. land and labor). The nuclear shock affects the farmer's ability to produce the crop since it alters the biophysical parameters, which impacts the inputs quality.

In CGE analyses, explicit factors used for production (e.g. capital, labor, and land) become important. Because the climatic change affects surface biophysical parameters relevant to agriculture production, we translate the simulated shocks to the crop models' yield, which project the effect of the nuclear war on biophysical parameters, to the Envisage model through significant changes to land productivity.

We describe our approach to modeling the nuclear war in section 2. We discuss the main results in section 3, and highlight policy implications in section 4. Section 5 offers concluding remarks.

2. The economic impact of a nuclear war: Envisage model

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

2.1. Climate and crop models

We used the Community Earth System Model, described in supplemental section S1 (available online at stacks.iop.org/ERL/17/054003/mmedia), to simulate a nuclear war between India and Pakistan. The two countries detonate 50 atomic weapons, each the size of the nuclear weapon used on Hiroshima (i.e. 15 kt) to attack cities in the other country. This nuclear war yields a 5 Tg black carbon injection into the upper troposphere and stratosphere (Toon *et al* 2007b). It produces global climatic change that alters the biophysical and biochemical parameters (Robock *et al* 2007b). The modified biophysical and biochemical parameters are the inputs of the gridded crop models.

In the Envisage model, we use crop productivity responses to climate perturbations from seven individual global gridded crop models (Robock *et al* 2007b, Mills *et al* 2014, Toon *et al* 2019), described in supplemental S2. Simulations from six of the crop models are from the AgMIP's Global Gridded Crop Model Intercomparison Project (GGCMI) (Jägermeyr *et al* 2020). The seventh model is the Community Land Model version 5.0 (CLM5.0) (Lombardozzi *et al* 2020). While the models participating in GGCMI simulated rice, corn, soybean, and wheat (spring and winter wheat separately), CLM5.0 simulated rice, corn, and soybean and spring wheat (no winter wheat), cotton, and sugarcane[5]. See tables S1, S2 and figure S1 for a list of the models, and their simulation results.

2.2. The Envisage model

We model the economic changes computed below using the Envisage model (van der Mensbrugghe 2018), a model 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 15 aggregate sectors, of which nine sectors belong to the Food & Feed sectors and the other six sectors do not (table 1). A nested structure of constant elasticity of substitution (CES) production functions represents this production structure (Hertel 1997, van der Mensbrugghe 2018), defined in the supplement section S3. The nested CES production function uses a land bundle as an input in the production of a crop. The production function nests lower level CES functions used to calculate the land bundles. The higher level CES functions, then calculate crop outputs (figure S2).

[5] Systematic comparison across models helps reduce the uncertainty inherent to an analysis assessing future impacts of climatic changes on agriculture productivity (Wiebe *et al* 2015, Van Meijl *et al* 2018).

Table 1. Economy sectors in the envisage model.

Food and feed sectors (9 total)	Other sectors (6 total)
Rice	Mining and extraction
Wheat	Light manufacturing
Corn	Heavy manufacturing
Oilseeds (henceforth, soybean)	Utility and construction
Sugarcane and sugar beet (henceforth, sugarcane)	Transport and communication
Fruit and vegetables	Other services
Plant-based fiber (henceforth, cotton)	
Processed food	
Livestock	

The climate models simulate the effects of the nuclear war on yield for each of the 2° × 2° grid cells. Then, after downscaling, the crop models simulate the impact of the nuclear war under 1° × 1° for CLM5.0 and 0.5° × 0.5° for the other six models. The crop models simulate the impact of the nuclear war on corn, rice, soybeans, sugarcane, wheat [spring/winter], and cotton while leaving other crops unchanged. We then aggregate the output of the crop models to the Food and Agricultural Organization (FAO) Agro-Ecological Zones (AEZ) (known as the Global Agro-Ecological Zones, GAEZ)[6] at the country level. We use the term 'land productivity shocks' to describe crop productivity changes per unit area while holding all prices constant. This land productivity serves as input to the Envisage model. The productivity shocks to the seven crops are aggregated to the country level using a mapping from one-degree by one-degree grid cells to the various countries. Now, we have one yield shock per crop per country. Next, we translate the yield shock to a percentage shock, which we then multiply by the AEZ specific productivity parameter. Then, the crop production function nests lower level CES functions used to calculate the land bundles. The higher level CES functions, then calculate crop outputs. We start with biophysical parameters that spatially disaggregate land within a region when calculating land bundles. We employ GAEZ data and calculate the land share of each type of AEZ in each region (Baldos 2017). Total land supply in each AEZ is fixed and crops, pasture and forestry compete for land use subject to a single-nested transformation frontier with an assumed finite elasticity. We assume land of one type of AEZ is an imperfect substitute to other AEZs. We assume a farmer can plant a crop on different AEZs. However, yield per acre varies across AEZs with some AEZs exhibiting significantly higher yield per acre than others (see also supplementary S3).

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 the government collects revenues via taxes. To simplify the analysis, we fix total government expenditure as a share of nominal gross domestic product. Throughout, the allocation of government expenditures follows the same relative distribution as that of the base year 2011.

We use the GTAP V9 with the base year 2011. Because of the numerical and algorithmic limitations of the solver, it is necessary to aggregate the data. The aggregation needs to balance between two effects (Britz and van der Mensbrugghe 2016), the numerical and algorithmic constraints borne from 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 (figure 1).

The Envisage Model is defined using annual time steps, and we cannot use it to understand the implications of a nuclear war on global food supply and food security in the months following the conflict. 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. Because not much adaptation is possible during the first year following the war, we use the Envisage model to analyze the second-year post-nuclear war and onward. Thus, we focus 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 years after the nuclear war). We assume inelastic parameters that limit the farmer's ability to adapt for the short run. In contrast, in 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's ability to adapt over time to the changes brought upon the industry through a regional nuclear war. While the short-run encompasses 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). However, the calculations below do not account for the physical devastation created by the nuclear war.

[6] 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.

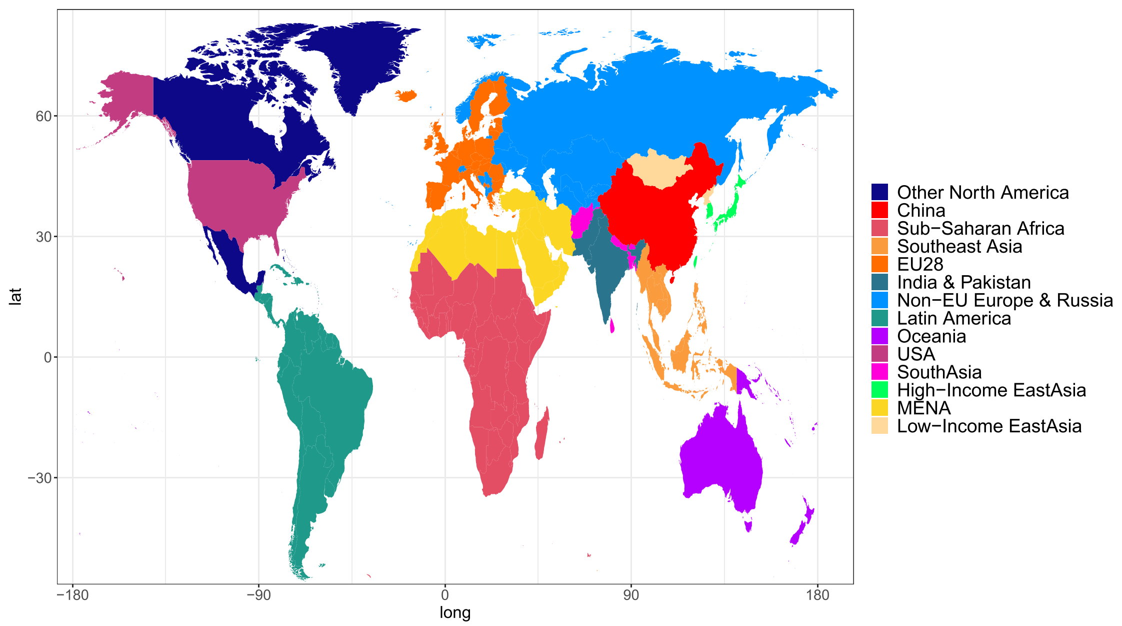


Figure 1. Map of the 14 regions.

Another point worth emphasizing, albeit more technical, is that the production process modeled via Envisage 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, less than 20% of the yield shocks passes through the production process and affects output. 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 and de Lima 2020). 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 (see also S4 of the supplementary and table S2).

2.3. Modeling the nuclear war shocks

The production process modeled via the Envisage introduces mathematical expressions that link physical units of input with those of output. It describes the boundary or frontier representing the limit of the product obtainable from the possible combination of inputs.

In contrast to partial equilibrium models (supplement section S4), which focus only on one section of the economy, the Envisage looks at the entire economy and considers the interactions among the economy's different segments. Thus, an analysis under the Envisage can shed light on the broader economic impact of regional nuclear war and reveal its indirect or unintended effects. Besides, unlike the input-output models that focus only on the demand side and assume no capacity constraints, the Envisage incorporates both the demand and supply sides, allowing for price movements. However, these price movements 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. Also, seeds, knowledge, and any management or infrastructure needed to support changes in production are available with no time delays.

Gridded crop models are a way to represent process-based knowledge about crop growth and phenological development in interaction with surface biophysical parameters. However, the set of crop models simulations used here do not take into account the farmer's ability to adapt to the perturbed climate (e.g. shifting planting dates or different varieties) or altered agronomical conditions (e.g. switching to different crops).

Therefore, in what follows, crop models and the Envisage will define the lower and upper bounds of plausible production change scenarios with respect to potential farming system adaptation. The Envisage model projects that production shifts because of changes in output prices (output substitution), inputs prices which redirect inputs to alternative production chains (input substitution), and international trade[7]. The Envisage framework models the change in 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 food supply and regional food shortages.

When simulating the crop model results, the nuclear war is assumed to start in 2020, where the post-event outcomes are for 2021 through 2035. Throughout the analysis, we focused on a single narrative for the future, namely Shared Socioeconomic Pathway 2 (O'Neill *et al* 2017). These assumptions assume modest population and income growth rates and a slow rate of trade liberalization. It is considered a middle-of-the-road scenario.

3. Quantifying the economic effects of a nuclear war: Envisage

As input for the Envisage model, we use crop model outputs from Jägermeyr *et al* (2020) for six crop models (table S3) and output from the CLM 5.0 (table S3). The major crop productivity plotted in figures S3 and 2 give an example for one region.

The main text compares the outcome of the crop models for the three main crops, corn, rice, and soybeans; the gridded crop models project that the regional nuclear war substantially impacts crops in high latitude regions. In contrast, those native to the tropical areas marginally benefit from the cooling of the Earth.

However, when introducing the Envisage model, the effects of the land productivity shocks shrink drastically (figure S5). 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 two post-nuclear war (i.e. 2022) suggest that the nuclear war results in a decline in global corn (−15%), rice (−4%), and soybean (−18%) productivity (table S3). However, when we allow farmers to adapt to the climatic changes caused by the nuclear war, the effects on output are significantly modified. The results also suggest significant substitution away from other agricultural activities. The Envisage short-run scenario (figure S5) 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 emphasis on corn, soybean, and rice production, is caused by the increase in the price of these commodities relative to other agriculture activities not negatively impacted by the simulated climatic changes.

The Envisage model's economic analysis suggests that changes in prices result in the global agricultural system shifting resources toward crops most impacted by large adverse land productivity shocks. To this end, the land shocks generated by the crop models results in price spikes of the crops negatively affected by the nuclear war. The spike in the relative price of the crops leads farmers to shift resources toward the production of those crops. These resources, however, need to come from other activities. For example, while focusing on the short-run economic scenario, we observe that the shock to livestock is 44% more than corn, even though the crop models do not shock livestock. When simulating the various scenarios, we do not modify livestock productivity parameters. Farmers respond to the change in prices and shift resources to maximize their profits. Another example, while focusing on the short-run economic scenario, we observe vegetables and fruits contracting more than corn, even though the crop models do not shock vegetables and fruits when simulating the various runs.

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, analyzed in the CLM5.0 crop model, but not the other six models. The CLM5.0 gridded crop model's projections for year two post-nuclear war (i.e. 2022) suggest that the nuclear war increases global cotton (+2%) and sugarcane (+1%) productivity. However, under the short-run economic scenario (where we assume limited adaptation), cotton productivity 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 productivity. The Envisage projects this drop in cotton production continues through 2031, with cotton production dropping by −1.2% in 2031. The decline in the relative price of cotton, relative to corn and soybean, leads to output substitution away from cotton. When farmers can freely adapt to the climatic changes caused by the nuclear war, the effects on production are significantly modified.

Practically, however, the substitution implied by the short-run economic analysis might be too large. The reason is that the shocks projected by the crop model were very substantial, and it is not likely they will get absorbed entirely within the first few years following the nuclear war. When looking at the last

[7] Recently, scholars began researching alternatives to the CES specification. One such alternative is the multinomial logit that preserves physical additivity: Under the multinomial logit, the sum of goods over sources equals total volume (e.g. Zhao *et al* 2021). However, the analysis in Zhao *et al* 2021) suggests that the multinomial logit and the Armington specification yield similar production outcomes when using the same elasticities. A conclusion we confirm when running the modified form of the constant-elasticity-of-transformation (CET) preference function under the Envisage model (Dixit and Rimmer 2006).

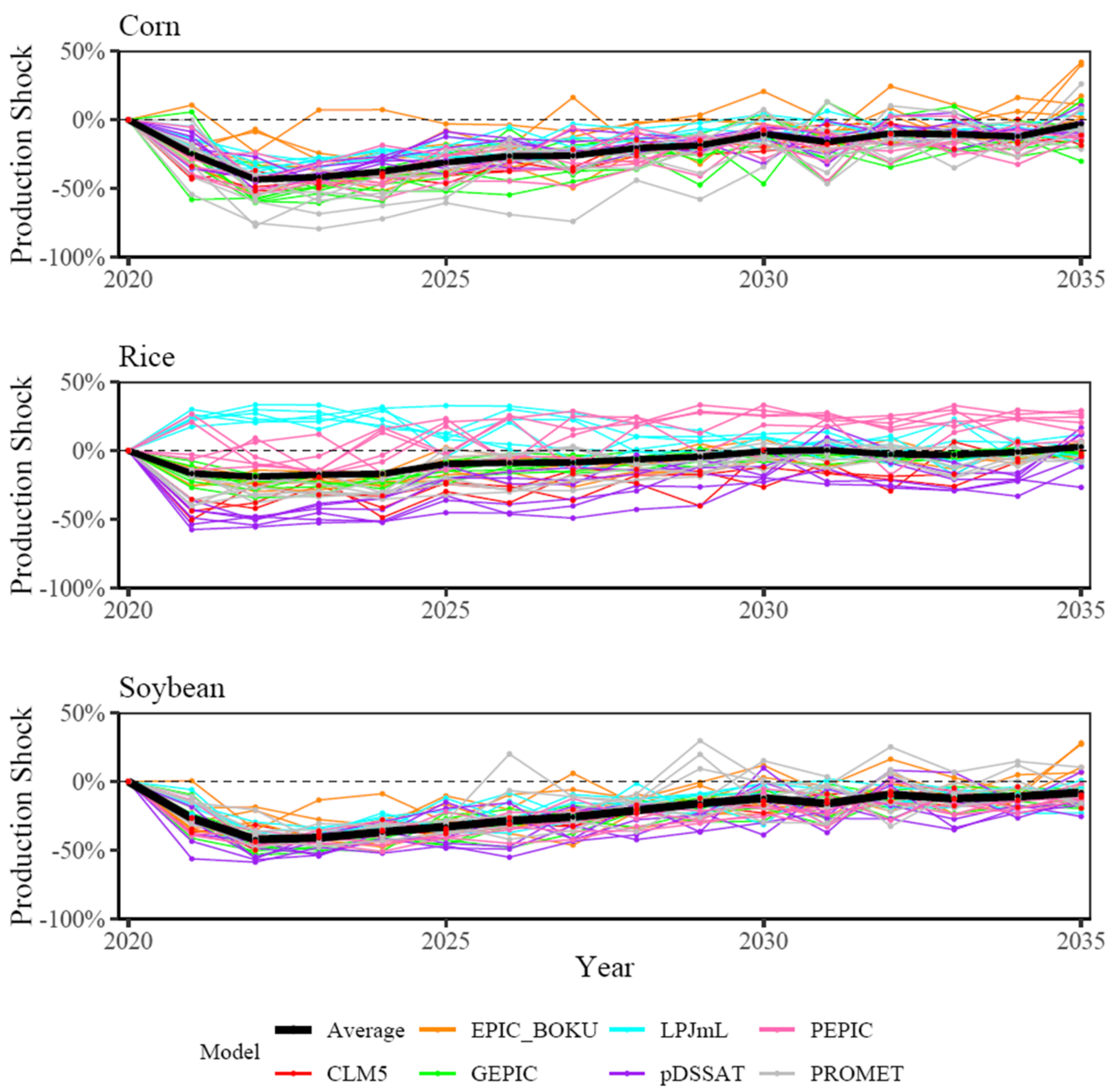


Figure 2. An example of the land productivity shocks introduced to the Envisage model. This is for the region non-EU European countries and Russia (see figure 1). The rest are in figure S3. The models are described in table S1. See also supplementary material S2 and figure S3, where it suggests that the GEPIC crop model results in significant impacts on winter wheat. This impact results in substantial effects on regions located in high latitude areas.

several decades, we do identify a few major events that stimulated a major shock to the global food supply.

One such event is the shock to staple crop in 2007–2008. That shock resulted from rising oil prices, significant hikes in global demand for staple crops, and increased biofuel production by ushering policies and mandates. The spike in the prices of staple crops created a global crisis that caused political and economic instability and social unrest in both poor and developed nations. The implications to crops were a spike in their prices during the months following the shock. The staple crop industry adjusted accordingly, only to have food crop prices returning to their long-run averages within a few years (Hochman and Zilberman 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 climatic changes, some regional supply chains contract significantly under some scenarios. Under other unsuccessful paths, the model drifts toward its boundaries with supply chains approaching zero, yet the model does not solve (see supplement section S5). In the real world, this may lead to changes in behavior or the collapse of the global food system.

The global averages mask heterogeneous outcomes, with some regions much more severely impacted than others. Like projections of the crop model, high latitude regions exhibit the most significant negative variation in production, including Russia and North Korea, Canada, and Europe. While soybean production in Other North America (i.e. the North America region while excluding the United

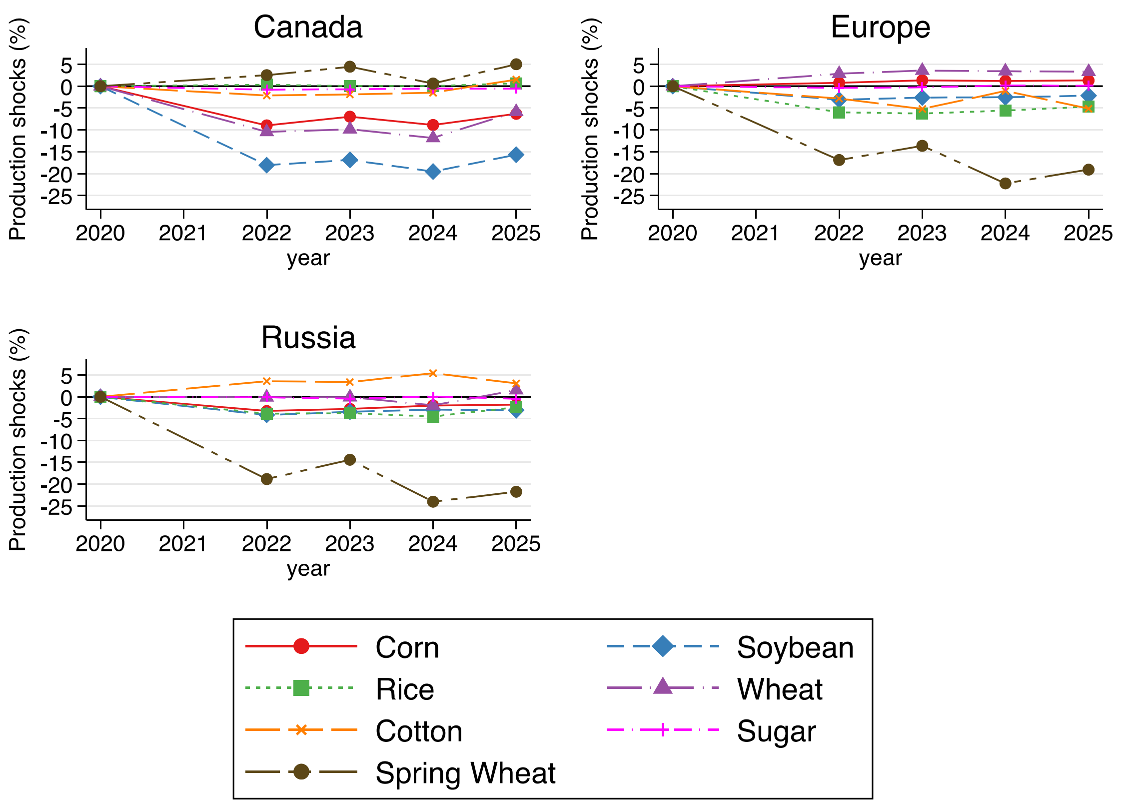


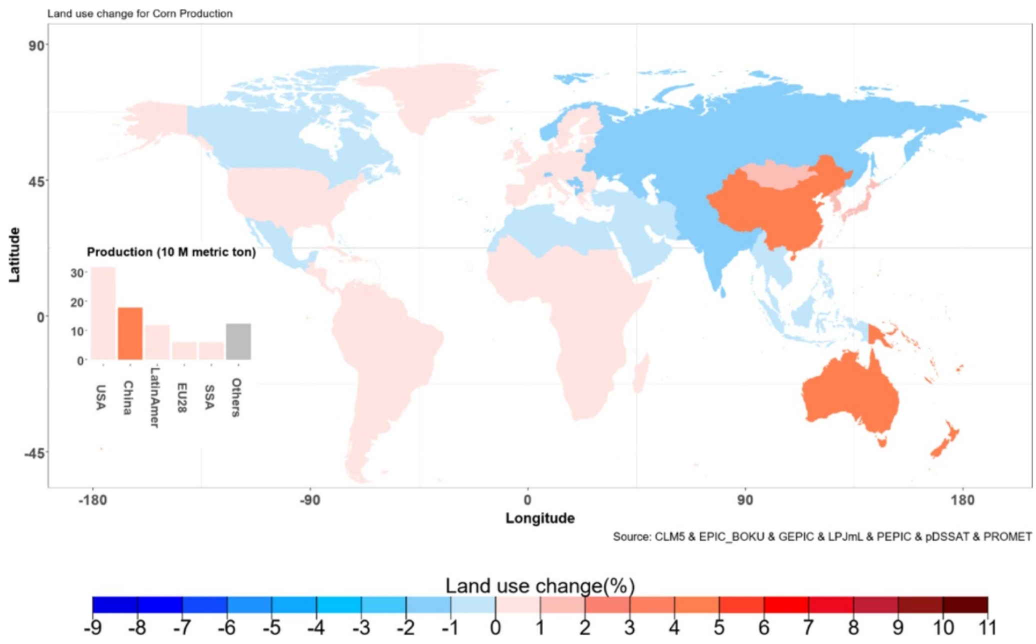
Figure 3. Three examples of the effect of the land productivity shocks on countries located in high latitude regions, from the Envisage CGE model. The focus is on other North America, Europe, and non-EU European countries and Russia.

States)[8] drops by almost 20% annually from 2022 to 2025, corn production drops by about 10% annually, from 2022 to 2025 (figure 3(a)). 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, we focus on the US and Europe as examples. Starting with the CLM 5.0 crop model, the nuclear war between India and Pakistan moderately affects the United States. We observe the most significant yield decline in 2025 (the alternative crop models depict similar outcomes). US production drops by less than 10% under all scenarios in 2022 and 2025. One exception is in 2025, where US cotton production declines by about −14%. Europe, on the other hand, faces a 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% (figure 3(b)).

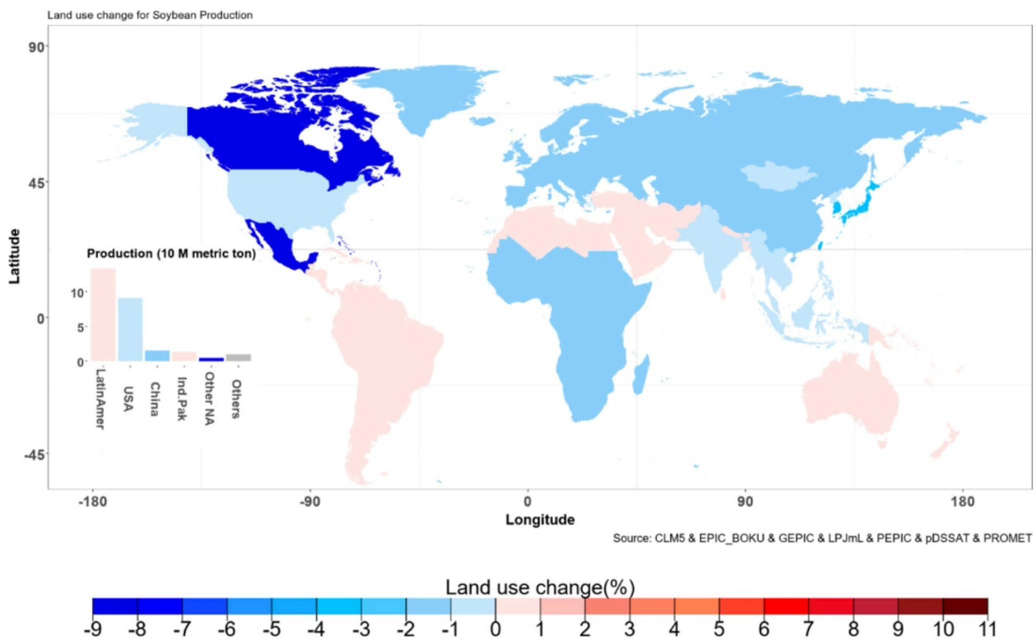
The variation across countries borne from the above heterogeneity is illustrated when solving the partial equilibrium analysis (section S4 in the supplementary). The partial equilibrium framework uses the Envisage-NW parameters to model the crop markets of interest, using corn and soybeans as examples and introducing supply and demand curves for each crop. The heterogeneity results in large variations across crops within a country and for the same crop across countries. Starting with a 5 Tg nuclear war between India and Pakistan, figure S3 depicts the change in quantity in three key countries: the United States, China, and Brazil. The figure shows the outcome of the simulation given the parameters used in the Envisage-NW analysis.

Our partial-equilibrium analysis suggests a significant 10%–12% reduction in caloric intake. For example, when starting with the average 2000 and 2500 calories consumed by women and men, respectively, daily, a reduction of 500 calories a day (25% and 20% for women and men, respectively) results in these individuals losing half a kilogram (1 pound) a week. These rough calculations suggest that the effect of a regional nuclear war can significantly impact food security and cause the average daily calories per person to contract significantly. This concern is amplified several folds when we consider stunting in many developing world countries (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’

[8] 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, Other North America.



(a) Corn



(b) Soybeans

Figure 4. Changes in land used for production compared to the business-as-usual in 2025 under the short-run scenario. Colors reflect plausible changes to the land used to grow the crops within each of the regions, but these colors do not imply that a crop is grown throughout the region. Actual production is shown in the insets. In figure S5, we depict the other four crops: wheat (spring and winter), only spring wheat, cotton, and sugarcane. In each map, we calculate the ratio of land used in the production of crop i in region r (henceforth, $l_{i,r}$), where land under the nuclear war scenario (denoted with superscript NW) divided by the amount of land used under the business-as-usual scenario (marked with superscript BAU); i.e. $l_{i,r}^{NW}/l_{i,r}^{BAU}$.

(World Health Organization—viewed: February 15, 2020)), and famine is already prevalent.

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. 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. Returning to the CLM 5.0, we find land substitutes away from cotton and into corn

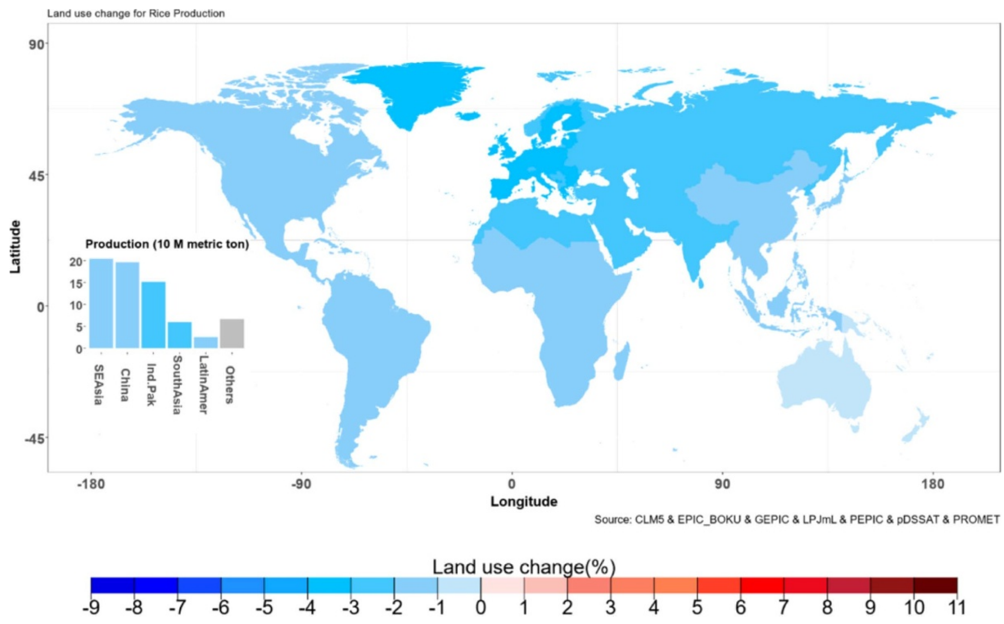


Figure 4. (Continued.)

and spring wheat. To better understand how changes in land impact crop production, we plot the analysis results in figure 4, which plots the outcomes for 2025 (see figure S5). These maps depict the change in food production in the various regions five years after a nuclear war. 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.

If we focus on the long-run scenario and calculate the amount of land moved into the production of the crops impacted by the nuclear war, in 2025, the 5 Tg soot results in 17.6 million ha of land moving into the production of the six crops, globally (table S14). While we observe the most substantial increases in land use for corn and spring wheat, land allocated to both cotton and sugarcane remains stable over time with only marginal decreases or increases documented globally through the years. The literature documents similar patterns following the spike in food prices caused by corn-ethanol in 2008, e.g. the spike in corn prices because of corn-ethanol resulted in a short-run spike in food prices in the months following the shock (McPhail and Babcock 2008, Carter *et al* 2012, Hochman and Zilberman 2018).

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 impact of the nuclear war on agriculture. For example, under the short-run scenario, 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 the different effects across regions, international trade reduces the damage to the global supply chain and reduces fluctuations in food consumption.

In the supplement section S6, we estimate a Poisson Pseudo Maximum Likelihood model using the simulated data. The analysis quantifies the importance of the Armington assumption and identifies the following key factors affecting the volume of bilateral trade:

(a) When the world food system is negatively affected, regions increase trade.
(b) 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 more considerable negative average global change in land productivity, ceteris paribus, suggests world prices increase, so the incentive to sell abroad is higher. However, if the change in land productivity affects the region, ceteris paribus, domestic prices rise, magnifying the incentive to sell locally. In the supplementary material S7, we show that the collapse of trade in India and Pakistan yields a collapse in all regions, with India and Pakistan's trading partners hurt the most.

4. Implications and policy discussion

A nuclear war between India and Pakistan can lead to climate perturbations with potentially major disruptions to regional food supply chains (from farm to fork). However, the magnitude of this disruption not only depends on the size of the conflict, but also on farmers' and producers' ability to adapt to the changes. Although the effect of the nuclear war on India and Pakistan depends on assumptions about the direct impacts, its magnitude is likely to wipe out these two nations' transportation and market infrastructure. At the same time, radiation contaminates the goods in the region. These direct impacts affect India and Pakistan and their trading partners severely. Although these direct regional nuclear war effects dwarf the indirect climatic effects, we did not include them in the analysis since we wanted to focus on the significant indirect global negative climatic ramifications of the regional nuclear war on the world. The paper strives to show how black soot emitted to the stratosphere results in global climatic ramification. However, when abstracting from the physical devastation (Glasstone and Dolan 1977) and immigration, the paper is likely underestimating the true significant negative ramifications of a nuclear war.

Throughout the analysis, we assume that the substitutability both within and between production processes captures this ability to adapt. 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 simulate that, on average, global corn productivity drops by 13% while global soybean productivity collapses by almost 20% one year after the war. Introducing limited output substitution via the partial equilibrium analysis does not yield major changes to crop production's regional nuclear war effect (supplement section S4). The partial equilibrium model suggests devastating effects on the global food supply during the first few years following the regional nuclear war.

When transitioning from the partial equilibrium to the general equilibrium analysis, not only do we assume greater substitutability, but we also assume that the climatic shock affects land productivity, which then affects agricultural output. The land productivity shock contrasts to the partial equilibrium analysis, whereby the shock directly affects output. The CGE modeling explicitly introduces the mechanism through which the regional nuclear war alters the climate and food production. We believe this is key when trying to understand the greater substitutability the Envisage Model introduces into the analysis. Furthermore, if the crop models' yield shock affects only land productivity it underestimates the actual adverse effects of the regional nuclear war. It may detract from other ramifications brought by the nuclear war to the supply and productivity of labor and the war's implications for capital flows. The analysis also abstracts from the physical devastation caused by the nuclear war between India and Pakistan, further straining Southeast Asia, a region where 20% of the world population resides. This could imply major immigration outflows from the region. As recent years have taught us, such major waves of immigration likely result in further destabilizing unstable regions.

However, even though the CGE model (Envisage) introduces greater substitutability into the analysis, some regions still experience severe impacts and food insecurity following the regional nuclear war. These significantly impacted regions are not necessarily located close to the war and may be on the other side of the globe. Even though the global impact of the war subsides within a few years, the effect and severity on high latitude regions does not diminish when simulating with the Envisage model. For example, five years after the assumed nuclear war between India and Pakistan, spring wheat and soybean production in the EU-28 drops by about 20% under the CLM5 scenario. Another example is for the Rest of the World, where non-EU European countries and Russia dominate wheat production. Figures 2 and S3 plot production of Non-EU Europe and Russia and Other North America. In the former region, the accumulated decline over 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.

How can a regional nuclear war through the Envisage model bring us to famine and food insecurity? What would get us to a point where a regional conflict leads to a global collapse and massive food insecurity and demand for massive adaptation and modification of existing production technologies and processes? At the outset, malnutrition and stunting harm the poor. The small regional nuclear war only worsens this challenge, especially in the high latitude regions, since the price shocks are extreme. The shock to production results in food prices spiking, significantly restricting food consumption, especially for those most vulnerable to price spikes—i.e. the poor. The analysis suggests three channels through which economic behavior responds to the regional nuclear war: (a) production switching where changes in crop prices result in farmers swapping crops with lower profit margins for those with higher margins; (b) input switching, whereby the demand for land shifts from production activities with lower economic value to those with higher value, and (c) international 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 responds to the positive shock to cotton (recall that cotton production under the crop model increases by 5% and more, yet under the Envisage-NW model it basically declines or remains constant). Another example is the very large negative land productivity shock to corn and soybeans, whose impact on production was substantially reduced under the Envisage model. 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 where consumers and farmers substitute one food for another in subsequent years based on changing market prices, and this reduces food scarcity. Regional shortages also result in those 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. Furthermore, these outcomes also depend on assumptions about how trade would continue in a post-war economic environment via hoarding and trade barriers.

This unrest created by the climatic change 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. To this end, armed conflicts negatively impact food security and result in ongoing insurgence around food security (Adelaja and George 2019, Adelaja *et al* 2019, George *et al* 2020). 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. Although, our analysis ignores storage, suggesting it overestimates price fluctuations if the shocks are sufficiently small (Hochman *et al* 2014). Current food stock holdings can alleviate single-year food production shocks, but continuous multi-year production losses at the scale simulated here would deplete food stocks in the first year and then directly trigger significant disruptions to global food supplies (Jägermeyr *et al* 2020). Also, investment in outreach and infrastructure that improves the management of food supply distribution and enhances productivity can 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.

5. Concluding remarks

Economic models aiming to inform the agricultural and development policy debate require analysis of 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 vital for countries' abilities to respond to the climatic change from the regional nuclear war; (e) vulnerability of high latitude regions to the cooling of the planet is significant.

Concerning 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 by a potential regional nuclear war. Climate connects regions globally, and a regional nuclear war disrupts the climate significantly with far-reaching implications to the supply of food. These severe ramifications are likely more extreme than suggested above. The focus on a select number of crops while leaving other crops' yield per acre unchanged probably lead to underestimation of the negative ramifications of a regional nuclear war on world food supplies. These conclusions suggest the strong need for policies aimed at the 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, updating these estimates over time, and showing 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 significant economic totals.

A crucial implication of our analysis is that even when introducing greater substitutability via the Envisage, a small regional nuclear war yields havoc on the globe. The small regional nuclear war results in some regions experiencing severe impacts and food insecurity, even though these regions are on the other side of the world. Although the global economy absorbs the negative ramifications of the war within a few years, the effect on high-latitude areas remains extreme for several years after the nuclear war. The magnitude of the adverse land productivity shocks for high-latitude regions (e.g. non-EU European countries and Russia, EU 28, and Canada) and the severity of its impact do not diminish when we introduced the Envisage model, and likely to have significant negative ramifications to the poor and their ability to access food.

Data availability statement

All relevant data are within the paper and its supporting information files, or available from the authors upon request.

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgment

This work is supported by the Open Philanthropy Project.

Conflict of interest

The authors have declared that no competing interests exist.

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