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Environmental Stressors Can Intensify the Impacts of Pandemics on Earth's Natural Resources and Global Food Systems

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This study estimates the likely impacts of the COVID-19 pandemic when combined with environmental stressors. We identify the conditions under which a combination of economic recession and drought conditions leads to intensified food insecurity. We also identify which regions are more influenced by other regions through changes in other parts of the world. We integrate SIMPLE (Simplified International Model of agricultural Prices, Land use, and the Environment) with WBM (Water Balance Model). The WBM projections show changes in the hydrological supply of water resources and agronomic demand for water. The SIMPLE model provides agricultural production, food security, and caloric nutrition outcomes. It also determines the irrigation water demand around the world. The prices of crops, livestock, and processed food commodities are determined considering the international trade of agricultural products. In an interconnected world, water-scarce regions are expected to import water-intensive commodities from relatively water-abundant regions. However, the degree of scarcity depends on availability relative to demand. We consider the changes in water supply relative to the changes in water demand in case of water scarcity combined with the economic lockdown.

1 Introduction

COVID-19 has posed remarkable challenges to the global economy and significantly affected environmental quality. Even with the extreme forest fires of 2020, it was estimated that greenhouse gas emissions were at the lowest levels in decades (Diffenbaugh et al., 2020; Liu et al., 2020; Mostafa et al., 2020). While population change, climate change, and improvements in technology are major drivers of changes in water and land use (Baldos and Hertel, 2014; Hertel and Baldos, 2016; Baldos et al., 2020), recent earth observations suggest that the pandemic has altered the environment significantly through the ensuing slowdown in economic activities (Diffenbaugh et al., 2020). Meanwhile, the impacts of the pandemic on food security have varied across countries. In many countries, it has resulted in income losses and reduced household purchasing power. Restrictions in population movements due to the COVID-19 pandemic have resulted in soaring unemployment and reduced GDP across the world (Beckman & Countryman, 2021). The World Bank has estimated the COVID-19 recession could push an additional 100 million people into extreme poverty (World Bank, 2020).

For the countries already in crisis due to a combination of conflict, consecutive years of severe droughts, natural hazards, and pests (desert locust invasion), the pandemic has exacerbated pre-existing and ongoing drivers of food insecurity (FAO-WFP, 2020). These natural disasters have the potential to intensify the negative impacts of COVID-19 and can change the spatial pattern of the ensuing damages. The direct impacts of the disasters include the loss of human lives, assets, and harvest or livestock, as well as heightened food insecurity. These indirect costs are often termed higher-order costs (Hallegatte and Przyluski, 2010). Some of these indirect losses are due to the output losses that arise from a decrease in production, because of the disaster itself, or because of the reduction in the productivity of inputs of production including labor, capital, and land (Haqiqi and Bahalou, 2021). Part of the indirect negative impact is a result of the damages to the infrastructure, such as electricity and transportation. Some other negative impacts may be due to the disruption of supply chains. A Compound disaster such as the coincidence of a pandemic with natural disasters can diminish the resilience of key economic sectors such as agriculture, environment, and energy (Bahalou and Haqiqi, 2020). These compound disasters augment disruptions in the production of field crops and livestock and can lead to higher prices of food and agricultural products. The coincidence of natural stress and a pandemic may also lead to food insecurity problems amongst the most vulnerable households.

Fortunately, during the COVID-stressed year of 2020, the world did not experience widespread droughts or heatwaves. However, the future is uncertain. More frequent and intense weather extremes are projected. This begs the question: “what if a pandemic is combined with a widespread drought or an extended heatwave?”. All indications are that this could be catastrophic. However, a more complete answer requires quantitative research. The answer to this question is not straightforward, as there are opposing drivers at work, along with numerous sources of uncertainty.

There are some studies about the likelihood of individual shocks to human and environmental systems such as income reduction, heat stress, water stress, and change in costs of production on the land, water, and food security (Haqiqi and Bahalou, 2021; Haqiqi et al., 2021; Mishra et al., 2021; de Lima et al., 2021; Mora et al., 2018; Fujimori et al., 2018). However, to our knowledge, there exists no study that examines the compound impacts of these shocks on environmental sustainability and food security. This study estimates the likely impacts of the COVID-19 pandemic combined with environmental stressors. Specifically, we investigate the global impacts of economic lockdowns combined with fine-scale heat stress and water scarcity affecting food systems. Several scenarios of pandemic and environmental stress are considered. Two categories of systemic shocks are pandemic-related and include the impact of the pandemic on income and job creation, on the one hand, and the impact of the pandemic on agricultural productivity, on the other. The other category of shocks considered relates to the environment and includes the potential impacts of heat stress, irrigation water shortages, and crop damage. Further, we identify the conditions under which a combination of an economic recession and drought leads to intensified food insecurity. We also identify which regions of the world might be indirectly affected by developments in other regions through changes in the international trade of food. Throughout this analysis, we employ a variety of indicators. On the environmental sustainability front, we consider Greenhouse Gas (GHG) emissions from the food system composed of CO2, N2O, CH4 emissions, groundwater withdrawals, and cropland area changes. The food security indicators include the share and the absolute number of undernourished people as well as food prices.

To quantify the impact of these compound disasters, we integrate SIMPLE (Simplified International Model of agricultural Prices, Land use, and the Environment) with WBM (Water Balance Model) and the Global Crop Water Model- Gridded Emulator (GCWM-GE). The SIMPLE economic model predicts food security and caloric nutrition outcomes and determines crop production, land use, and irrigation water demand. The shocks to water availability and evapotranspiration come from global simulations of the hydrology model, WBM, from 2012-2018. The shocks to crop yields are simulated based on GCWM-GE for an aggregate measure of irrigated and non-irrigated yields based on average weather conditions and local technological characteristics.

The results of this study quantify the extent to which pandemics can reduce water withdrawal and curb cropland expansion while increasing hunger and undernutrition. The results also indicate that environmental disasters can increase water and land stress, while also increasing hunger and undernutrition. Consequently, compound pandemics and environmental shocks can significantly worsen hunger, while the impact on environmental indicators is ambiguous.

1. Methods

The SIMPLE model determines the changes in consumption and production decisions as a consequence of changes in global drivers. Here, we introduce income and productivity shocks to mimic the food system impact from the pandemic. The model considers various transmission channels as well as different adaptation channels for each shock (e.g. change in diets, irrigation expansion, international and intranational trade). The model also determines crop production, land use, and irrigation water demand around the world. The prices of crops, livestock, and processed food commodities are determined considering international trade in agricultural products. In an interconnected world, water-scarce regions are expected to import water-intensive commodities from relatively water-abundant regions. The shocks to water availability and evapotranspiration are taken from WBM global simulations from 2012-2018. The model utilizes precipitation and air temperature to project crop by crop irrigation requirements from both surface water and groundwater. As the degree of scarcity depends on availability relative to demand, the extent of scarcity will be affected not only by changes in the physical system but also by economic changes such as the presence of a pandemic-induced recession. The shocks to crop yields are simulated based on GCWM-GE for an aggregate measure of irrigated and non-irrigated yields based on average weather conditions and local technological characteristics.

1.1. SIMPLE Model and data

This study employs a global multi-scale comparative static partial equilibrium economic model for agricultural and food systems. It considers global markets for international trade of crops, livestock, and processed food. The world is divided into 17 market regions. Then, consumption and production of each food commodity are modeled for global market regions following the SIMPLE model. SIMPLE is historically validated and widely used for land use and food security analysis (Baldos and Hertel, 2014, 2015; Hertel and Baldos, 2016a; Liu et al., 2017; Hertel, 2018). Here, the food consumption decision depends on prices, income, and dietary choices. The regional consumption follows per capita consumption and population growth. The per capita consumption level is determined by employing carefully estimated demand parameters governing the dietary shifts (the mix of food basket). Food prices are determined in the model according to the dynamics of supply and demand. The equilibrium production at each market region is modeled considering local production conditions, environmental change, and technological changes. For the production sector, the SIMPLE model considers land and non-land inputs. The non-land input category includes an aggregate measure of fertilizer, labor, capital, seeds, etc. For each production unit, the production function is characterized to show local technology, cost structure, input utilization, and yields. The production function has a constant elasticity of substitution (CES) form. The model also considers intensive and extensive margins of land use. While this depends on landowners' behavior, it also depends on land quality, soil, ecosystem, ecology, and other local characteristics of the land embedded in model parameters. This study employs a version of the model with irrigated versus rainfed production to account for water withdrawal in agriculture. Finally, international trade of food commodities is linked to the change in the pattern of production, land use, and consumption (Liu et al., 2014; Baldos and Hertel, 2015; Hertel et al., 2019). Local production can be supplied to the domestic market or the world market (exports) depending on relative prices. This follows a constant elasticity of transformation (CET) function assuming imperfect transformation between domestic and global supply. Also, the consumption in each region is either from domestic production or imports. This follows a constant elasticity of substitution (CES) function that determines the imports based on relative prices. For full details about the model, look at Hertel and Baldos, (2016b) and Baldos et al. (2020).

1.1.1 GHG emissions from food systems

We consider emissions from the food system. It is a small part of CO2 emissions but does account for the majority of non-CO2 GHGs. In general, CO2 emission is coming from energy consumption in production, input use, and pumping for irrigation. We combine CO2 and non-CO2 emissions with CO2 equivalent measures (Chepeliev, 2020). Here, the CO2 emission will not be specifically modeled by the source. For simplicity, we assume an emission factor, the ratio of CO2 emitted to the volume of production for each production process for each country. In this study, the emission factor is fixed to avoid within sector adaptation and to focus only on one sustainability strategy at a time. The emission is calculated via the following equations. Total emission is a simple sum of emissions from crop production, livestock production, and processed food production.

$$CO2_r = CO2_r^{crop} + CO2_r^{livestock} + CO2_r^{processed\,food} \tag{1}$$

For each production activity, there is a linear relationship for CO2 emissions considering an emission factor as the followings:

$$CO2_r^{crop} = ef_r^{crop}.Q_r^{crop} \tag{2}$$

$$CO2_r^{livestock} = ef_r^{livestock}.Q_r^{non-feed} \tag{3}$$

$$\mathrm{CO2}_r^{processed\,food} = ef_r^{processed\,food}.Q_r^{non-crop} \tag{4}$$

Where, ef_r^{crop} stands for emission factor for crop production in region *r*, Q_r^{crop} is total crop production, $ef_r^{livestock}$ shows livestock emission factor, $Q_r^{non-feed}$ is the total non-crop inputs in livestock production, $ef_r^{processed\,food}$ represent processed food emission factor, and $Q_r^{non-crop}$ is the total of non-crop inputs in processed food production. Similar logic is followed for CH4 and N2O emissions.

1.1.2 Global data for 2017

The national-level crop sector, food security, and other macroeconomic data in SIMPLE are taken from FAOSTAT (2021). Crop sector data includes crop production, producer prices, and cropland area. Crop production for different crops is converted into corn-equivalent production using the producer prices and the world price for corn. Key macroeconomic variables include population and real GDP which are the main sources of crop demand in the model. In SIMPLE, food security is based on calories. Specifically, changes in average caloric intake and caloric undernutrition are tracked using data on daily food intake per grams and per calories, minimum daily dietary intake as well as caloric distribution parameters characterized by a lognormal distribution following Neiken (2003).

The crop trade shares, crop utilization shares, and input cost shares for the crops, livestock, and processed food sectors are calculated based on the GTAP database (Global Trade Analysis Project), which is a widely used global economic data on the production and trade of commodities (Aguiar et al., 2019). The standard GTAP database provides information about the production structure, trade, and consumption of commodities for 141 regions and 65 sectors. In SIMPLE, they are aggregated into 17 regions and 4 production sectors. For this study, we have aggregated the emission data (CO2, N2O, CH4) provided by GTAP Power Data Base (Chepeliev, 2020). Land use, water withdrawal, and nitrogen application data are embedded in the SIMPLE model (Baldos et al., 2020a).

1.1.3 Land use module and parameterization

For the Americas, we adopt the estimates of cropland supply elasticities provided by Villoria and Liu (2018). The foundation for this estimation is to predict the propensity of a land parcel being converted to cropland from other land types using biophysical and socio-economic characteristics because the probability of land being cultivated is determined by not only suitability but also profitability. Fine-scale data (5-arc min) compiled from various sources that measure the growing conditions represented by agro-ecological zones (AEZs), soil pH value, soil carbon content, as well as socio-economic indicators such as the extent of irrigation, market access, urbanization, are used to fit a fractional Logit model. And the coefficient associated with market access is further adjusted to obtain the cropland supply elasticity, which is defined as the response of cropland supply to a given change in cropland returns. The spatial pattern of this elasticity is validated using observed land use change data at the county, state, country, and ecoregion levels.

1.2. Water Balance Model

WBM is a global-scale, gridded hydrological model that links the changes in weather to changes in the water cycle. It simulates both the vertical exchange of water between the underground water, surface soil moisture, and the atmosphere, as well as the horizontal transport of water through runoff and stream networks. The original WBM predicts spatially and temporally varying components of the hydrological cycle. The more recent development of WBM expanded its modeling framework to many anthropogenic interactions with hydrological cycle such as irrigation (Wisser et al., 2010) and agricultural land use (Grogan et al., 2017). We will employ global outputs of WBM for 2010-2018 and aggregate them to an annual time scale. The variables of interest include reservoir storage, shallow groundwater, unsustainable groundwater, evapotranspiration, temperature, and precipitations.

1.3. Global Crop Water Model- Gridded Emulator

We have employed GCWM-GE to translate the outputs of WBM to changes in rainfed crop yields. The emulator takes evapotranspiration, temperature, and precipitation as input and provides the likely change in corn-equivalent yields at the grid cell level. The original GCWM (Siebert and Döll, 2010) has been used for construction of GTAP irrigation Data Base and value of water (Haqiqi et al., 2016).

2. Scenarios and Results

2.1. Scenario Designs

In this study, we assume the income shock of the COVID-19 pandemic is combined with the 2016 global drought. The demand shock is mainly the change in income (GDP). We take the estimated impacts of the COVID-19 on GDP from the World Bank. Figure (1) shows the scenarios of the change in GDP worldwide. It is estimated that due to the COVID-19 pandemic, China may experience a 2 percent increase in GDP while other regions of the world may face a reduction in GDP. The greatest reduction in GDP is estimated to happen in South America and India (9 percent), and Europe (8 percent).

The supply shocks include gridded shocks on water availability from WBM and agricultural yields from GCWM-GE. Also, we assume a 2.5% reduction in agricultural productivity based on findings by Haqiqi & Bahalou (2021) for the US. While this can be different across regions, we assume a uniform productivity shock at this stage.

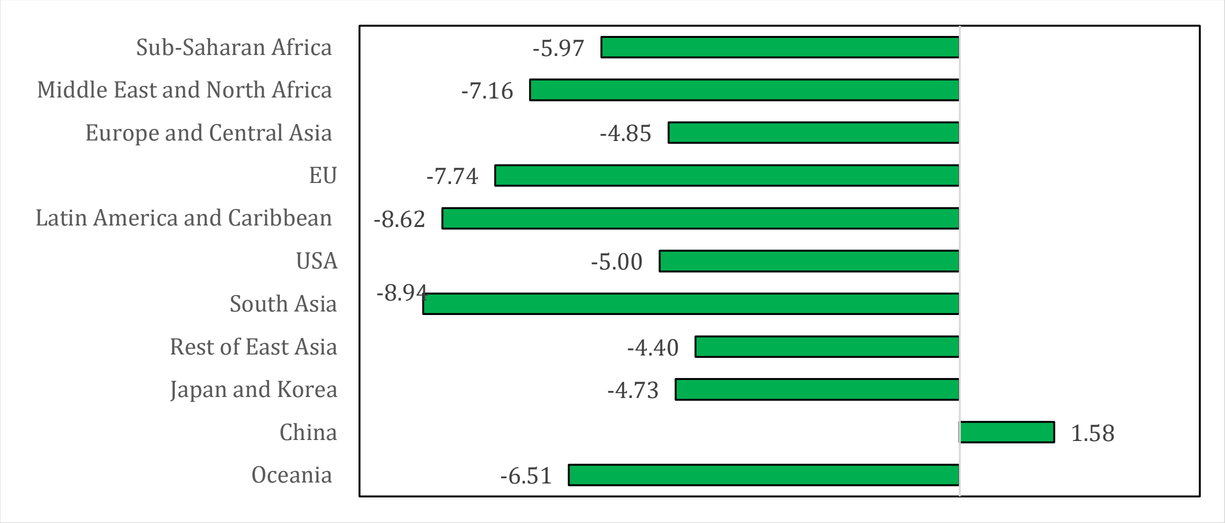

Figure 1: Percentage change in income due to COVID-19 compared to business as usual.

Figure (2) plots the scenarios of water stress in terms of groundwater withdrawal in the regions of the world. This is based on WBM output for 2015-2016 droughts which represent a widespread global drought. We estimated that some areas of India and Europe suffered more from water stress during that period. In some regions in the U.S. water availability has increased. This scenario will give us a more realistic picture of what can happen.

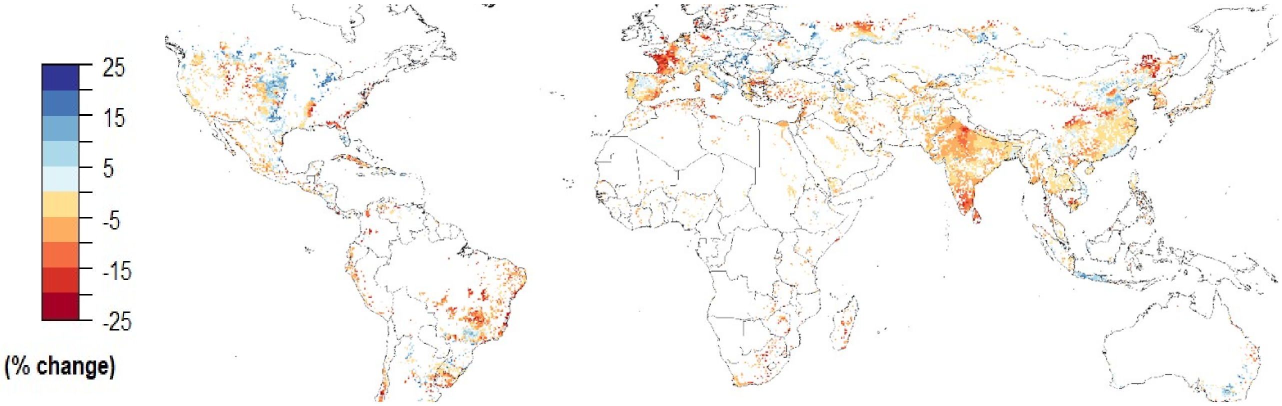

Figure 2: Percentage change in surface water available for irrigated agriculture

Finally, Figure (3) illustrates the scenario of change in crop yields for rainfed agriculture on the global scale for 2015-2016 based on GCWM-GE. It is estimated that in most regions of the world the crop yield has diminished for rainfed agriculture. The highest reduction in the crop yield has taken place in North America and some areas of India. While we are aware of differences between yield and productivity, we consider this as a productivity shock for rainfed agriculture at the gridded scale. This can be another close-to-reality scenario of heat stress on agricultural productivity.

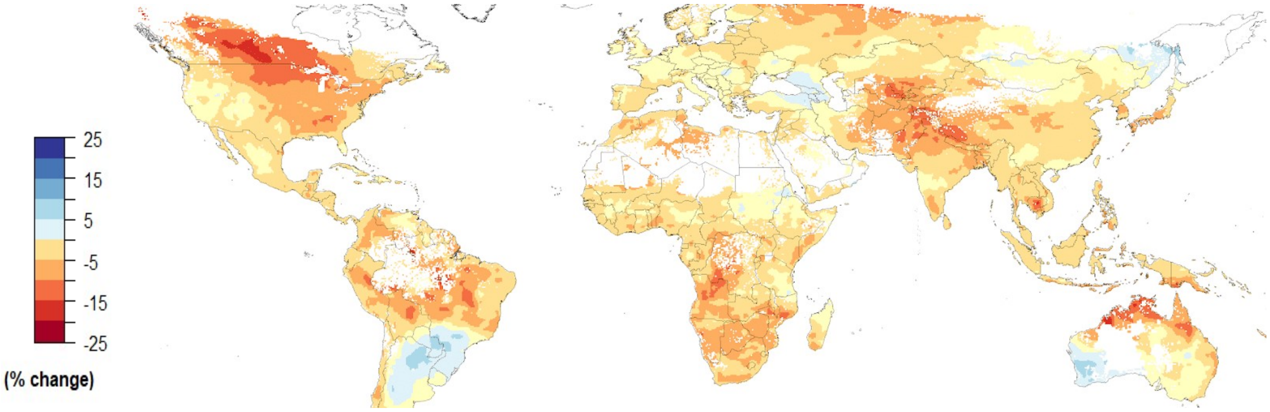

Figure 3: Percentage change in crop yields for rainfed agriculture due to heat stress

2.2. Preliminary results

Figures (4) show the preliminary results of this study using SIMPLE model. We aggregate the yield and water shocks from grid cells to market regions. Overall, hunger and food prices have increased. Here, hunger is defined as the number of people without having the minimum caloric requirement. This number is estimated to increase by 35% in Sub-Saharan Africa (SSA) and by 12% in South Asia. The compound shock will reduce the GHG emissions from the food system in all regions. The impact on land use and water withdrawal varies by region. In the US and China, land use and water withdrawal have been increased, while in South Asia and South America the land use and water withdrawal have been declined. The decomposition of the results offers significant findings. The impact of income and heat stress on all the metrics is substantial. The heat stress has intensified the impacts of the pandemic on food insecurity in SSA drastically (28.8% and 8.8% respectively). We estimate less severe but similar intensification in South America.

On the other hand, the income reduction due to the pandemic is estimated to improve sustainability measures (lower GHG emissions, lower water and land use). The pandemic is expected to reduce the GHG from the food system by around 3.2% in South Asia, 2.1% in South America, and 1.4% in East Europe, while it can reduce water withdrawal in South Asia by 2.1%. However, the heat stress can offset that. For example, heat stress like 2015-2016 can cause an expansion in land use by 1.3% and can increase water withdrawal by 1.9% in the US.

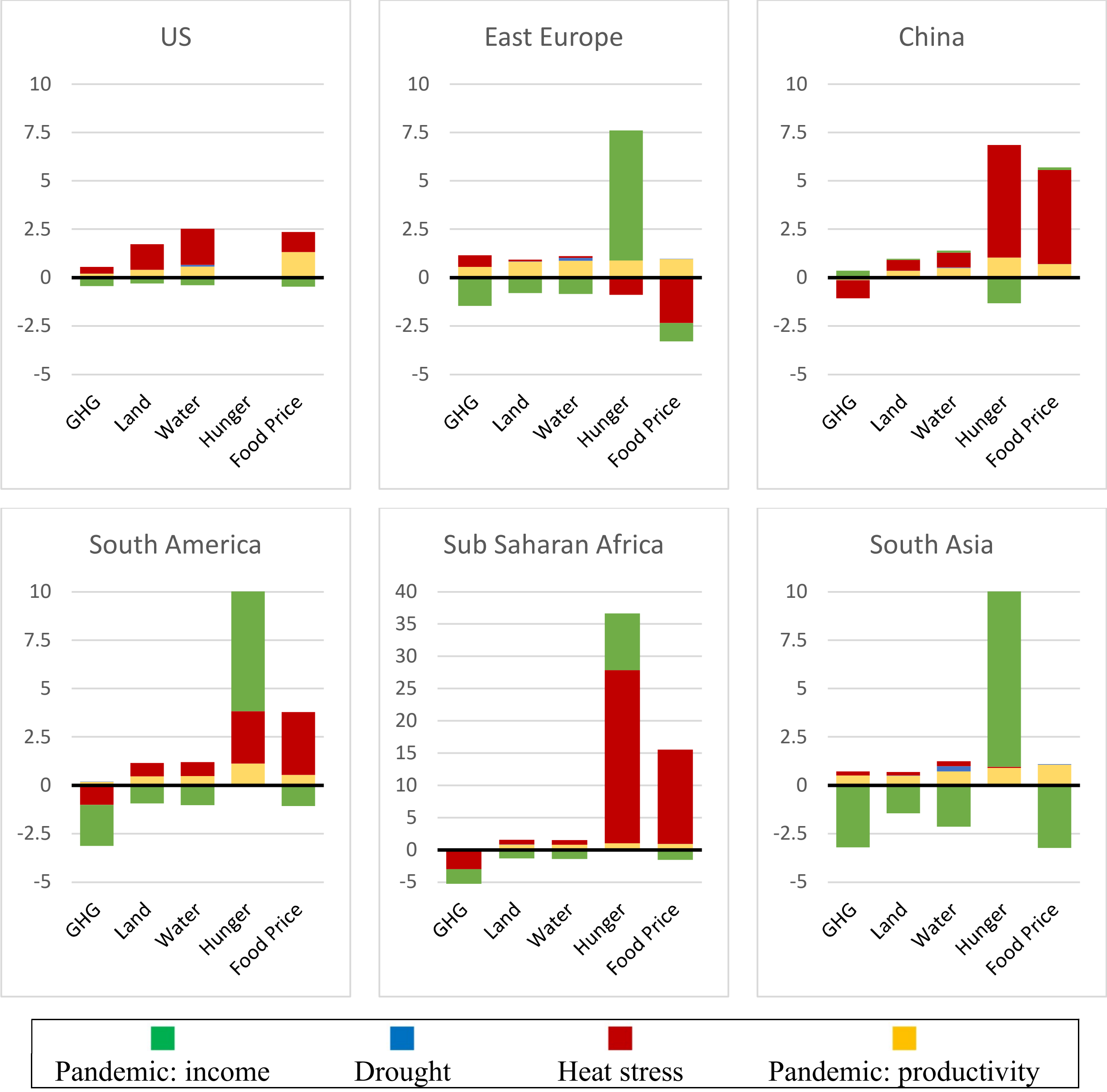

Figure 4: Impact of a pandemic compound with drouth and heat stress

3. Conclusions

The world has been fortunate that the COVID-19 pandemic did not coincide with major climate disasters affecting food production. However, in the future, with increasing climate extremes, it is possible that such a pandemic could coincide with severe environmental stresses. To investigate the potential consequences for food and environmental security, we employ a global gridded hydro-agro economic framework that permits us to explore the interactions between pandemic and nature-induced stresses on the global food system. Specifically, we investigate the global impacts of economic lockdowns combined with fine-scale heat stress and water scarcity affecting food systems. Various scenarios of pandemic and environmental stress are considered. Further, we identify the conditions under which a combination of an economic recession and a drought leads to intensified food insecurity.

The results illustrate the significance of a pandemic combined with environmental stresses. Employing gridded version of SIMPLE in the future, we will be able identify the hotspots of food insecurity vulnerable to compound shocks. Also, we can identify which local parameters and biophysical conditions are most important in limiting the adaptation options at each location. The results show that pandemics can reduce water withdrawal and land use but will increase hunger and malnutrition. The results also indicate that environmental shocks can increase water and land stress while also increasing hunger and malnutrition. A compound pandemic and set of environmental shocks can greatly increase food insecurity, while the impact on environmental indicators is ambiguous.

The results of this study are important from a policy perspective. The results highlight the significance of economic and financial relief to combat hunger and malnutrition and to alleviate the damages on land and water resources. Given the uncertainty of environmental disasters, we can decrease the likely future costs of these shocks combined with the pandemics by mitigating climate change. Finally, the adverse effects of pandemics and environmental shocks can be mitigated through global trade. World trade boosts the collective resilience to environmental disasters and pandemics.

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