Chapter 17
Interplay Between the Pandemic and Environmental Stressors

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1 Introduction

In this chapter, we aim to provide an introduction to multisystem dynamics. Our primary focus is to demonstrate how SIMPLE-G can be integrated with Earth system models to generate more accurate and holistic evaluations of the impacts of multiple shocks on agriculture. We look at the case of a compound pandemic–weather extreme event. Through this example, we showcase how Earth system models can offer multiple inputs to SIMPLE-G, including changes in crop yields and water availability. We also demonstrate how SIMPLE-G can calculate the amount of greenhouse gas (GHG) emissions released by the food system, which is crucial for assessing climate change. Moreover, we delve into how SIMPLE-G can connect the dynamics of hydroclimatic systems to food security outcomes. By examining the relationship between hydroclimatic conditions and crop growth and incorporating

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Data availability statement: The files needed to replicate this application are available at https://gtap.agecon.purdue.edu/simple-g/

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market connections, we can better understand how changes in weather patterns can impact food security and identify potential adaptation strategies.

Short-term extreme events can threaten global food security through negative impacts on food production, food purchasing power, and agricultural economic activity. While the impacts of weather-based extremes such as droughts and floods have been well studied (Konapala et al. 2020; Pokhrel et al. 2021), societal disasters like pandemics are only more recently being evaluated (Diffenbaugh et al. 2020; Mishra et al. 2021; McDermott and Swinnen 2022; Vos et al. 2022). The potential for additional global pandemics, along with the increasing frequency of weather extremes (Pokhrel et al. 2021), also requires us to consider the impacts of compound pandemic–weather events and potential adaptation options.

The COVID-19 pandemic posed remarkable challenges to food security, impacting local, regional, and global food security through several mechanisms. Under- and unemployment-induced income losses led to reduced food purchasing power for many households, decreases in agricultural production were caused by restricted population movements, and supply chain disruptions resulted in losses to global economic production (Diffenbaugh et al. 2020; World Bank 2020; Haqiqi and Horeh 2021).

Widespread weather-based impacts on crop yields can also reduce food production and agricultural economic activity (Boyer et al. 2013; Kim et al. 2019). Droughts have a particularly negative impact on food security in developing countries (Morton 2007; Cooper et al. 2019) and have been linked not only to increased malnourishment in those countries but also to conflicts and social instability (Hsiang et al. 2013; Gleick 2014; Cooper et al. 2019).

From a food security perspective, the world was fortunate that weather outcomes during the COVID-stressed year of 2020 were largely favorable to food production. But what if the pandemic had coincided with global-scale water stress events? There have been studies of individual shocks to human and environmental systems on food security (Fujimori et al. 2018; Mora et al. 2018; Chateau et al. 2020; De Lima et al. 2021; Haqiqi et al. 2021), but very few studies have examined the interaction and compound impacts of multiple, simultaneous shocks to food security and environmental outcomes (Chateau et al. 2020; Mishra et al. 2021; Smith et al. 2021).

Here, we evaluate the impacts of compound stresses resulting from a pandemic such as COVID-19 coinciding with widespread drought and heat waves. We further quantify the role of interdependent local, regional, and global adaptation options in response to these compound stresses. This is accomplished through the lens of SIMPLE-G, linked to hydrologic and crop yield models, which are in turn driven by climate model outputs (Fig. 17.1). We build on the global gridded model from Chap. 16 and extend it to incorporate additional systems. Using this framework, we look at both undernourishment outcomes and GHG emissions for the compound disaster scenario and adaptation options.

The multimodel structure includes climate data (gray), hydrologic modeling (blue), crop yield modeling (green), and economic modeling (yellow and peach). Daily weather data allow the hydrologic model to simulate changes in agricultural water requirements and availability; the crop yield model uses these same weather

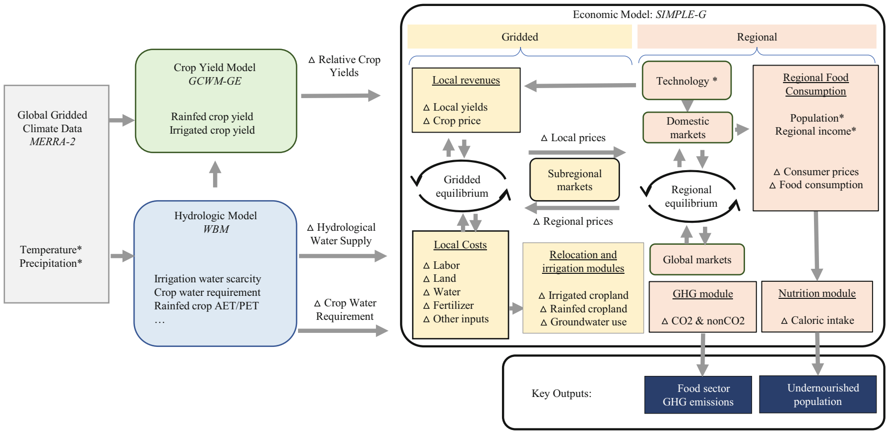

Fig. 17.1 Method overview

data, along with outputs from the hydrologic model, to simulate weather-induced changes in crop yields. The economic model uses pandemic-based shocks to income, along with the water supply and crop yield changes from the other two models, as inputs to a coupled fine-scale gridded (yellow) and regional (peach) equilibrium supply–demand system. The full modeling system produces the key metrics evaluated here: changes in food sector greenhouse gas (GHG) emissions and undernutrition as a result of the combined pandemic and weather shocks. Asterisks (*) indicate exogenous inputs to the system.

2 SIMPLE-G Model Used in This Chapter

In this chapter, we introduce a new version of SIMPLE-G that is more appropriate for short-run analyses. We employ two sets of SIMPLE-G-Global models (Haqiqi et al. 2022) that are designed to evaluate the impact of multiple shocks. The first model is that used in Chap. 16, which incorporates local production and resource use decisions that respond to market prices. This means that the model considers the market dynamics of land, water, and other inputs for both irrigated and rainfed production. The second model, called SIMPLE-G-Global-Climate, is a new version of SIMPLE-G that provides a short-run evaluation of the impact of multiple shocks. In this model, a critical assumption is that local land and water use decisions have already been made in the short run, and local production is affected by weather conditions through yield and water availability. This model considers the environmental factors that influence agricultural production, such as weather extremes, to provide a more accurate assessment of the short-run impact of shocks.

We evaluate key outputs from this multimodel system: changes in GHG emissions from the food sector and changes in undernourished populations in developing countries. Undernourished population is defined as the number of people who do not consume the minimum caloric requirement, as defined by the Food and Agriculture Organization of the United Nations (FAO 2021). GHG emissions are computed as the sum of all emissions from different stages of production in the food system and include CO_2, N_2O, and CH_4. We further evaluate multiscale endogenous adaptation responses to reduce negative food security impacts, as detailed in Haqiqi et al. (2023).

The SIMPLE-G framework is particularly well suited to this multisystem analysis of compound extremes since the economic decisions play out at a fine scale but are also spatially connected through regional and global markets. This distinguishes SIMPLE-G from most economic equilibrium models, which operate at the regional level. Because SIMPLE-G offers a combined gridded and regional economic model framework, it is well-positioned to make the best use of the fine-scale gridded results coming from the hydrologic and crop yield models. These gridded results are important to include in economic modeling because impacts on water supply and crop yields can vary greatly within a single region. Averaging these grid-cell-level biophysical model results prior to economic modeling would fail to capture changes in the spatial patterns of agricultural production that rely on local natural resources and are impacted by fine-scale weather events.

The SIMPLE-G-Global model used in this study determines crop production, land use, and irrigation water demand for each of the 1.3 million grid cells (recall Chap. 16). These grid cells are connected through agricultural markets and their relative production costs and land and water availability determine the scale of production at each location. We also use the nutrition module within SIMPLE which was developed by Baldos and Hertel (2014) based on Neiken (2003). In addition, we use a GHG emission module to estimate changes in emissions from the food system (CO_2, N_2O, and CH_4) based on the GTAP Power Data Base (Aguiar et al. 2019; Chepeliev 2020).

3 Experiment Design

To evaluate the impacts of the compound disaster posed by a co-occurring global pandemic and a global low-yield agricultural year, we need to connect the biophysical agricultural system with the global economic system. To do this, we use a coupled model framework that integrates gridded physical models from hydrology and agronomy with equilibrium models from economics (Fig. 17.1). These models are (1) a process-based gridded hydrologic model that simulates changes in agricultural water requirements and availability based on daily weather inputs, (2) a gridded crop yield model emulator that simulates changes in irrigated and rainfed crop yields based on both daily weather and hydrologic model output, and (3) a gridded-regional economic model that integrates both the pandemic-related shocks to income and the agricultural shocks from weather as simulated by the other two models.

3.1 Hydrologic Model

The hydrologic model used here is the water balance model (WBM), a global gridded hydrological model that simulates the land surface component of the water cycle based on daily weather inputs (Grogan et al. 2022). The WBM has been used and validated globally (Wisser et al. 2010; Grogan et al. 2017), including in multimodel systems coupled with economic models (Zaveri et al. 2016; Liu et al. 2017; Haqiqi et al. 2021). The WBM simulates both the vertical exchange of water between groundwater, surface soil moisture, and the atmosphere as well as the horizontal transport of water through runoff and stream networks. The WBM represents many anthropogenic interactions with the hydrological cycle, including irrigation (Wisser et al. 2010) and agricultural land use (Grogan et al. 2017). Here, the WBM is used to simulate changes in water supply and changes in crop water requirements.

3.2 Crop Yield Model

This chapter examines the interactions between multiple, punctuated extreme shocks (e.g., pandemics, short-term droughts, and heat stress). Note that we are not looking at long-term climate changes and regime shifts that can permanently move human and environmental systems to a new state. To simulate yearly changes in crop yields due to weather impacts, we develop an emulator from the crop yield component of the Global Crop Water Model (Siebert and Döll 2010), which we call the Global Crop Water Model General Emulator (GCWM-GE). The yields are estimated based on beneficial degree days between 10 °C and 30 °C and harmful degree days above 30 °C as well as evaporative stress for five climate zones. While this tool does not capture yield damage due to frost, extreme winds, flooding, pests, or disease, it has the great advantage of eliminating the need for a crop-by-crop calculation of yield while modeling the relative pattern of crop yields in a statistical framework. Overall, GCWM-GE is capable of explaining around 50% of yield variation circa 2000 (Haqiqi et al. 2023).

3.3 Scenario Design

To simulate a compound pandemic and weather crisis, we construct three shocks that are simultaneous inputs to the economic modeling system. These shocks comprise changes to key values within the economic framework that cause the system to fall out of equilibrium, triggering multiple adjustments in the global economy. Table 17.1 lists all shock values at the regional level, and Fig. 17.2 shows the global, weather-based crop yield shocks at the grid-cell level.

Table 17.1 Pandemic and weather shock scenario design

Region	Pandemic shocks	Weather shocks		Other shocks
	Gross domestic product (GDP) shock (%)	Water resources shock[a] (%)	Crop yield shock[b] (%)	Additional shock to crop yields[c] (%)
East Europe	−5.35	−0.36	−5.02	4.89
North Africa	−6.30	−3.52	−1.22	13.87
Sub-Saharan Africa	−5.58	−1.69	−8.94	10.78
South America	−8.78	0.46	5.47	−0.45
Brazil	−8.78	−2.23	6.17	−1.76
Australia and New Zealand	−6.51	−5.28	4.80	−5.93
Europe	−7.76	−3.00	−11.10	8.59
South Asia	−8.94	1.94	5.15	−8.42
Central America	−8.78	−0.73	−0.68	1.96
South Africa	−5.58	−14.39	−12.57	6.54
Southeast Asia	−5.70	−7.86	−1.32	5.67
Canada	−5.00	−1.06	−4.78	9.74
United States	−5.00	1.11	0.50	−1.41
China	1.17	−2.84	5.22	1.32
Middle East	−6.30	5.66	1.26	7.76
Japan and Korea	−4.73	−2.55	−1.14	−4.95
Central Asia	−5.35	18.94	1.69	−0.16

[a] These shocks are applied at the grid-cell level. Regional aggregate values are reported in this table for the purpose of describing the shock scenario. See Fig. 17.2 for the grid-cell shock to rainfed crop yields

[b] Crop yield shocks are estimated by the crop model at the grid-cell level.

[c] Other yield shock is the portion of the change in reported regional average yield that is not captured by the crop model. This shock is applied at the country level

3.3.1 Pandemic Shocks

The economic shocks from a pandemic are represented here as changes in regional income due to lockdowns and changes in productivity due to supply chain disruptions. We use the estimated impacts of the COVID-19 pandemic in 2020 on income and production from the World Bank (2020) *Global Economic Prospects* report as inputs to the regional economic model. We believe that this is indicative of the global economic impact that a future pandemic might have.

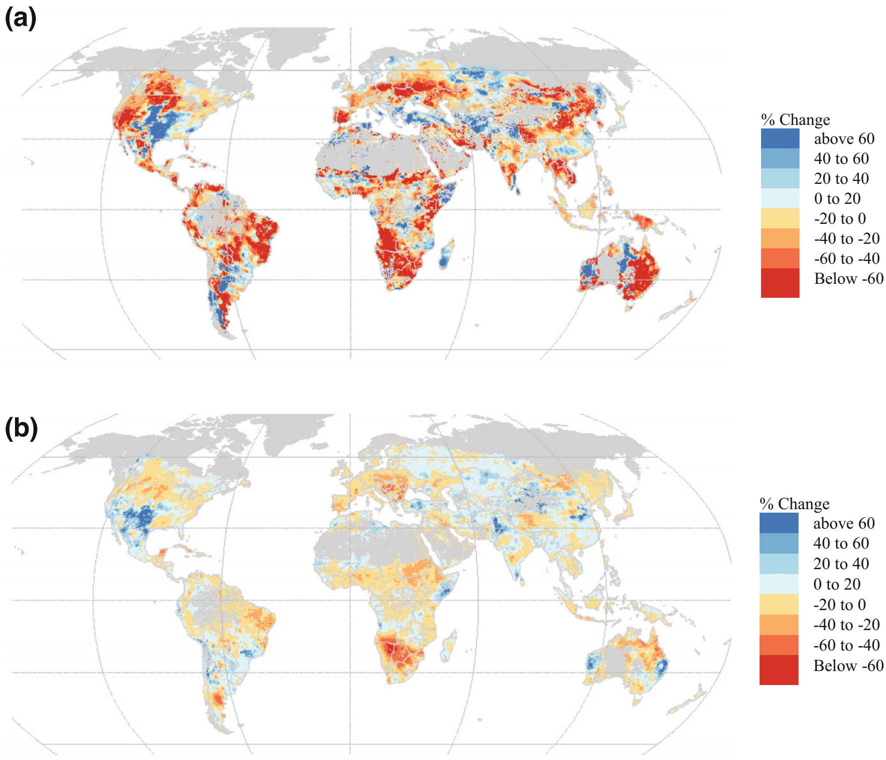

Fig. 17.2 Grid cell shock to (**a**) rainfed crop yields and (**b**) surface water supply due to weather impacts The gridded yield shocks are calculated using the global yield emulator model, while the shock on surface water is based on the outputs of the water balance model

3.3.2 Weather Shocks

While there is interannual variability in global agricultural production, 2015 was a particularly poor year for crop production compared with the recent past (2000s and 2010s), largely due to concurrent droughts in key breadbasket regions that year, according to the World Bank (2020) crop production index. To simulate this weather shock, both the hydrologic model and the crop yield model were used to simulate outcomes over 2012–2018 based on daily input weather data. The shocks to water resources and crop yields are computed as the difference between the model output for 2015 and the average output over the 7-year simulation period. These shocks are applied at the grid-cell level and are assumed to represent the kind of adverse weather events that could exacerbate the impacts of a pandemic.

3.3.3 Additional Crop Yield Shocks

Weather extremes explain only a portion of the variation in crop yield anomalies (Ray et al. 2015; Vogel et al. 2019). In addition to heat and water stress, there are many other factors affecting food production that are not captured in the GCWM-GE or the WBM, including human system components (e.g., political changes, economic policies, labor strikes, conflicts, migration, technology, growth, and recession) and environmental factors (e.g., frost, flooding, pests, and disease). We use annual reported agricultural production and yields from the World Bank by country to produce a residual change in crop yields. These observed outcomes from 2015, which lie outside the predictions of the crop yield model, are treated as an additional yield shock.

3.3.4 Adaptations to Shocks

The SIMPLE-G gridded economic model encompasses the equilibrium adaptation responses considered in this study at the local (irrigation), regional (production pattern), and global levels. Specifically, these adaptation options include surface water and groundwater substitution for irrigation on existing irrigated cropland, changes in the amount of water applied to land, rainfed-to-irrigated (or irrigated-to-rainfed) land conversions, expansion or contraction of cropland, relocation of cropland, input substitutions in the livestock and processed food sectors, consumer responses to price changes, dietary changes, and international trade. Water, land, and fertilizer inputs are treated as exogenous and unchanging in the no-adaptation scenario.

3.4 Decomposition Methods

We use the GEMPACK software utility to decompose the results in two ways. First, we utilize GEMPACK's "subtotal" feature (Harrison and Pearson 1996; Harrison et al. 2000) to identify the relative importance of the pandemic, weather, and other shocks on each of our outcome metrics. Second, we decompose the relative influence of local water, regional land, and global trade adaptation options on undernutrition metric outcomes by successively turning these options off in the model simulations.

4 Results

We assess the impact of compound events for adaptation and no-adaptation scenarios. Comparing the two scenarios highlights the value of global adaptation channels (e.g., changes in international trade) and local adaptation measures (e.g., irrigation).

4.1 Change in GHG Emissions in the Absence of Adaptation

Globally, the compound pandemic and weather shocks lower GHG emissions from the food sector by 11.5%, with the largest changes occurring in South Africa and Europe (Fig. 17.3a). These reductions are due to relatively larger negative shocks, lower agricultural production levels, and reduced food transportation. This finding is consistent with observations made during the first year of the COVID-19 pandemic (Diffenbaugh et al. 2020). However, GHG emissions from the food sector increase slightly in the Middle East, China, and Central Asia. These increases are caused by higher crop production and transportation occurring in regions with the capacity to produce more food under the combined shock scenario. In all three of the regions showing increases in GHGs, total shocks to crop yields (weather and additional shocks) are positive, allowing them to become key suppliers in the short run.

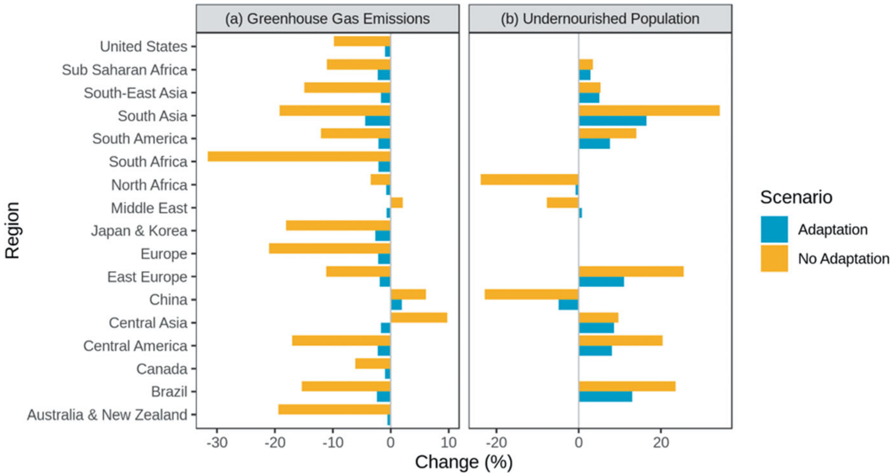

Fig. 17.3 Percentage change in (**a**) greenhouse gas emissions from the agricultural sector and (**b**) undernourished populations in developing nations due to the compound shocks, with and without adaptations The magnitude of the impacts on both emissions and food security varies regionally, although most regions experience a decline in emissions and an increase in the undernourished population. Comparing the adaptation (*blue*) to the no-adaptation (*yellow*) scenarios shows that adaptations reduce the impact of the compound disaster in all cases. In Table 2 and Fig. S3, Haqiqi et al. (2023) report results for the undernourished population in units of millions of people. Note that wealthier regions have no estimate of the change in undernourished population as the FAO methodology is only appropriate for low-income regions; these omitted regions are the United States, South Africa, Japan, Korea, Europe, Canada, Australia, and New Zealand

4.2 Change in Food Security in the Absence of Adaptation

Without adaptations, global food security declines significantly. The number of undernourished people in developing countries increases by 12.51%, from 426 million to 479 million people (Table 17.2). Notably, there are changes in both directions due to regional variations; we arrive at the net change of 53 million people through an increase of 66 million people in negatively affected regions and a decrease of 13 million people in positively affected regions (Table 17.2). The regional variation is considerable, with changes of up to ±20%. Decomposition of the shocks' relative impacts on nutritional outcomes (Fig. 17.4a) shows that all three shocks (pandemic, weather, and additional) contribute to a decline in the number of undernourished people in China. For all eight regions with increases in undernourished populations, the pandemic shock (red bar) is the largest contributor to the food security crisis (Fig. 17.4a).

Table 17.2 Undernourished population by region in the initial condition (no disaster) and change in undernourished population due to the compound disaster with and without adaptation

	Initial undernourished population (million people)	Compound disaster impact, no adaptation (million people)	Compound disaster impact, with adaptation (million people)	Change due to adaptation (million people)
Sub-Saharan Africa	119.58	4.16	3.40	−0.77
Southeast Asia	39.88	2.12	2.02	−0.10
South Asia	148.85	51.19	24.49	−26.70
South America	9.43	1.32	0.72	−0.60
North Africa	2.34	−0.56	−0.02	0.54
Middle East	15.97	−1.25	0.14	1.38
East Europe	6.50	1.66	0.72	−0.94
China	50.16	−11.45	−2.44	9.00
Central Asia	9.29	0.90	0.80	−0.10
Central America	14.84	3.04	1.20	−1.84
Brazil	9.18	2.17	1.20	−0.97
Total	426.01	53.30	32.21	−21.09

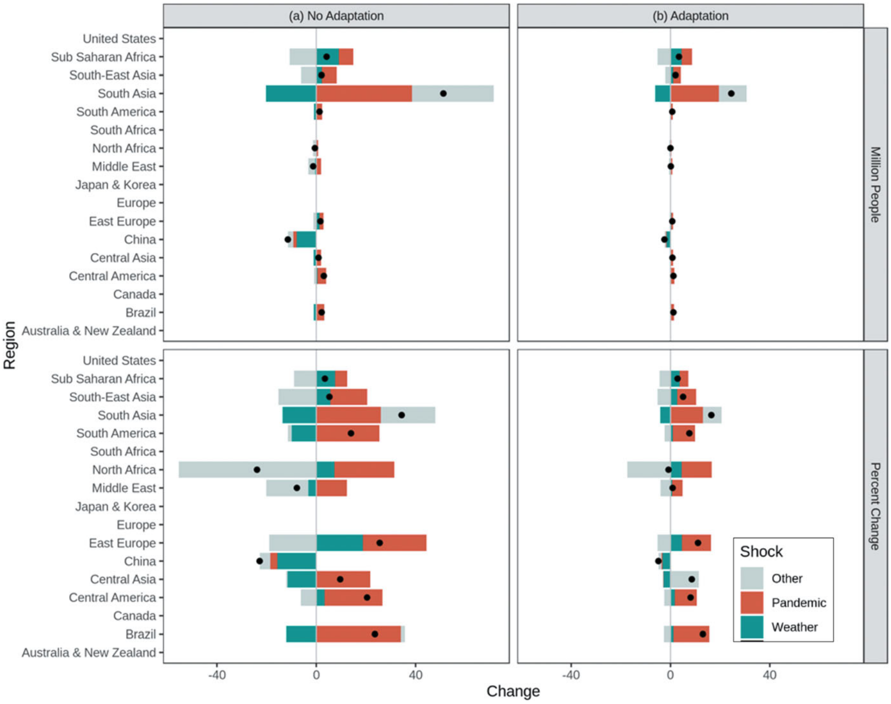

Fig. 17.4 Decomposition of the drivers of change in undernourished populations under the (**a**) no-adaptation scenario and (**b**) adaptation scenario The top row shows undernourished population changes in units of millions of people, and the bottom panel shows results as percentage changes. For each region, the impact of component shocks on the final outcome is shown; individual impacts can be positive or negative. The total resulting outcome is shown with a black dot. Note that developed regions have no estimates of change in undernourished population; these regions are the United States, South Africa, Japan, Korea, Europe, Canada, Australia, and New Zealand

4.3 Changes in GHG Emissions Under Adaptation

When adaptations are included, GHG emissions from the agricultural sector decline by 1.8% globally in the compound disaster scenario. This is a smaller decline than that under the no-adaptation scenario, as the adaptations help reduce the shocks' negative impacts on agricultural production through higher volumes of international trade and transportation. There are two exceptions: Central Asia and the Middle East, where declines in GHG emissions from the no-adaptation scenario switch to increases in GHG emissions when adaptation options are allowed to play out (Fig. 17.3).

4.4 Changes in Food Security Under Adaptation

In the scenario of a combined shock including adaptations, there is a 7.6% increase in the undernourished population in developing nations. While an increase of ~32 million people is an adverse development, it is an improvement over the increase of 53.3 million people that occurred in the no-adaptation scenario (Table 17.2). Adaptations prevent the compound disaster from causing undernourishment for approximately 21 million people in developing nations, with most of the change occurring in South Asia (Figs. 17.3b and 17.4). Adaptations have significant impacts on reducing undernourishment and mitigating the adverse consequences of compound disasters within and across regions.

The reduced impact and spatial distribution of undernourished populations in this scenario, compared with those in the no-adaptation scenario, arise from factors at the global, regional, and local levels. With global international trade, farmers with relatively more favorable weather conditions can benefit from higher prices in local and global markets, earning higher profits while simultaneously producing more food for the global market (thus pushing down prices) and reducing the malnourishment caused by high food prices. Local irrigated farms will also benefit from higher yields for irrigated crops compared with rainfed crops, especially under heat stress. Farmers with access to groundwater may benefit more when responding to surface water scarcity and higher local prices. Additionally, consumers in regions that experience large reductions in domestic production can buffer against high increases in local prices by importing food from overseas.

In the three regions where food security improves under the no-adaptation scenario, the outcome is less favorable under adaptation: In the Middle East, where undernourishment fell by −8% under no adaptations but increased by +1% with adaptations, North Africa (−24% to −1%), and China (−23% to −5%). While all three adaptations contribute to this reversal, the largest driver is global trade (Fig. 17.5). As an example of one of the few regions with positive shocks to crop yields, the Middle East (mostly Türkiye) is able to produce more food in both the no-adaptation and adaptation scenarios; even without any adaptations, the positive crop yield shock causes higher food production. Under the no-adaptation scenario, the produced food could only be supplied domestically (within the Middle East). With adaptations, this extra food was exported from Türkiye in the Middle East region to take advantage of the higher global crop prices. (Global crop prices increase by 8.84% in the adaptation scenario.) This price rise leads farmers in the Middle East to benefit financially from exports but causes regional consumers to suffer from the price increase, boosting undernourishment.

Positive values indicate that the adaptations increase the undernourished population relative to the no-adaptation scenario; negative values show that adaptations lead to improvements in food security by reducing the number of undernourished people. Each adaptation can cause positive or negative changes; the net change in each region is shown with a black dot. Note that developed regions have no estimate

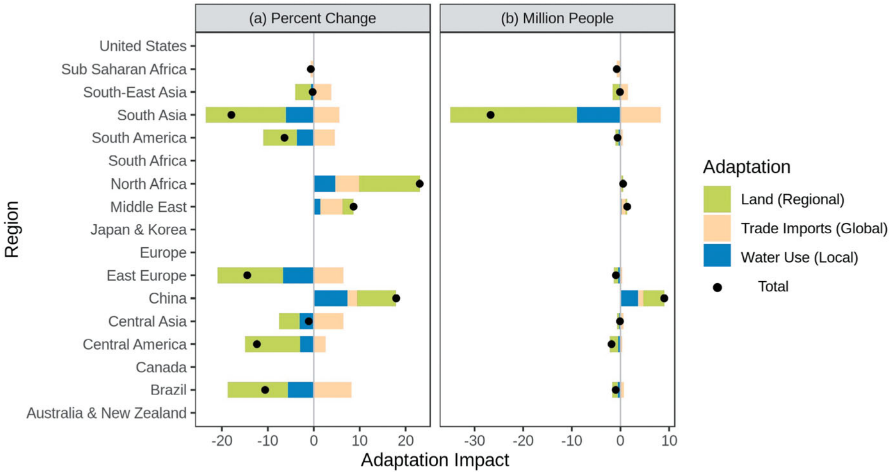

Fig. 17.5 Decomposition of adaptation contributions to changing undernourished populations compared with the no-adaptation scenario in (**a**) percentage change and (**b**) millions of people

of change in undernourished population; these regions are the United States, South Africa, Japan, Korea, Europe, Canada, Australia, and New Zealand.

Overall, global trade adaptations have the largest impact on changes in the undernourished population (Fig. 17.5), accounting for 57% of the improvement in food security when compared with the no-adaptation scenario. In total, global trade reduced undernourished populations by approximately 12 million people compared with numbers under the no-adaptation scenario, and regional variation shows that this net change is due to an increase of around six million and a decrease of around 18 million in the number of undernourished people (Fig. 17.5). The next largest adaptation impact is from land adaptation at the regional level, which accounts for 36% of the total adaptation impact; local water adaptation accounts for the remaining 7%.

5 Discussion

The COVID-19 pandemic and climate change are two major threats facing humanity. Extreme weather events such as droughts, floods, heat waves, and storms can have devastating effects on food security, water availability, infrastructure, and ecosystems. When these events happen alongside a pandemic, they create compound weather–pandemic stresses that can overpower the ability of individuals, communities, and nations to cope with them. This section discusses the likely impacts of this compound stress and evaluates its implications for global and local food security.

5.1 Model Limitations

This study uses a linked modeling framework; each model has its own limitations, uncertainties, and biases. A general discussion of these limitations can be found in the model-specific literature of the hydrologic model (Wisser et al. 2010; Zuidema et al. 2020; Grogan et al. 2022), the global crop water model (Siebert and Döll 2010; Haqiqi et al. 2023), and the SIMPLE-G model (see Part III) and related applications (Baldos et al. 2023; Haqiqi 2023; Liu et al. 2023; Ray et al. 2023).

The most important model limitation to discuss here is the assumptions about the distribution of undernourished population. It is likely that this model underestimates the food security outcomes from the combined pandemic and weather events. We believe this to be the case because of our assumptions that the income shock is homogeneous across the entire population and that within-country income distributions do not change. In reality, individuals living in poverty tend to suffer greater impacts under both pandemic-type income shocks and all types of food price increases (Hoogeveen and Lopez-Acevedo 2021; World Bank 2022). This suggests that a compound pandemic–weather shock would disproportionately impact people in the lower range of the income distribution and that this income distribution would shift so that a larger share of the population would occupy the lower range.

The modeling framework used here provides novel insights into some key impacts of the combined shock implemented. However, no model can capture all social, economic, and environmental impacts, the combined shock evaluated here would inevitably have impacts on parts of the system not captured by our modeling framework. These impacts include—but are certainly not limited to—health metrics other than undernourishment, migration spurred by changing socioeconomic conditions, economic impacts on the nonagricultural sectors of the global economy, and changing ecosystem services and their economic impacts as patterns of crop production change.

5.2 Adaptation Codependencies

We simulated three adaptations here: changes to local water use, changes to regional cropland use, and changes in global trade. These options span the local-to-global scales at which agricultural activity and the global food market adjust to shocks, and it may seem that such disparate scales operate separately; however, this modeling framework was built because each scale interacts with the others, aggregating local changes up to global level and global changes in turn impacting local action. While we decompose the relative impacts of each of these adaptations, it is important to note that implementing any of these impacts independently within the modeling framework would not result in the changes reported by the decomposition, because they interact with one another. Increased exports to the global market are driven in part by increased production; this extra production will not occur unless regional and/or local adaptations provide greater inputs of land and/or water. Conversely, local adaptations aimed at increasing production will only occur if global food prices make such extra investments in land and water profitable.

5.3 Compound Shock Interactions

The compound shock scenario evaluated here was designed to stress multiple interacting components of the human–earth system. While we decompose the relative importance of each of the two hazards (Fig. 17.4), this decomposition does not tell us the impact of each hazard alone, nor does it show whether the interaction of the two hazards reduces or increases the impacts. To test whether the interaction effect is synergistic or additive, we have calculated the magnitude of this effect (Haqiqi et al. 2023). Isolating individual stressors and regions reveals that the interaction effects can be synergistic (e.g., when looking at prices) or antagonistic (e.g., when looking at undernourishment), as shown in Fig. 17.6. However, this is not a general rule: Rather, the direction and magnitude of the interaction effect depend on location-specific elasticity parameters. Food price elasticities are important in responses to supply-side shocks (weather-driven) and demand shifts (pandemic-driven). For more details, refer to Haqiqi et al. (2023).

Figure 17.6 illustrates the interaction effect if we isolate only one region, SSA (Sub-Saharan Africa), and two shocks (pandemic or weather). The scenarios show a reduction in gross domestic product (GDP) (5% or 10%) and/or crop yields (10%) only in SSA. (**a**) A indicates the magnitude of the impact of the weather-only shock and B indicates the interaction effect. (**b**) C indicates the magnitude of the impact of the weather-only shock and D indicates the interaction effect.

5.4 Environmental Impacts

There has been discussion in the literature about the potential for the pandemic to reduce negative anthropogenic impacts on the environment, especially GHG emissions (Diffenbaugh et al. 2020; Khan et al. 2021; Smith et al. 2021; Kumar et al. 2022). Our findings show that GHG emission reductions from the agricultural sector are modest in the face of combined pandemic and weather shocks. Under the no-adaptation scenario, we find an 11.5% reduction in GHG emissions from the agriculture sector. As this sector accounts for approximately 30% of annual GHG emissions, this represents a reduction of 3–4% in total global GHG emissions. Forward-looking economic studies suggest that the short-term declines in GHG emissions, even when considering larger emissions reductions from the transportation sector, will quickly return to pre-COVID levels and potentially even exceed those levels as countries relax emissions policies in an attempt to reverse economic losses (Smith et al. 2021), while others point to the dramatic short-term changes in

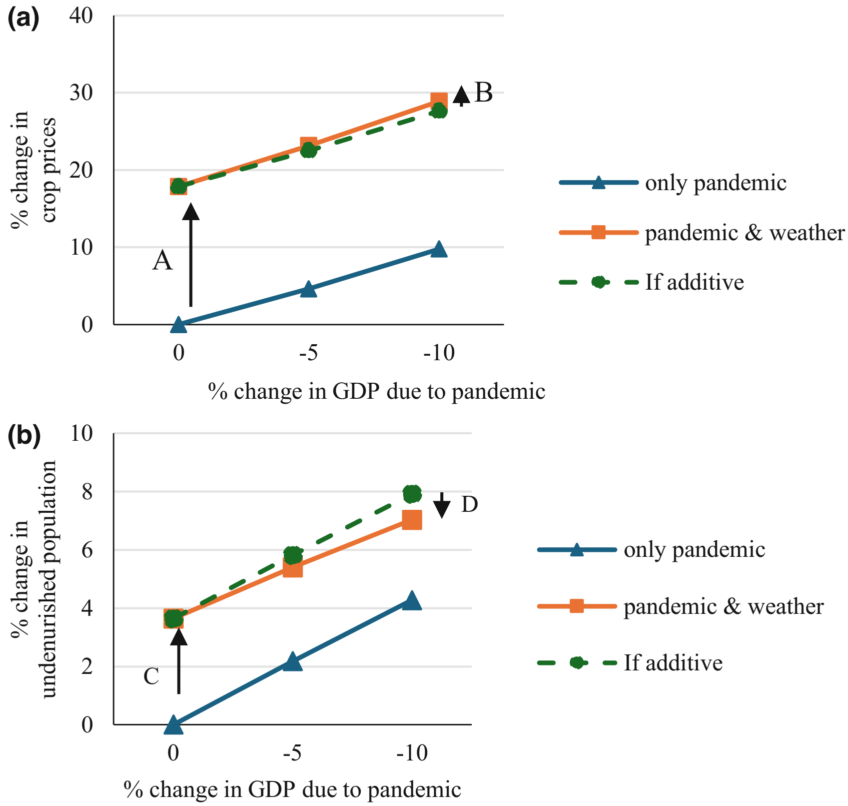

Fig. 17.6 The interaction effect of weather and pandemic on (**a**) crop prices and (**b**) undernourishment outcomes in Sub-Saharan Africa

GHG emissions and other pollutants as evidence that anthropogenic impacts can be reversed (Le et al. 2020; Khan et al. 2021). We add to this discussion the point that GHG emissions are not independent of adaptations. These adaptations are critical for reducing food security impacts on an annual time scale, and both the environment and food security should be evaluated in a cohesive framework. Echoing recent literature that considers both the economy and weather extremes together, more aggressive policy interventions will be required to maintain decreases in GHG emissions while recovering economically from the pandemic (Cheng et al. 2021; D'Orazio 2021; Smith et al. 2021), as pandemics and weather are short-term shocks while climate change occurs on decadal (approximately 30-year) time scales. Furthermore, while there has been a focus on how the pandemic has altered environmental indicators like GHG emissions, we argue that it is also important to consider the reverse: Protecting the environment and natural resources like land and water during nonstress years can make a difference in our ability to quickly adapt to short-term stresses. For example, one component of the water adaptation simulated here is the ability to switch from surface water to groundwater for irrigation. This is only possible if aquifer resources are protected against depletion during nonstressed years (recall Chap. 16) and if policies that enable annual-scale investment in infrastructure like groundwater wells and pumps are enacted.

6 Conclusions

The COVID-19 pandemic did not coincide with major weather shocks affecting food production. However, with increasing weather extremes, it is possible that such a global economic shock could coincide with severe environmental stresses. To investigate the potential consequences for food security and sustainability, we employ a global gridded biophysical-economic framework that permits us to explore the interactions between economic and nature-induced stresses on the global food system. The results illustrate the significance of adaptation options in the case of a pandemic combined with environmental stresses. Employing this modeling framework, we can identify hotspots of food insecurity vulnerable to compound shocks.

We find that, of the three adaptations implemented, global trade has the largest beneficial impact on food security. While irrigation is also important at the local level, international trade can buffer the impact of future rainfall and irrigation shortfalls (Liu et al. 2014). While global trade was the largest driver of food security improvements between the no-adaptation and adaptation scenarios, increased trade could not have occurred if there had been no adaptation in demand and supply capacity. Effective adaptation requires adaptations across scales, from local to global.

Even with adaptation, there will be a significant increase in the number of undernourished people in South Asia, Sub-Saharan Africa, and Central and South America in the presence of such a compound pandemic–weather event. These results are relevant to policy, as they highlight the significance of economic and financial relief to combat hunger and undernutrition caused by compound short-term stresses. Given the likelihood of environmental stressors and future pandemics, we can decrease the future costs of such compound events by mitigating climate change and ensuring that resources like land and water—along with the investments and the infrastructure (Lobell et al. 2013; Baldos et al. 2020a, b) required to make full use of those resources—are available. Finally, the adverse effects of pandemics and environmental shocks can be mitigated through global trade most effectively when paired with adaptive local and regional resource use.

We have explored the complex relationship between compound pandemic–environment extremes and their significant impact on food security and emissions. However, many intriguing questions need further investigation. For instance, what are the effects of changes in food loss and waste combined with a pandemic on a global scale? What about the human element? Will rising temperatures slow the productivity of agricultural labor? Finally, can sustainable groundwater governance act as a resilient buffer, supporting our food systems against future extreme shocks? These fascinating questions, which are still unanswered, are an invitation to the next chapter of future directions. It is clear that as we continue to explore the intricate linkage between environmental pressures and food security, we need both rigorous analyses and measurements of adaptation. Through continued research and innovative policies, we hope to create a more sustainable future where food security thrives and the environment is protected by sustainable practices.

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