Online Resource 2

How resilient is the United States' food system to pandemics**?**

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Supplemental 1 – Experiment 1: The effect of worker absenteeism on the transportation system

In the model, the transportation system moves necessary inputs to farms, from farms to processors, from processors to distributors, and from distributors to retail outlets. The only variable manipulated is the rate of worker absenteeism in the transportation system (i.e., a sensitivity analysis). No other variables were manipulated in the model. All other systems and their corresponding variables in the model were set to operate at their maximum capacity (e.g., communication, electricity, fuel, water, and waste). In real life, worker absenteeism could cause degradation to these other necessary systems and their disruption could independently disrupt the food and system. These combinations of disruptions are not tested. The inventory of the food supply upstream of food processors (at farms), which is the largest food storage in the system, is never transported to consumers (Figures S1 & S2 and Table S2). Therefore, there is essentially no food available to consumers at pandemic-level worker absenteeism (30% worker absenteeism peaks in the middle of a 188 day wave).

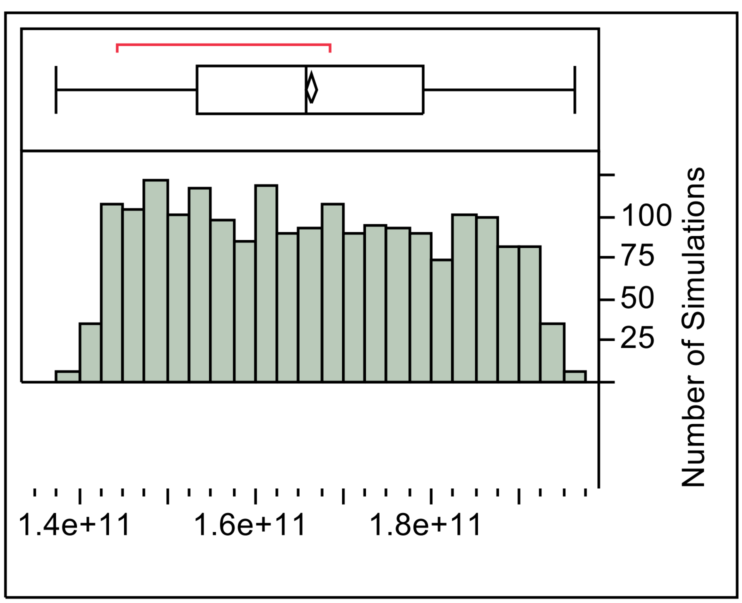

Figure S1. Histogram (below) stacked with box and whisker plot (above) of the distribution of cumulative hunger-days (X axis) over 800 days, over 2,000 model simulations. The results indicate a significant reduction in the amount of available food during a pandemic. The median of 2,000 simulations is roughly 566 hunger-days per person, in the United States.

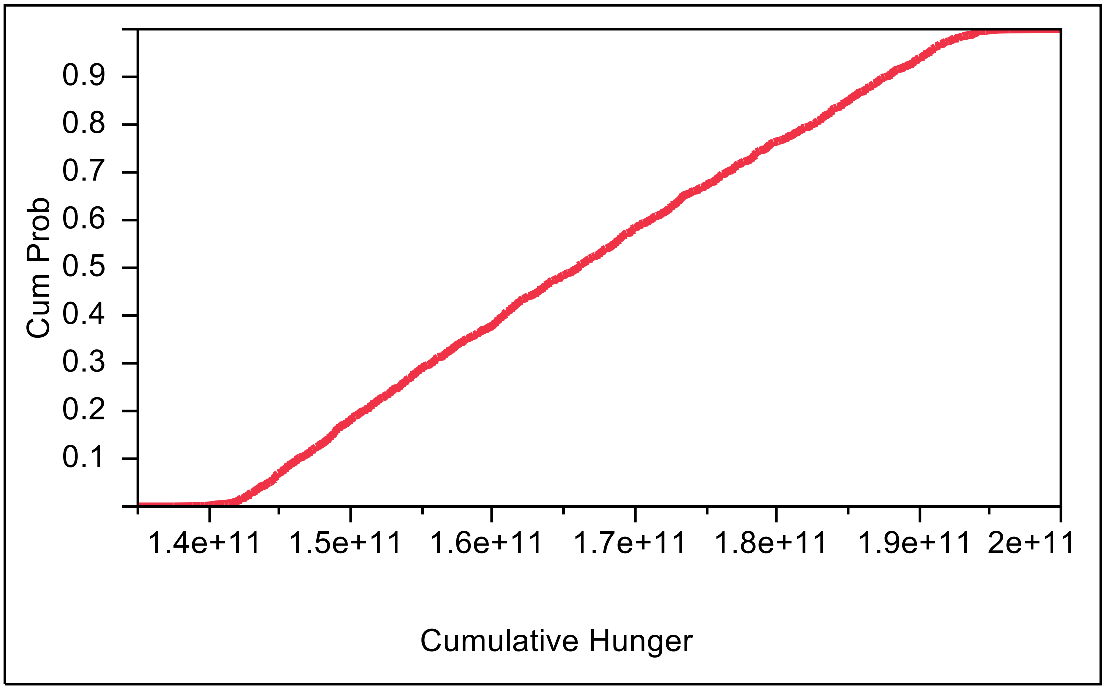

Figure S1. The cumulative distribution function plot illustrating the relationship between cumulative hunger-days and their probability of occurrence.

Table S1. Quantiles and moments; all quantiles result in an amount of hunger-days that are not survivable.

Quantiles			**Moments**	
100.0%	maximum	2e+11	Mean	1.664e+11
99.5%		1.9e+11	Standard Deviation	1.504e+10
97.5%		1.9e+11	Standard Error Mean	336,362,593
90.0%		1.9e+11	Upper 95% Mean	1.67e+11
75.0%	quartile	1.8e+11	Lower 95% Mean	1.657e+11
50.0%	median	1.7e+11	N	2,000
25.0%	quartile	1.5e+11		
10.0%		1.5e+11		
2.5%		1.4e+11		
0.5%		1.4e+11		
0.0%	minimum	1.4e+11		

Supplemental 2 – Experiment 2: The effect of worker absenteeism on food production

In the model, workers are necessary at farms, and at processing and packaging facilities, to produce food. The only variable manipulated is the rate of worker absenteeism in food production (not transportation). All other systems and their corresponding variables in the model were set to operate at their maximum capacity, including transportation. Thus worker absenteeism variable was only manipulated within the food production elements within the food system (i.e., farms, processors and packagers, and in retail outlets). This scenario analyzes the dependency between worker absenteeism and the production of food in the food system.

Allowing food production to occur with some fraction of the available workforce gives insight into the second research question (described in the methods section). With the workforce coefficients sampled log-uniformly between 0.1 and 1, the median (.5) run has less than 1 hunger-days (.74 hunger-days per person in the United States), implying that existing food stores might satisfy the aggregate demand with a reduced workforce in food production (given adequate functioning of food transportation). However, the peak number of hunger-days observed in 2,000 simulations was 81 billion (270 days of hunger for every person in the United States), and the upper quartile value of 12 billion hunger-days (Table S2) still represents a significant problem of food availability during a pandemic (40 days of hunger for every person in the United States), as illustrated in Figures S3 and S4.

Table S3. Quantiles and moments; only quantiles above 50% result in an amount of hunger-days that are not trivial (greater than 40 hunger-days per person in the United States).

Quantiles			Moments	
100.0%	maximum	8.1e+10	Mean	7.7992e+9
99.5%		5.9e+10	Standard Deviation	1.228e+10
97.5%		4.3e+10	Standard Error Mean	274482247
90.0%		2.5e+10	Upper 95% Mean	8.3375e+9
75.0%	quartile	1.2e+10	Lower 95% Mean	7.2608e+9
50.0%	median	2.23e+8	N	2,000
25.0%	quartile	0		
10.0%		0		
2.5%		0		
0.5%		0		
0.0%	minimum	0		

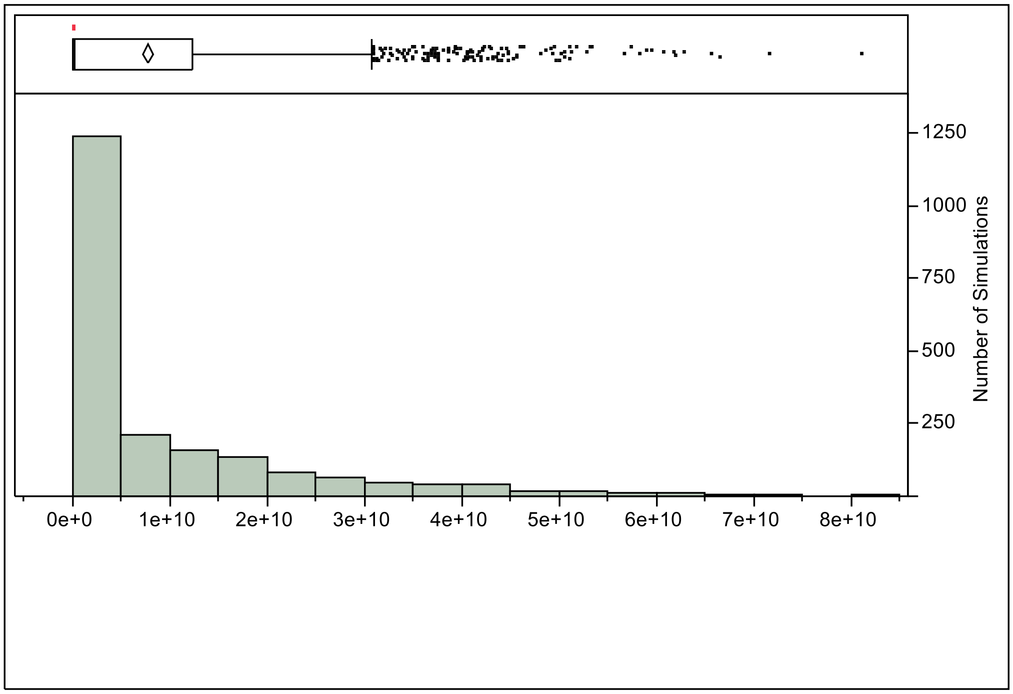

Figure S3. Histogram (below) stacked with box and whisker plot (above) of the distribution of cumulative hunger-days (X axis) over 800 days, over 2,000 model simulations. The results indicate a significant reduction in the amount of available food during a pandemic due to worker absenteeism in food production (not transportation). The median of 2,000 simulations is roughly 16 hunger-days per person.

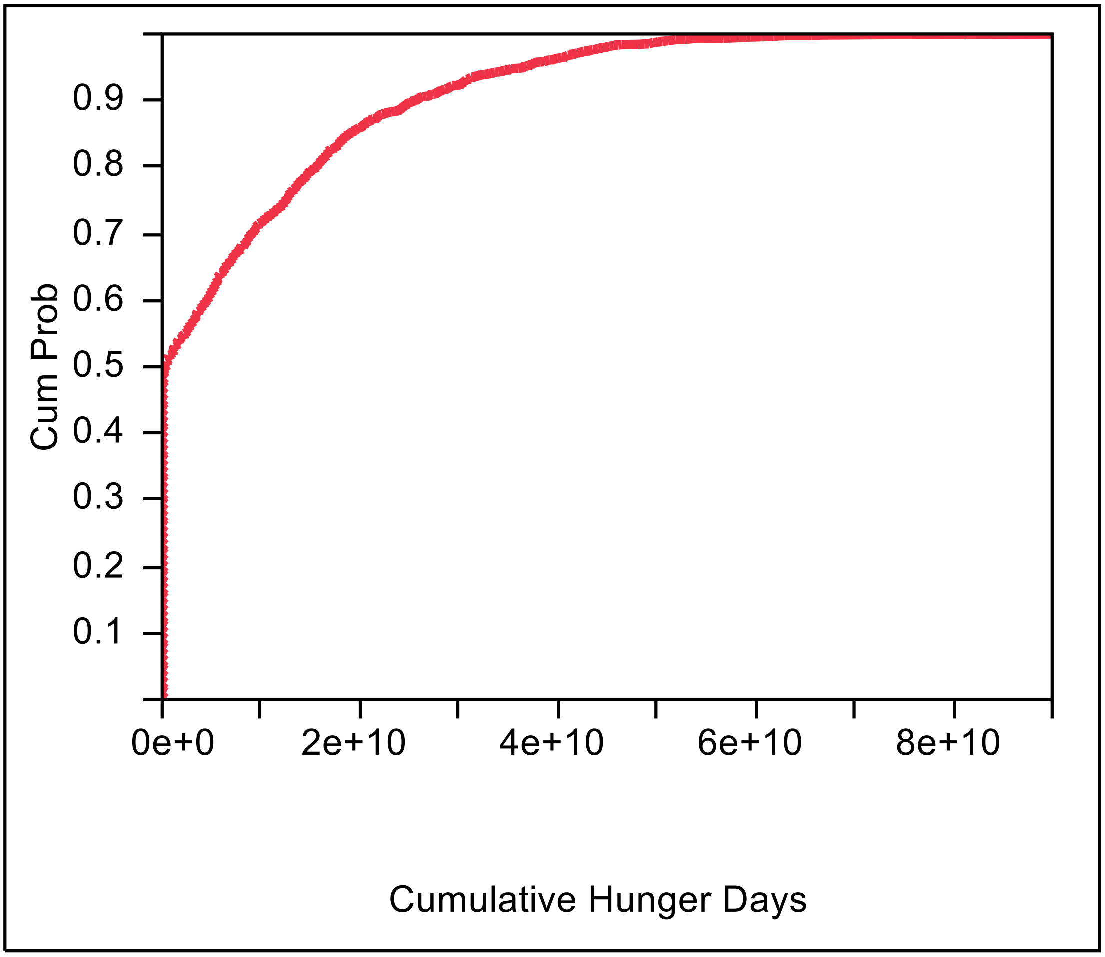

Figure S4. The cumulative distribution function plot illustrating the relationship between cumulative hunger-days and their probability of occurrence. There is greater than a 50% chance that worker absenteeism in food production will result in a non-trivial amount of hunger-days

Supplemental 3 – Experiment 3: Increasing food storage at farms when food production is decreased

In this experiment, the amount of food stored at farms was increased. In the model, and in reality, there is a limited amount of food stored at all points in the food supply chain (i.e., at the farms, at processor and packaging facilities, at distribution centers, and at retail stores). Typically the largest sources of storage in the system are at farms and at retail outlets, with only the minimum amount of food stored in the middle of the supply chain (due to the just-in-time nature of the United States food system). In previous simulations, a value between 50-150 days of food was randomly selected for each simulation. The amount of food available was increased by randomly selecting from a range of 200-500 days of food. While increasing the amount of stored food at farms would be a difficult policy to implement, the purpose was to determine if increasing the amount of stored food would have an effect on food availability when food production was diminished due to worker absenteeism.

The primary factors controlling food system performance are the production/labor coefficient (worker absenteeism) on farms, and the food inventory on hand at farms and at processors. Small values of the production/labor coefficient (labor production sensitivity), which correspond to high sensitivity of the food production rate (due to labor unavailability or worker absenteeism), are associated with the most consequential outcomes (Figure S4). The policy option of storing additional food at the farm is analyzed, and additional food storage at the farm level does not greatly reduce the amount of hunger-days (Figure S5). The most sensitive parameter continues to be worker absenteeism in food production (Figure S6). The probability of the event did not change greatly compared to supplemental 2, and is illustrated in Figure S7.

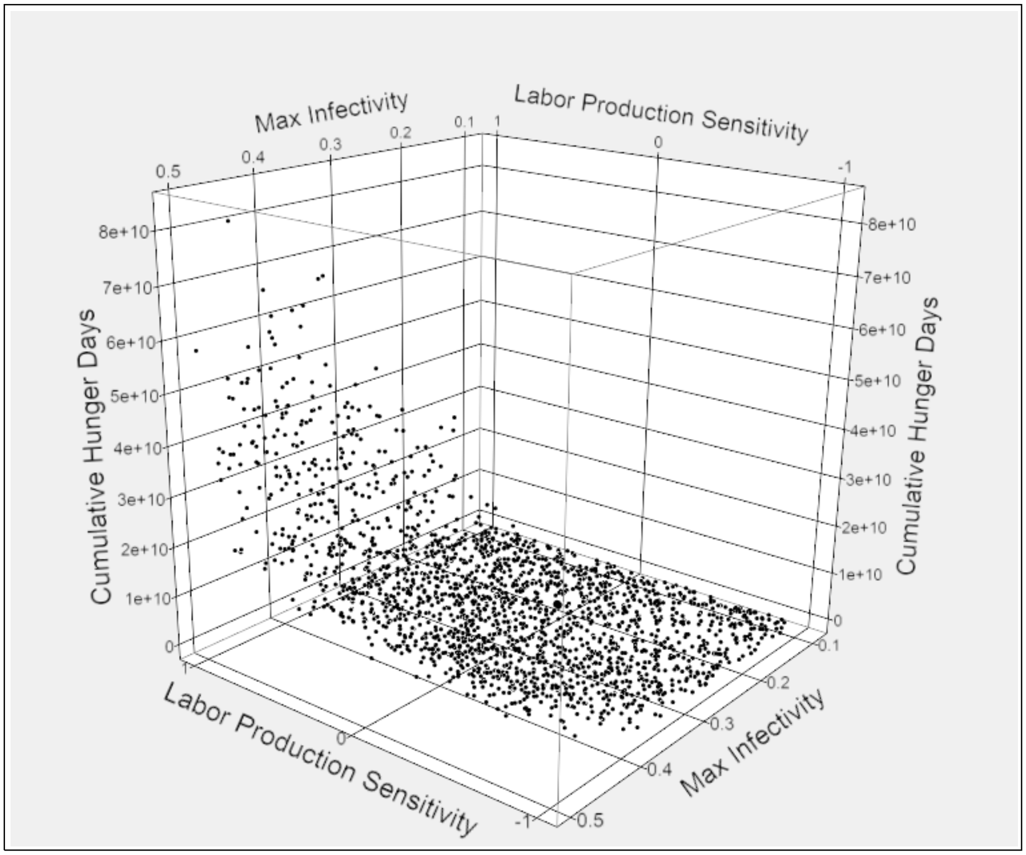

Figure S4. A three-dimensional scatter plot of the results of 2,000 simulations, over 800 days, where less than 50% of the simulations do not result in food shortages of significance. The relationship between excess stockpiles at the farm level is compared with worker absenteeism and the effects are measured in cumulative hunger-days. This portion of the analysis and illustration does not account for the effects of system interdependencies (i.e., transportation, sanitation and waste, water, electricity, fuel). Of most significance, worker absenteeism (infectivity) has a more dominant influence on the amount of hunger-days than food storage, thus food storage was not included on this plot.

Figure S5. Comparison of food stored on farms and cumulative hunger-days. As the amount of food stored at farms was increased, there was not a significant decrease in the amount of hunger-days in the United States.

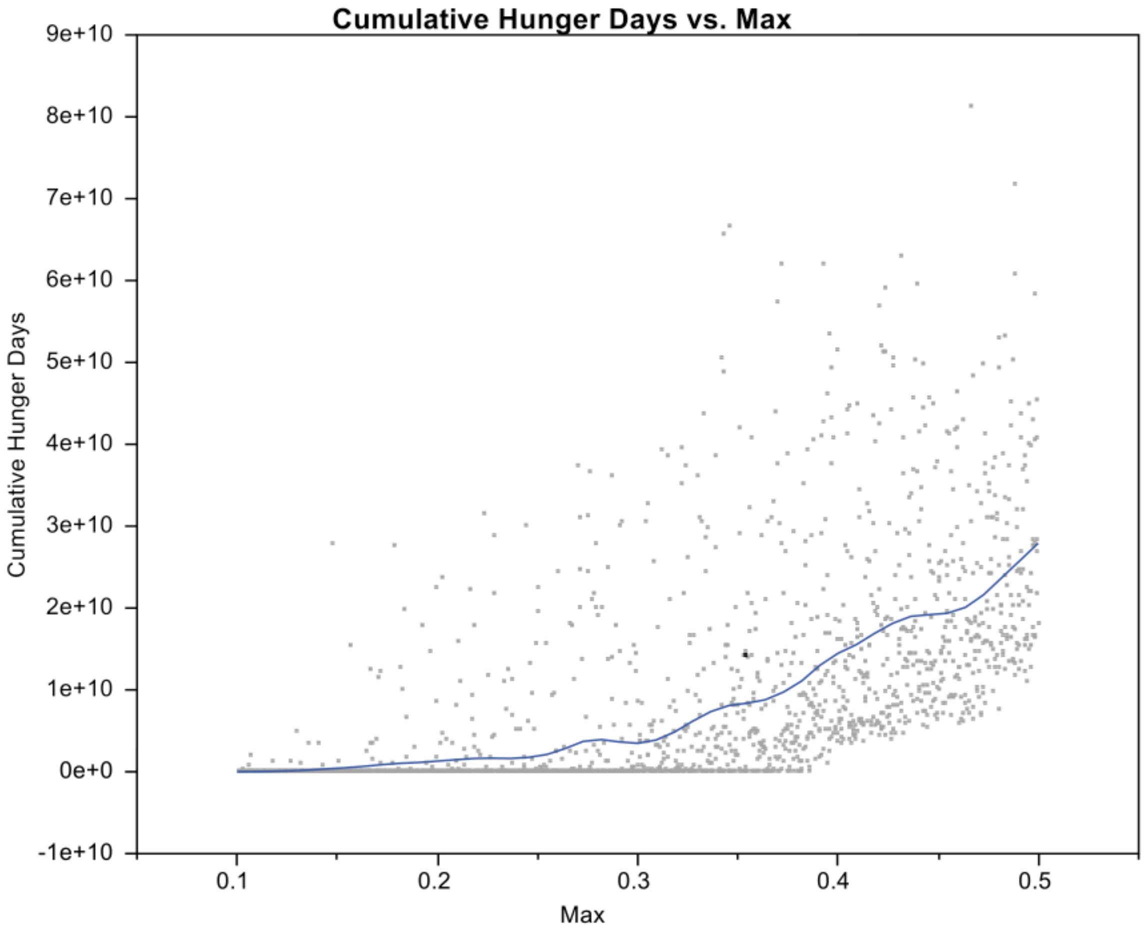

Figure S6. Worker absenteeism (x axis) is the most sensitive parameter, and additional food storage has little effect on the amount of cumulative hunger-days. The blue line is the median of cumulative hunger-days.

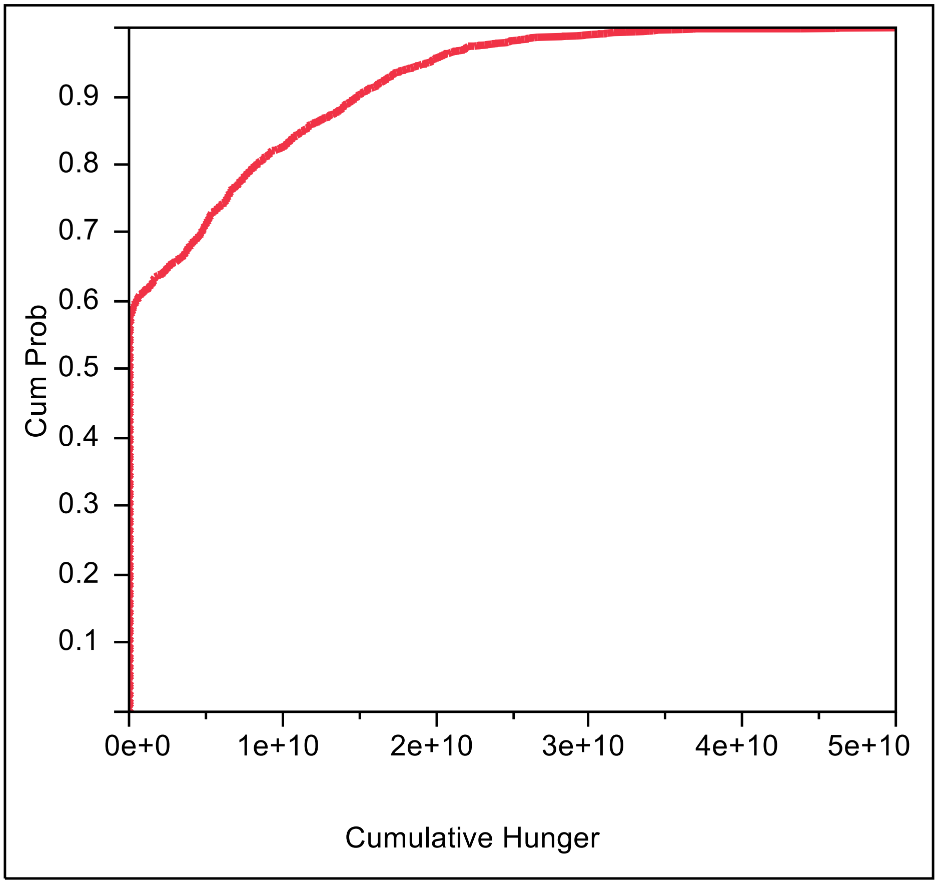

Figure S7. The cumulative distribution function plot illustrating the relationship between cumulative hunger-days and their probability of occurrence. There is greater than a 60% chance that worker absenteeism in food production will result in a non-trivial amount of hunger-days, even when food storage is increased at farms.

Supplemental 4 – Experiment 4: Worker absenteeism effect on food production and transportation

Worker absenteeism was restricted to 30% maximum in transportation. While worker absenteeism was restricted to 30%, the sensitivity of worker absenteeism on transportation and food production were tested. In this case, worker absenteeism gradually rises over the first wave from 10% to 30%. This scenario is meant to test a more realistic situation where a pandemic causes worker absenteeism in food production and in food transportation.

Significant shortages appear when the food production coefficient is greater than 0, (i.e., when the proportional difference in food production is larger than the proportional reduction in the workforce). The food system is more tolerant of reduction in transportation capacity; however, as the transportation coefficient approaches 1 all simulations show widespread shortages of food, and the probability of the event does not change greatly compared to other scenarios, and the severity of hunger-days is reduced (Table S4), as illustrated in Figure S8.

Table S4. Quantiles and moments; only quantiles above 75% result in an amount of hunger-days that are not trivial (greater than 15 hunger-days per person in the United States).

Quantiles			Moments	
100.0%	maximum	5.9e+10	Mean	4.3023e+9
99.5%		4.7e+10	Standard Deviation	8.4632e+9
97.5%		3.2e+10	Standard Error Mean	189242255
90.0%		1.5e+10	Upper 95% Mean	4.6734e+9
75.0%	quartile	4.56e+9	Lower 95% Mean	3.9311e+9
50.0%	median	1.52e+8	N	2,000
25.0%	quartile	0		
10.0%		0		
2.5%		0		
0.5%		0		
0.0%	minimum	0		

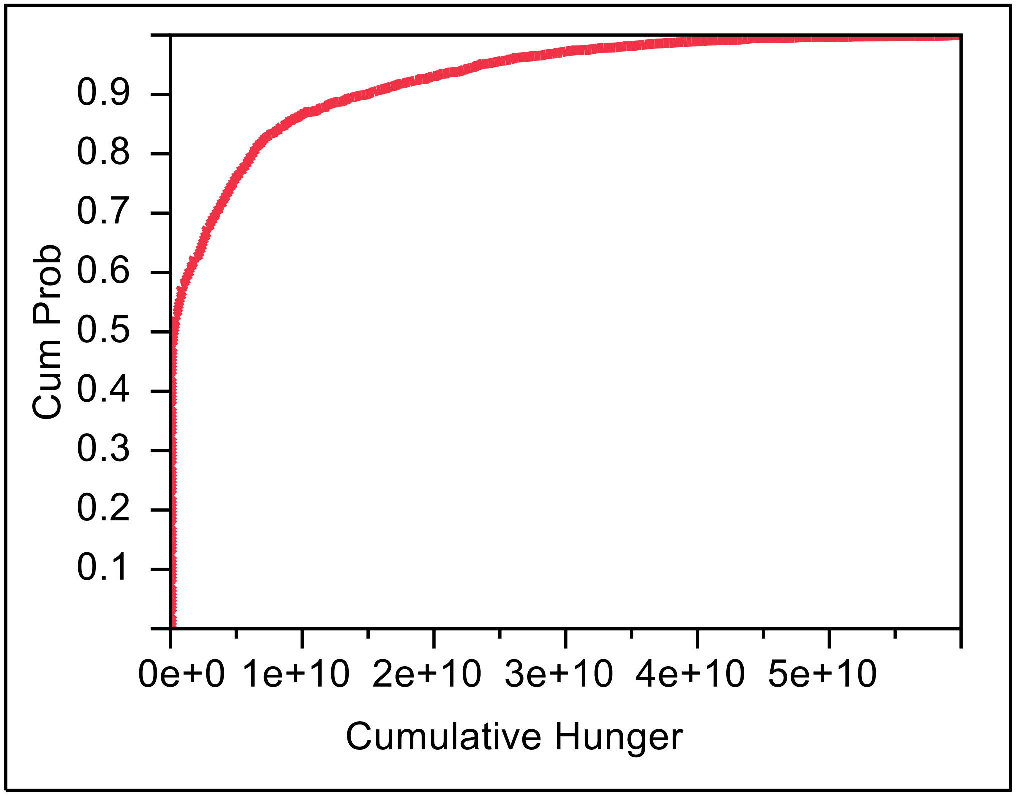

Figure S8. The cumulative distribution function plot illustrating the relationship between cumulative hunger-days and their probability of occurrence. There is a 50% probability that worker absenteeism in food production will result in a hunger-days, although the severity is somewhat reduced.

Supplemental 5 – Experiment 5: 20% fixed worker absenteeism

Worker absenteeism is restricted to a fixed 20% during the pandemic waves. While this is not realistic, the resulting simulation provides information on the effects of lower levels of worker absenteeism on the food system and the overall available amount of food. The resulting simulation provides information on the effects of lower levels of worker absenteeism on the food system and the overall available amount of food. There is a higher probability of no starvation (Table S5), which is reasonable given the non-linear effect of labor loss on production for the high-consequence cases (Figure S9).

Table S5. Quantiles and moments; only quantiles above 75% result in an amount of hunger-days that are not trivial (greater than 15 hunger-days per person in the United States). The population is not severely effected until the 90% quantile.

Quantiles			Moments	
100.0%	maximum	6.2e+10	Mean	2.7021e+9
99.5%		3.7e+10	Standard Deviation	7.1315e+9
97.5%		2.6e+10	Standard Error Mean	159464825
90.0%		1.1e+10	Upper 95% Mean	3.0148e+9
75.0%	quartile	2.67e+8	Lower 95% Mean	2.3894e+9
50.0%	median	0	N	2,000
25.0%	quartile	0		
10.0%		0		
2.5%		0		
0.5%		0		
0.0%	minimum	0		

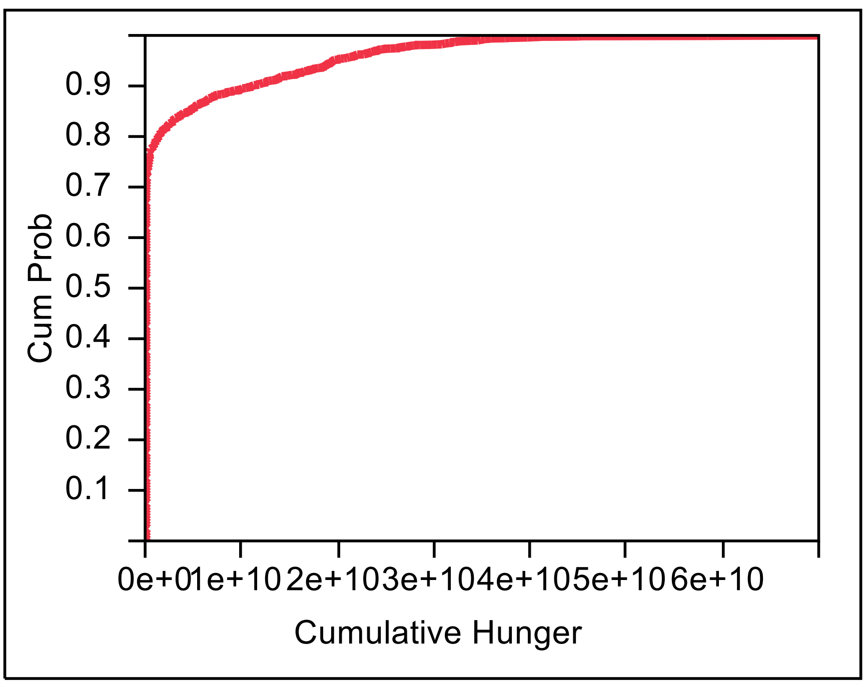

Figure S9. The cumulative distribution function plot illustrating the relationship between cumulative hunger-days and their probability of occurrence. There is greater than an 80% chance that worker absenteeism in food production will not result in hunger-days. However, the severity is not greatly reduced.

Supplemental 6 – Experiment 6: A single wave pandemic with 35% worker absenteeism

A single wave of absenteeism occurs with: 15 days of worker absenteeism at 10%; followed by 20 day period where worker absenteeism increases from 10% to 35%; then 30 days at a peak of 35% worker absenteeism. At the end of the duration of the peak worker absenteeism period, worker absenteeism declines to 10% over 20 days and is followed by 15 days of worker absenteeism at 10% before the simulation is stopped. The population could experience roughly 4 hunger-days (Table S6) during a 120 day time period (Figure S10).

Table S6. Quantiles and moments; only quantiles above 75% result in an amount of hunger-days that are not trivial (greater than 4 hunger-days per person in the United States). The population is not severely effected until the 90% quantile.

Quantiles			Moments	
100.0%	maximum	6.75e+9	Mean	146,083,321
99.5%		4.51e+9	Standard Deviation	609,387,097
97.5%		2.13e+9	Standard Error Mean	13,626,310
90.0%		7.6e+7	Upper 95% Mean	172,806,577
75.0%	quartile	0	Lower 95% Mean	119,360,064
50.0%	median	0	N	2,000
25.0%	quartile	0		
10.0%		0		
2.5%		0		
0.5%		0		
0.0%	minimum	0		

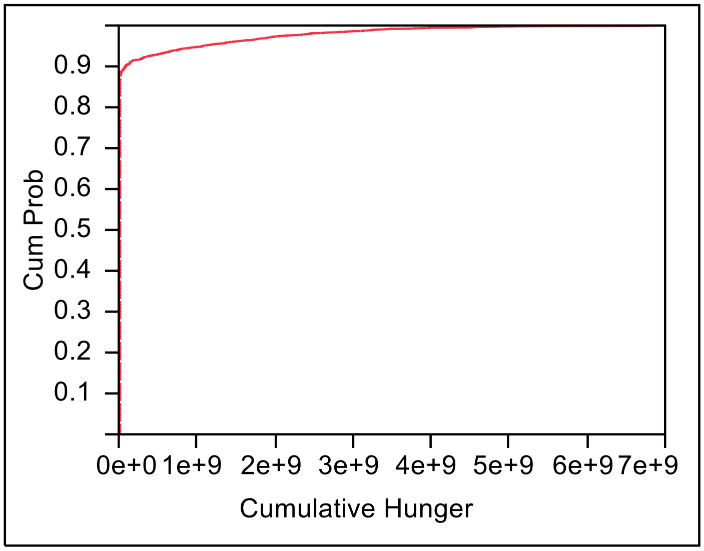

Figure S10. The cumulative distribution function plot illustrating the relationship between cumulative hunger-days and their probability of occurrence. There is greater than an 85% chance that worker absenteeism in food production will not result in hunger-days. However, the severity is not greatly reduced.