Food Security for Whom? The Effectiveness of Food Reserves in Poor Developing Countries

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Abstract

During the Global Food Price Crisis of 2007-2011, millions of people suffered from hunger because food had become expensive. To cope with this problem, the governments of several countries decided to establish public food reserves in order to stabilize domestic prices. In this paper we develop a model to evaluate the optimal grain storage policy for a poor grain-importing country. Households are heterogeneous in their income endowment, and those who cannot afford enough food suffer from hunger. The international price of grain follows a Markov process with two states (tranquil periods and food crises), and households are unable to self-insure against changes in this price. The objective of the reserve operation is to reduce hunger rates. The model captures the trade-off in implementing the policy: raising a stock to prevent hunger tomorrow requires resources that could be used to reduce hunger today. Parameters are calibrated to reflect food supply and demand in Haiti. Our results suggest that rather than storing food, a better approach for a poor country is to focus on fighting poverty directly, since the modest social protection provided by a storage policy could be also be obtained through relatively small improvements in income per capita and income distribution.

Key words: food crisis, food security, hunger, grain reserve, Haiti

1 Introduction

During the Global Food Price Crisis of 2007-2011, millions of people suffered from hunger because food had become expensive. The Crisis was particularly dramatic from late 2005 to mid 2008, when world cereal prices increased by 150% (see Figure 1). Although prices initially subsided over the next two years, they have remain highly volatile, at least when compared to price variations from 1990 to 2005.

Export restrictions and panic purchases played an important role in the Crisis. As prices began to rise in 2006-2007, several grain exporting countries restricted their sales in an attempt to curb food inflation in their economies. For example, India and Vietnam curtailed rice exports in late 2007. This restriction induced rice importers –most notably the Philippines–to purchase excessive amounts of rice in early 2008, as a safeguard against prolonged trade disruptions. However, this excessive demand further pushed the price of rice, prompting a new wave of export restrictions by Vietnam, Cambodia, and Egypt. The situation was similar in the wheat market. Following a poor harvest in Australia, wheat prices rose 32% during 2005-06. In response, Ukraine imposed export quotas in late 2006, followed by a complete ban in July 2007, forcing its usual clients to buy wheat from Argentina, the U.S., Kazakhstan and Russia. Argentina raised its wheat export tax in November 2007, while Kazakhstan and Russia restricted exports in early 2008 as their stocks were plummeting. Meanwhile, U.S. wheat exports surged, mainly because of increased demand from Egypt. As pressure on American exports rose, the price of wheat kept increasing, reaching US$440 per tonne in March 2008, 115% above the

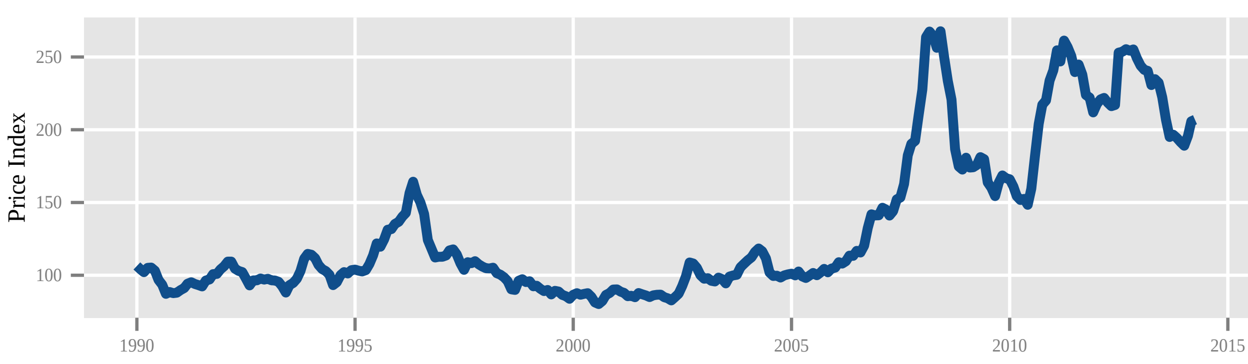

Figure 1: FAO's Cereal Price Index

December 2006 level.[1]

In the developing world, expensive cereals are especially harmful to the poor, since most of them are net food buyers who spend a sizable share of their income on food. Their plight is further complicated by the fact that the prices of maize, rice and wheat —grains that account for 60% of the world's food energy intake (FAO 1995)—spiked simultaneously, hindering the possibility of substituting one expensive stable with a cheaper alternative. In many countries, the threat of starvation dragged vulnerable populations into despair, resulting in social turmoil: in 2008 more than 60 food riots occurred worldwide in 30 different countries (Lagi, Bertrand, and Bar-Yam 2011; Schneider 2008; Bellemare 2011).

To cope with the Crisis, several authors recommend the use of public food reserves as a tool to mitigate price uncertainty. For example, Sampson (2012) justifies this intervention by pointing out that the Crisis exposed the inadequacies of relying on the market to address volatile agricultural prices, due to uncertain commitment by key exporters. Crola (2011) argues that local and national food reserves can play a vital role in price stabilization, as long as they are operated on based on predefined rules, so as to reduce the political uncertainty. Perhaps not surprisingly, countries from the Middle East, Sub-Saharan Africa, Asia and the Caribbean decided to increase the size of their strategic grain reserves. One example is Saudi Arabia, which intends to keep a 6-month wheat supply on stock (McKee 2012). Another example is Haiti, which in July of 2013 began construction of a storage complex with capacity for 35,000 metric tonnes of grain.

This renewed interest in the use of public food reserves has motivated work on the optimal implementation of such policy. Notable examples are Gouel and Jean (2012), who analyze the optimal combination of storage and trade policy in a small, open developing country; and Gouel (2013), who studies the optimal food price stabilization policy for a self-sufficient developing country. Our paper contributes to this new literature on optimal storage policy. One key difference in our approach is in the definition of *optimality*. Unlike previous work, where the optimal reserve operation is defined in terms of a social welfare function, we focus on the effect of the reserve on the hunger rate of the

[1] For a detailed discussion of the several causes of the Crisis, see Headey and Fan (2008) and Headey and Fan (2010).

country. After all, the main concern about the Food Crisis is its effect on hunger among the poor.

A second difference is that our model assumes absence of private storage. This assumption is motivated by Wright and Cafiero (2011) observation that in several developing countries, particularly in MENA, private storage markets cannot be relied upon to guarantee adequate food supplies. They explain that in times of crisis politically powerful consumers press their governments to force traders, often decried as "hoarders", to surrender stocks to the government or directly to consumers, often without compensation. Since governments commitments not to confiscate stocks in emergencies are not credible, anticipation of such treatment discourages private storage in times of plenty.

Having defined hunger as the yardstick to evaluate the performance of the reserve, our model offers a simple mechanism to quantify the transmission of shocks in global grain prices into the country's hunger rate. Households in this country prepare food by combining two ingredients, a locally grown "vegetable" and imported "grain". The amount of food consumed by a household depends on its income and the prices of the two ingredients. Households are heterogeneous in their income endowment, and those who cannot afford enough food suffer from hunger. The global price of grain follows a Markov process with two states (tranquil periods and food crises), and households are unable to self-insure against changes in this price.

To prevent hunger spikes during crises, the government sells grain from its reserve and uses the revenue to subsidize grain imports. In turn, the accumulation of grain during tranquil periods is financed by a tariff on grain imports. The model thus captures the trade-off in implementing the policy: raising a stock to prevent hunger tomorrow requires resources that could be used to reduce hunger today. For a poor developing country this trade-off is not trivial, as many people suffer from hunger even when food is inexpensive.

Since the model lacks a closed-form solution, it is solved numerically using orthogonal collocation methods. Its parameters are calibrated to reflect food supply and demand in Haiti, where grain imports account for one-third of the food budget. We simulate a food crisis by introducing an 85% increase in the price of grain, which roughly corresponds to the variation in the price index of Haiti's cereal imports during the Global Crisis.

We find that most of the time the storage policy, whether of grain or cash, would fail at avoiding hunger during a crises, because the reserve is below the optimal level due to having been depleted in previous crises. More importantly, our results suggest that rather than storing food (or cash), a better approach for a poor country is to fight poverty directly, since the modest social protection provided by a storage policy could be also be obtained through relatively small improvements in income per capita and income inequality.

The rest of the paper is organized as follows. Section 2 develops the model, while section 3 describes the parameter calibration and the numerical techniques required to solve the model. Results are presented in section 4. Section 5 concludes.

2 The model

We now develop a model of the food market in a poor, grain-importing country. In the model, the government's problem is formulated as a Bellman equation, which we solve by numerical methods in the next section. To derive the Bellman equation, we first describe the demand for food, the distributions of income and food consumption, and the dynamics of grain prices.

The country's population is normalized to 1. There is a continuum of households indexed by $i \in I := [0,1]$. Households have identical preferences but different income. Households do not have access to financial services, including deposits, credit, and insurance. Households prepare their food by combining an imported grain and a local vegetable. Since all grain is imported, households' nominal income does not depend on the price of grain, and we can analyze the effect of the crisis on consumers alone. Because of fluctuations in the international price of grain and lack of financial services, the country's hunger rate is also volatile.

2.1 The demand for food

Households' utility depends on the consumption of two final goods: food and a non-edible good (the numeraire). Households prepare their *food* at home by combining two *ingredients*, an imported grain and a domestic vegetable, according to a CES recipe:

$$f(x_g, x_v) = \left(\theta^{\frac{1}{\sigma}} x_g^{\frac{\sigma-1}{\sigma}} + (1-\theta)^{\frac{1}{\sigma}} x_v^{\frac{\sigma-1}{\sigma}}\right)^{\frac{\sigma}{\sigma-1}} \tag{1}$$

Here, f is the amount of food prepared by combining x_g units of grain and x_v units of vegetable, θ is the relative importance of the grain in the recipe, and σ is the elasticity of substitution, which reflects the households' willingness to substitute ingredients in response to changes in their relative price.

The international price of grain is p_g^*, which is imported subject to a tariff rate τ. There are no transportation nor retailing costs, so the consumer price of grain is $p_g = (1+\tau)p_g^*$. On the other hand, the price of the domestic vegetable is p_v.

Household i has a food budget M_i to spend on the two ingredients. Given this budget, the household problem is to maximize the amount of food consumed:

$$\max_{x_g, x_v} f(x_g, x_v) \tag{2a}$$

subject to

$$p_g x_g + p_v x_v \leq M_i \tag{2b}$$

Solving this problem, household i buys

$$\hat{x}_g = \theta \left(\frac{P}{p_g}\right)^{\sigma} \frac{M_i}{P}, \qquad \hat{x}_v = (1-\theta)\left(\frac{P}{p_v}\right)^{\sigma} \frac{M_i}{P} \tag{3}$$

units of grain and vegetables, respectively, which allows it to prepare and consume

$$f_i(\hat{x}_g, \hat{x}_v) = \frac{M_i}{P} \tag{4}$$

units of food. In (3) and (4), P is an aggregate price that adjusts for the substitution between the two ingredients:

$$\begin{aligned} P &\equiv P(\tau, p_g^*, p_v) \\ &= \left\{\theta[(1+\tau)p_g^*]^{1-\sigma} + (1-\theta)p_v^{1-\sigma}\right\}^{\frac{1}{1-\sigma}} \end{aligned} \tag{5}$$

Since the solution satisfies

$$P(p_g, p_v) f(\hat{x}_g, \hat{x}_v) = M = p_g x_g + p_v x_v,$$

we can think of P as the effective price of food, and (5) quantifies the impact of an increase on the international price of the staple grain on the domestic food price index (the *pass-through*, for short). In what follows we assume that p_v is constant and, to simplify notation, the dependence of the food price index P on the price of vegetables p_v will be implicit.

The next step in determining the amount of food consumed by household i is to specify how much it spends on food, M_i. Assume that the income elasticity η and the price elasticity α of the demand for food f_i^d are constant, that is, $f_i^d = \zeta P^{-\alpha} y_i^{\eta}$, where ζ is a scale parameter, and y_i is household i's income. Then household i spends $M_i = \zeta P^{1-\alpha} y_i^{\eta}$ on ingredients, and food consumption is given by (substitute on (4))

$$\begin{aligned} f_i(\hat{x}_g, \hat{x}_v) &= \frac{\zeta P^{1-\alpha} y_i^{\eta}}{P} \\ &= \zeta P(\tau, p_g^*)^{-\alpha} y_i^{\eta} \\ &\equiv f\left(y_i, \tau, p_g^*\right) \end{aligned} \tag{6}$$

Therefore, the amount of food consumed by household i ultimately depends on its income, the tariff rate, and the international price of grain.

2.2 The distributions of income and of food consumption

Household i is endowed with income y_i every period. The distribution of income across the population is described by a log-logistic, or Fisk, distribution (Fisk 1961):

$$\begin{aligned} F_y(y|a_y, b_y) &= \Pr(y_i \le y) \\ &= \left[1 + \left(\frac{y}{a_y}\right)^{-b_y}\right]^{-1}, \qquad (y \ge 0) \end{aligned} \tag{7}$$

where $a_y > 0$ and $b_y > 1$ are the scale and shape parameters, respectively. Define the functional $\mathbb{S}(g)$ as the sum of $g_i \equiv g(y_i)$ for all households, that is $\mathbb{S}(g) \equiv \int_I g(y_i)\,\mathrm{d}F_y$. The income distribution implies that per-capita income is[2]

$$Y = \mathbb{S}(y_i) = a_y \frac{\pi/b_y}{\sin(\pi/b_y)}$$

and the Gini coefficient is $G = \frac{1}{b_y}$ (Kleiber and Kotz 2003, p. 224). Given (6) and (7), food consumption has the Fisk distribution[3] $F_{\text{food}} \sim \text{Fisk}(a_f P^{-\alpha}, b_f)$, where $a_f = \zeta a_y^\eta$ and $b_f = \frac{b_y}{\eta}$.

2.3 Measuring hunger

A household that consumes less that c units of food in a period is considered "hungry" or "undernourished". The *hunger rate* Γ is defined as the share of the population who is hungry, and is given by

$$\begin{aligned} \Gamma(P) &= F_{\text{food}}(c\,|\,a_f P^{-\alpha}, b_f) \\ &= \left[1 + \left(\frac{cP^\alpha}{a_f}\right)^{-b_f}\right]^{-1} \\ &= \left[1 + \left(\frac{cP^\alpha (G\pi)^\eta}{\zeta Y^\eta \sin^\eta(G\pi)}\right)^{1/G\eta}\right]^{-1} \end{aligned} \tag{8}$$

[2]Notice that per-capita income equals aggregate income, because population is one.

[3]One useful property of the Fisk distribution is that if $x \sim \text{Fisk}(a, b)$, then $kx^\gamma \sim \text{Fisk}(ka^\gamma, b/\gamma)$.

That is, the hunger rate of the country depends on its per capita income Y, income inequality G, and the price of food P. In what follows, we assume that the income level and distribution are constant, to focus on the effects of the international price of grain and the import tariff on hunger.

2.4 The dynamics of grain prices

The international price of grain follows a discrete Markov process with two states: in a *tranquil* period $p_g^* = p_L$, while during a *food crisis* $p_g^* = p_H$, where $p_L < p_H$. The transition between tranquil periods and food crises depends on the probabilities $\pi_{jj'} = \Pr(p_{g,t} = p_j' | p_{g,t-1} = p_j)$, where $j, j' \in \{L, H\}$.

Equation (8) quantifies the effect of a food crisis on the incidence of hunger in the country. An increase in the price of imported grain raises the domestic food price index, inducing a reduction in food consumption and pushing some of the households into hunger. This is illustrated in Figure 2, which plots the density function of food consumption for two alternative grain prices. In the Figure, households with food consumption below the "hunger threshold" suffer from hunger; region **B** represents the share of population that is lead into hunger as the price of grain increases. In the absence of policy intervention (that is, $\tau = 0$), the hunger rate simply sticks to the price process, switching between $\boldsymbol{A} = \Gamma\left(P(0, p_L, p_v)\right)$ and $\boldsymbol{A} + \boldsymbol{B} = \Gamma\left(P(0, p_H, p_v)\right)$.

2.5 The government's problem

The government of the country is concerned with the potential episodes of extreme hunger ($\boldsymbol{A} + \boldsymbol{B}$ in Figure 2) that results from a price hike in the grain market. This is formalized by setting the government's one-period "utility" or "reward" function as

$$r_H(\tau, p_g^*) = \begin{cases} \frac{1}{1-\rho}[1 - \Gamma(\tau, p_g^*)]^{1-\rho}; & \text{if } \rho \neq 1 \\ \\ \log[1 - \Gamma(\tau, p_g^*)], & \text{otherwise} \end{cases} \tag{9}$$

where ρ is the government's relative risk aversion.

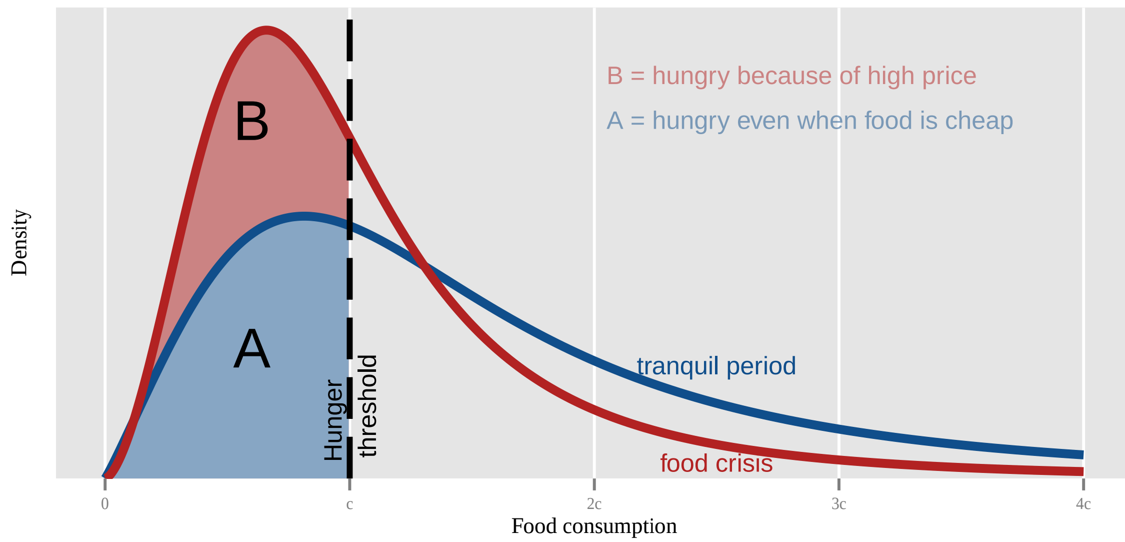

Figure 2: Food Consumption Density

Hunger occurs when food consumption is below c. When $p_g^* = p_L$ the hunger rate is $\boldsymbol{A}$; a price increase shifts the distribution to the left, dragging a proportion $\boldsymbol{B}$ of the population into hunger.

To avoid extreme hunger, the government operates a grain reserve as follows. During normal periods, the government uses the fiscal revenue Υ from the import tariff to buy and accumulate grain. During a crisis, the government eliminates the tariff and instead subsidizes grain imports; the subsidy is financed by selling all or part of the stock available at the beginning of the crisis. Thus, the size of the grain reserves s_t evolves according to:

$$s' = (1-\phi)\left[s + \frac{1}{p_g^*}\Upsilon\left(\tau, p_g^*\right)\right] \tag{10}$$

where ϕ is the cost of storing one unit of grain per period and the prime symbol indicates next period variables. The physical grain stock cannot be negative. The fiscal revenue is

$$\Upsilon\left(\tau, p_g^*\right) = \tau\, p_g^*\, \hat{x}_g = \tau\, p_g^* \theta\left[(1+\tau)p_g^*\right]^{-\sigma} \zeta P(\tau, p_g^*)^{\sigma-\alpha}\, \mathbb{S}\left(y^\eta\right) \tag{11}$$

The government cares for present and future hunger, so let us define its value function by

$$V\left(s_t, p_{gt}\right) = \max_{\tau} \mathbb{E}_0 \sum_{t=0}^{\infty} \delta^t r_H\left(\tau_t, p_{gt}^*\right) \tag{12}$$

where $\delta \in (0, 1)$ is a discount factor. Since this problem is recursive, it can be written in terms of the following Bellman equation

Policy case A:

$$V\left(s, p_g^*\right) = \max_{\tau, s'} \left\{r_H\left(\tau, p_g^*\right) + \delta\, \mathbb{E}_t\, V\left(s', p_g^{*\prime}\right)\right\} \tag{13}$$

subject to resource constraint (10) and to $s' \geq 0$.

We next consider two variations to the government problem. First, instead of explicitly reducing hunger, the government may focus on maximizing social welfare. Second, lacking storage facilities, the government can simply keep cash or deposits.

Maximizing welfare

For a household with food demand (6), the associated indirect utility is

$$v_i = v(y_i, \tau, p_g^*) = \frac{y_i^{1-\eta}}{1-\eta} - \zeta\, \frac{P(\tau, p_g^*)^{1-\alpha}}{1-\alpha}.$$

Integrating v_i over the income distribution, the one-period social welfare is

$$W(P) \equiv \mathbb{S}(v) = \tfrac{1}{1-\eta}\, \mathbb{S}\left(y^{1-\eta}\right) - \zeta\, \frac{P(\tau, p_g^*)^{1-\alpha}}{1-\alpha} \tag{14}$$

In this case, the one-period reward function is

$$r_W(\tau, p_g^*) = \begin{cases} \frac{1}{1-\rho} \mathbb{S}[v(\tau, p_g^*)]^{1-\rho}; & \text{if } \rho \neq 1 \\ \\ \log \mathbb{S}[v(\tau, p_g^*)], & \text{otherwise} \end{cases} \tag{15}$$

Financial reserve

The government could simply set a *financial* reserve. Assume that the it can buy bonds or deposits D that yield a risk-free interest rate r. In this case the resource constraint is

$$D' = (1+r)\left[D + \Upsilon\left(\tau, p_g^*\right)\right] \tag{16}$$

and its corresponding Bellman equation is

$$V\left(D, p_g^*\right) = \max_{\tau, D'} \left\{ r_H\left(\tau, p_g^*\right) + \delta\, \mathbb{E}_t\, V\left(D', p_g^{*\prime}\right) \right\} \tag{17}$$

subject to resource constraint (16) and to $D' \geq 0$.

In summary, our model encompasses five alternative policy cases: (A) avoid extreme hunger using a grain reserve; (B) avoid extreme hunger using a deposit; (C) maximize social welfare using a grain reserve; (D) maximize social welfare using a deposit; and (E) do not intervene.

3 Solving the model

We now describe the numerical methods that we employed to solve the model, as well as the choice of parameters to calibrate our model to the supply and demand conditions in Haiti.

3.1 Food storage in Haiti

The World Food Price Crisis was especially harsh in Haiti. Being the poorest country in the Western Hemisphere, hunger was widespread among its population even *before* the crisis: in 2005 half of the population suffered undernourishment (WorldDatabank). Furthermore, the country is highly dependent on imported foodstuff: in 2007, close to 70% of the cereals consumed were imported, and imports of food contributed 56% of the calorie intake of the population (FAO Food Balance Sheet).

As the World Food Crisis developed, food prices spiked in Haiti: the price of rice nearly doubled between December 2007 and April 2008. Tensions exploded on April 2 in Okay, where demonstrators clashed with United Nations peacekeepers. The following days, in "Port-au-Prince, thousands of protesters set up flaming barricades and threw rocks at the national palace, burned gas stations and looted businesses" (Lindsay 2008-04-16). On April 12, the government of Prime Minister Jacques Edouard Alexis was ousted by senators, while President Rene Preval responded to the social unrest by promising to support local farmers and to reduce the price of a 110-pound sack of rice from $51 to $43 (Delva and Loney 2008-04-12).

Years later, in July of 2013, the government of Haiti began the construction of a strategic reserve to store food in Lafiteau, about nine miles north of Port-au-Prince. The storage complex consits of four silos and a shed, with a combined capacity of 35,000 metric tons. In words of Prime Minister Lamothe,

> The construction of this strategic reserve reflects the desire of my Government to promote national agricultural production, stabilize the market price of commodities and combat food insecurity. Indeed, the fight against hunger and extreme poverty constitutes the main pillars of government action. (Primature, République d'Haïti 2013)

In what follows, we evaluate to what extent this new strategic reserve would succeed in stabilizing the price of food and averting extreme hunger. For simplicity, we assume that the reserve only stores imported grain. Hence, we do not address other potential benefits of the reserve, such as increasing the supply of domestic food by giving farmers the necessary facilities to store part of their crops. This

Parameter	Value	Description
α	0.788	price elasticity food demand
η	0.814	income elasticity food demand
σ	0.500	elasticity of substitution
θ	0.333	share of grain in food budget
c	30.258	hunger threshold
ζ	1.208	food demand scale
Y	114.925	income per capita
G	0.590	Gini coefficient
p_L	1.000	price of grain when low
p_H	1.850	price of grain when high
p_v	1.000	price of vegetable
γ	0.200	proportion of years in crisis
ψ	3.000	expected duration of food crisis
δ	0.970	government discount factor
ρ	2.500	government relative risk aversion
ϕ	0.025	marginal cost of storage
r	0.010	interest rate

Table 1: Parameters for Baseline Scenario

benefit is not trivial, since each year Haiti's farmers lose between 30% and 40% of their crops due to lack of storage space (Primature, République d'Haïti 2013).

3.2 Parameter calibration

We calibrated the parameters of the model to anticipate the performance of a grain storage policy in Haiti. The time unit is a quarter. The baseline values,shown in Table 1, were chosen as follows.

Income per capita in 2012 was US$459.7 (real, 2005 base), or $Y = 114.9$ dollars per day. The Gini coefficient was $G = 0.59$ in 2001 (WDI). We did not find estimates for the income- and price elasticities of food demand in Haiti, so we set these parameters to the average elasticities from countries[4] where income per capita is similar to Haiti's. The estimated elasticities for those countries are from Muhammad et al. (2011).

To determine the importance of food expenditure in households budgets, we estimated a linear regression of the consumer price index on its component indices (prices of food, clothing, rent, hous-

[4]The list includes Ethiopia, Guinea, Guinea-Bissau, Mali, Rwanda, Sierra Leone, Togo, and Uganda.

ing, health, transportation, education, and other) with monthly data for June 2004 to June 2013. Since all these indices have a common base, in the model we normalize all prices to one during a tranquil quarter, that is $p_L = p_v = 1$. From the regression we found that households spend nearly half of their income on food; this result is replicated in the model for a tranquil quarter by setting the demand scale to $\zeta = 1.21$.

Having calibrated the demand for food and the income distribution, we used the resulting food consumption distribution to set the value of the hunger threshold at $c = 30.26$, which implies a hunger rate of 44.5% in a normal year. This hunger rate coincides with Haiti's undernourishment rate for 2011 (WDI).

We assume that the two ingredients are relative complements ($\sigma = 0.5$). To set the weight of grain in the recipe (1) we followed two different procedures. In the first one, we used FAO's Food Balance Sheets from 2006 to 2009 to determine the proportion of the supply of calories that is accounted for by imports of wheat, rice and maize. In the second procedure, we estimated a linear regression of the food price index on its local and imported components. In the two procedures the weight of the imported food was close to $\theta = \frac{1}{3}$.

The price of grain during a crisis was computed as follows. With monthly data on the international prices for wheat, maize and rice for 1960M01 to 2013M08 (GEM Commodities), we computed a grain price index for Haiti, using the volume of imports for 2006 to 2009 as weights. We deflated this index with the CPI of the United States and then decomposed the resulting (log) real price index into a trend and a cyclical component using the Hodrick-Prescott filter. During the Food Price Crisis, the real price of imported grain reached a peak of 85% deviation over its trend value; thus in the model $p_H = 1.85$.

We assume that crises occur in one out of five quarters ($\gamma = 0.2$), and that they typically last $\psi = 3$ quarters. For a two-state Markov process, these two assumptions imply that the probability of having a crisis next period is $\pi_{HH} = \frac{2}{3}$ if currently in crisis, and $\pi_{LH} = \frac{1}{12}$ otherwise.

We also assume a discount factor of $\delta = 0.97$, the cost of storing food at $\phi = 0.025$ per unit of grain, and the interest rate of $r = 1\%$. All these values are quarterly. Finally, we set the government's risk aversion to $\rho = 2.5$.

In order to determine how sensitive the storage policy is to some of the key parameters, we consider four variations to the baseline (Scenario 1) from Table 1. In Scenario 2, the government is more risk averse ($\rho = 3$). In Scenario 3 crisis are expected to be longer ($\psi = 4$). In Scenario 4 the cost of storage is higher ($\phi = 0.05$). Finally, in Scenario 5 a food crisis is less severe ($p_H = 1.6$).

3.3 Numerical methods

Once the baseline parameters were chosen, we solved Bellman equations (13) and (17) using collocation methods. The numerical work was implemented in MATLAB, benefiting from the *CompEcon* toolbox available from Miranda and Fackler (2002). In particular, the value functions in (13) and (17) were each approximated as the sum of twelve Chebychev polynomials, using the corresponding Chebychev nodes for the continuous state variable s_t, and for discrete state reflecting the prices $p_g \in \{1.00, 1.85\}$. The model was solved using the *dpsolve* solver from CompEcon. Figure A4 plots the residuals for all scenarios and for policy cases A to C.[5]

Once the model was solved, we implemented a Monte Carlo simulation of the tariff rules over ten thousand periods, to compute the long-term distribution of the reserve and of the hunger rate for each scenario-policy combination.

3.4 Euler equation

We can get some insight about the solution of the model from the Euler equation. In Bellman equations (13) and (17) there are two policy variables (the tax rate and the ending stock) related by the resource constraints (either 10 or 16). While in the numerical solution to the problem it is convenient to substitute the ending stock and use the tax rate as the only policy variable, in this section we obtain an Euler equation by implicitly using ending stock as the policy variable. Assuming that the non-negativity constrain on ending stock is not binding[6], the Euler equation for government problems (13) and (17)

[5] Policy D is omitted because in all scenarios it is optimal to not intervene.
[6] This is the case for tranquil periods in all scenarios discussed in the Results section.

is

$$1 = \mathbb{E}_t \left[\delta \left(\frac{1 - \Gamma\,'}{1 - \Gamma} \right)^{-\rho} \frac{\Delta\Gamma\,'\Delta\Upsilon}{\Delta\Gamma\;\Delta\Upsilon'} \;\; R \right] \tag{18}$$

where the Δ operator indicates differentiation with respect to the tax rate, the prime indicates next-period variables, and R is the return of investing one unit of numeraire in ending stock:

$$R = \begin{cases} (1-\phi)\frac{p^*_{g,t+1}}{p^*_{g,t}} & \text{for grain stock;} \\ 1 + r & \text{for deposit.} \end{cases} \tag{19}$$

Since the price of grain fluctuates, investing in grain is risky. In particular, the expected return on grain bought during a tranquil period is

$$\mathbb{E}[R] = (1-\phi)\left[1 + \pi_{LH}\left(\frac{p_H}{p_L} - 1\right)\right] \tag{20}$$

i.e. the return is simply the expected capital gain, adjusted for storage cost. Notice that this capital gain is positively correlated with hunger: when the price of grain increases, both the capital gain and the hunger rate increase too.

4 Results

During a food crisis, the international price of grain increases by 85%. Without any policy intervention (see Table 2), the crisis leads to a 25% increase in the domestic price of food. The average household reduces its purchases of grain and vegetables by 31% and 6%, respectively. With less ingredients available, the household then reduces food consumption by 16%. Ultimately, the number of households suffering from hunger increases by 21%. These results are common to all scenarios except for Scenario 5, which assumes a less severe increase in the price of grain (60%), thus resulting in a smaller increase in the hunger rate (15%). Notice that in the worst situation, the cost of providing just enough food c to each household is equivalent to 33% of national income.

The pass-trough coefficient is 0.3, which is not significantly smaller than the weight of grain in the food budget (0.33). This follows from assuming that the ingredients are complements.

	Scenarios 1 to 4			Scenario 5		
Variable	p_L	p_H	$\Delta\%$	p_L	p_H	$\Delta\%$
P	1.00	1.25	25.5	1.00	1.18	18.4
$\mathbb{S}(f)$	50.86	42.54	-16.4	50.86	44.51	-12.5
$\mathbb{S}(x_g)$	16.95	11.68	-31.1	16.95	12.76	-24.7
$\mathbb{S}(x_v)$	33.91	31.76	-6.3	33.91	32.29	-4.8
$\mathbb{S}(w_g)$	0.33	0.40	21.4	0.33	0.39	16.2
$^{Pc}/_{Y}$	0.26	0.33	25.5	0.26	0.31	18.4
Γ	0.44	0.54	20.8	0.44	0.51	15.5

Table 2: No Policy: Results for All Scenarios

Note: The variables are food price index P; per capita consumption of food $\mathbb{S}(f_i)$, grain $\mathbb{S}(x_{gi})$ and vegetable $\mathbb{S}(x_{vi})$; share of grain in food budget $\mathbb{S}(w_{gi})$; share of critical food on national income Pc/Y; and hunger rate Γ.

4.1 Baseline model

The results in this section refer to the *baseline model*, which consists of policy case A with parameters from Scenario 1. First, we describe the optimal policy rule. Later, we analyzed the long term potential of the reserve to alleviate hunger.

The optimal policy rules

The optimal policy can be described in terms of the tariff rate, the size of the grain reserve, or the actual hunger rate. Figure 3 presents the optimal tariff rate as a function of the initial stock of grain and its international price. As expected, the tariff is always negative during a crisis, as the government sells grain from its stock to subsidize grain imports. In a tranquil period, the tariff rate is positive whenever the initial reserve is below its full capacity of 5.1 weeks of grain. The tariff rate is decreasing with respect to the initial stock both during crisis and tranquil quarters. However, the range of the optimal tariff rate is asymmetric around zero: in a tranquil period the maximum rate is set at 10.8% (when the reserve is empty), while during a crisis the maximum subsidy rate is 30.5% (when the reserve is full).

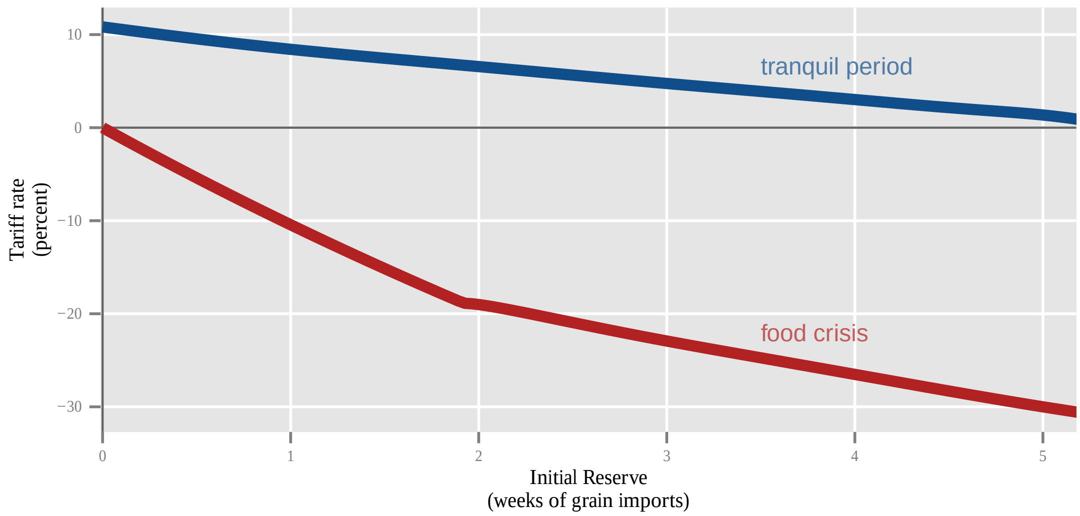

Figure 3: Optimal Tax Rate

When grain is cheap, the government collects income tax to buy and store grain. During a food crisis, it sells grain and transfers the revenue to households.

In terms of the numeraire, the tariff range implies that the domestic price of grain varies between 1.01 and 1.11 during tranquil periods and between 1.29 and 1.85 during a crisis. Clearly, the grain reserve would be ineffective at eliminating the variability of the food price, although in the best case (when the reserve is full) it would dampen the increase in the price of food, from 25% (no policy) to 9%.

Together with the transition equation (10), the tariff policy implicitly defines the optimal storage rule depicted in Figure 4. Starting with an empty reserve in a tranquil period, the government would use its fiscal revenue to accumulate 1.3 weeks of grain. As long as the price of grain remains low, the government would acquire additional grain, although at a slower pace because the optimal tariff revenue is decreasing on the initial stock. If no crisis occurs, the government would take two years to restock 90% of the stock capacity. Once the reserve is full, the tariff rate is set at 1.0% to cover the cost of maintaining the stock.

In contrast to the long time necessary to replenish the reserve during tranquil periods, a full reserve would be depleted in just two quarters if a crisis hits the country. Initially, the government would sell two-thirds of its stock at the beginning of the crisis. If the crisis persists for an additional quarter (which

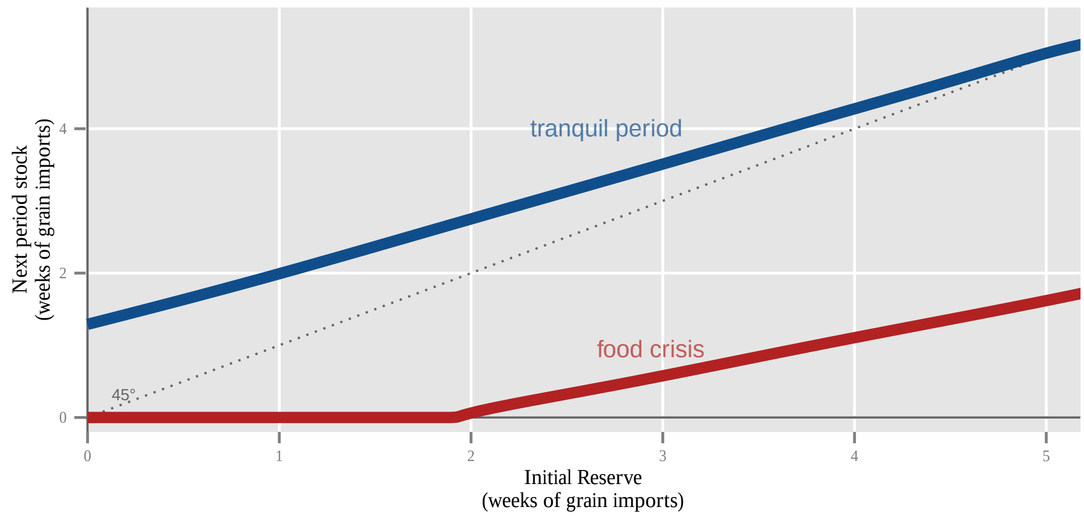

Figure 4: Optimal Food Storage

The maximum stockpile covers 5.1 weeks of grain imports. The country accumulates grain when it is cheap, to release it during crises.

happens with probability 0.67), then the government would sell its remaining stock.

Similarly, the tariff rule implicitly defines the optimal hunger rate shown in Figure 5: the level of the tariff affects the price of food (equation 5), which in turn affects the hunger rate (8). When the country faces a crisis with a full reserve, the government's grain subsidy ameliorates the drop in food consumption, resulting in a hunger rate of 48.1%. This is an improvement with respect to policy case E ("do not intervene"): without subsidies, the hunger rate would reach 53.8% instead. Therefore, when the reserve is full, the *benefit* of storing grain is a reduction of 5.7 percentage points in hunger during a crisis. As expected, this benefit is smaller if the size of the stock decreases, and it disappears once the reserve is depleted.

Figure 5 also illustrates the *cost* of storing grain: immediately after a stock depletion, the fiscal effort to rebuild the stock requires setting the tax rate at 10.8%. Doing so results in a hunger rate of 45.9%, compared to 44.5% that would prevail in the absence of policy intervention. That is, the cost of rebuilding the stock is 1.4 percentage points of increased hunger in a tranquil quarter. This cost declines as the stock reaches its full capacity, but it is never zero. Once the reserve is full, covering its operating cost (stock depreciation) implies a hunger rate of 44.64% —14 basis points above the

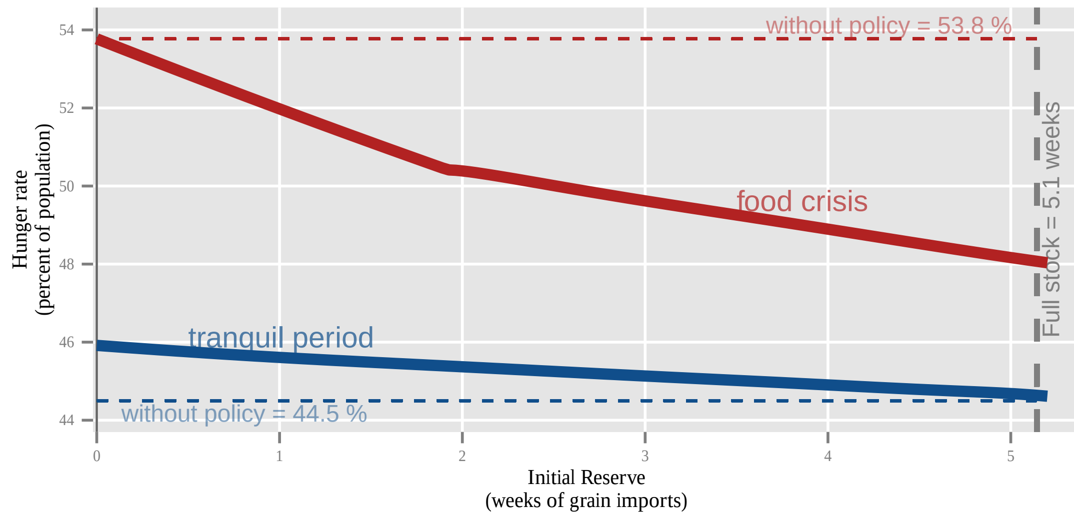

Figure 5: Hunger Rate Implied by Optimal Policy

With a full reserve of 5.1 weeks, Haiti could reduce the hunger rate during a crisis, from 53.8% to 48.1%. The downside: once the stock is depleted, restocking increases hunger from 44.5% to 45.9% during a tranquil period.

no-policy rate.

As mentioned earlier, the reserve is unable to stabilize the price of food. Consequently, the reserve is also unable to prevent extreme hunger. Depending on the initial grain stock at the outset of a crisis, the hunger rate will range between 48.1% and 53.8%, well above the non-crisis rate of 44.5%.

The reserve in the long-run

Analyzing the implications of the optimal taxation-storage rules in terms of the hunger rate allows to clarify the trade-off of implementing a grain reserve: the government increases the hunger rate between 0.1 and 1.4 percentage points during tranquil quarters, in exchange for a reduction of up to 5.7 percentage points during a crisis period. Although the potential benefit far surpasses the potential cost, it should be noted that in the long run the cost is incurred four times more often than the benefit is enjoyed.

Since the actual cost and benefit of implementing the policy depend on the amount of grain available at the beginning of each period, the long-term net benefit of the government's intervention depends on the joint distribution of the reserve size and the price of grain. Figure 6 shows the cumulative

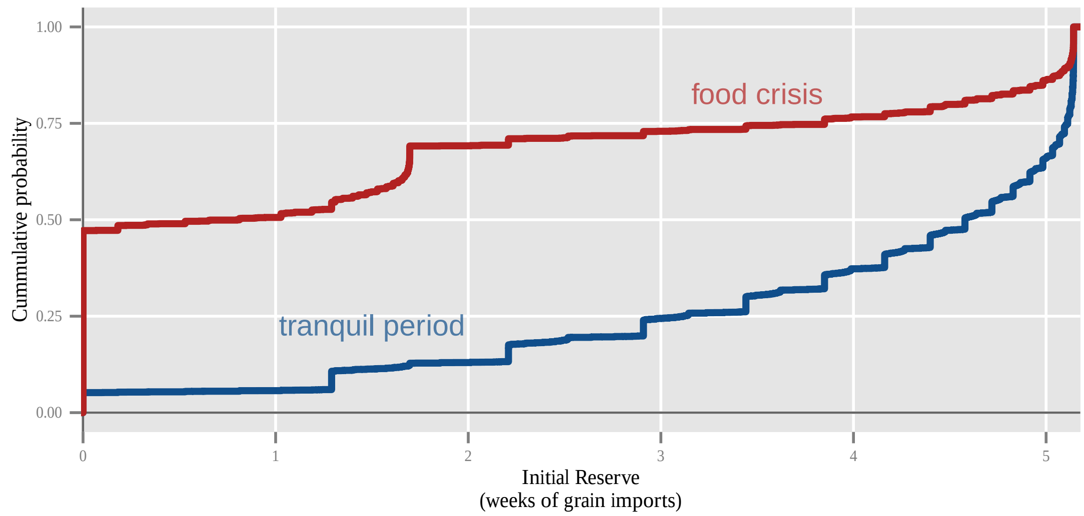

Figure 6: Size of Initial Stock in a Food Crisis (cdf)

The reserve would be empty in half of the crises. Only in one-fifth of crises the reserve would be higher than 90% of capacity.

distribution of the initial grain stock conditional on the two price states.

For example, because the stock is depleted in just two periods during a crisis, a subsequent period of high grain price would be faced without any grain in reserve. It would be impossible for the government to alleviate hunger in such a context. This is an important limitation of the policy intervention, as the mean duration of food crises is three quarters. In fact, over time the country would face nearly one-half of the crisis periods with an empty reserve (see Figure 6), while in only one-fifth of those episodes the reserve will be above 90% of its capacity.

The inability of the grain reserve to prevent extreme hunger is best illustrated in Figure 7, which shows a histogram of the simulated hunger rates, conditional on price state. In around 72% of food-crisis periods, more than one-half of households would still suffer hunger, and in nearly 50% of crisis periods the policy would not make any difference whatsoever, as the grain reserve would be empty. On the other hand, there would be little variation in the hunger rate during tranquil times: 90% of the time it would fall between 44.6% and 45.5%.

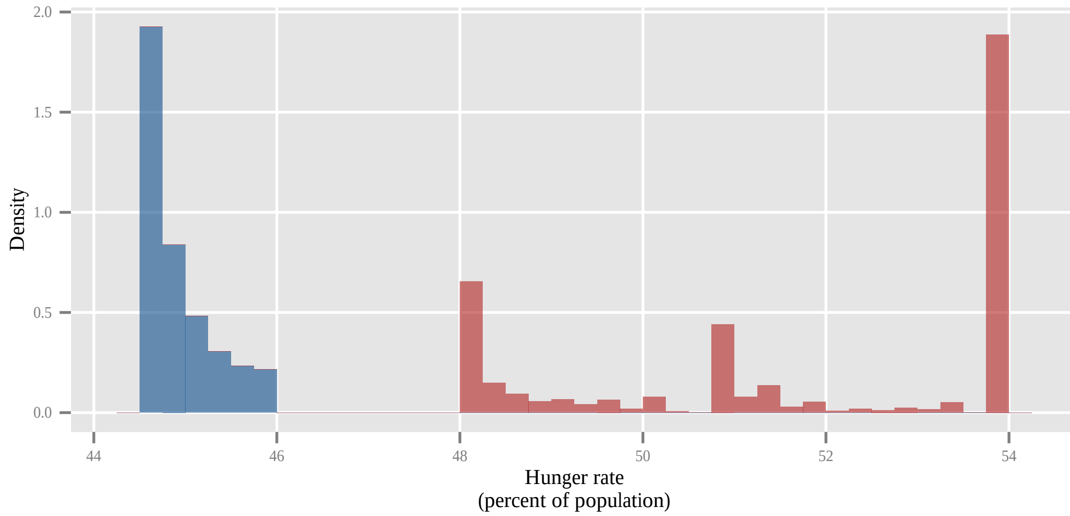

Figure 7: Distribution of Hunger

Without intervention, hunger rate would be 53.8% during crises. With intervention, hunger is below 50.0% in only one-quarter of those crises.

4.2 Alternative scenarios

Table 3 summarizes the simulations of policy A for all five scenarios. Scenario 2 evaluates the effect of increasing the coefficient of relative risk aversion from 2.5 to 3.0. As expected, a more risk-averse government would be more determined to avoid extreme hunger. It would keep a grain stock 15% larger than in the baseline (on average), with a maximum stock of 6.1 weeks, one week more than in the baseline. This larger reserve would allow the government to afford a higher subsidy in times of crisis (150 basis points on average), yet it requires a higher tariff in tranquil periods.

Despite the additional effort, the government would not succeed in avoiding extreme hunger. In nearly two-fifths of crisis periods the reserve would be empty. The average hunger rate would drop by only 0.18 percentage points during crises, while it would increase by 0.07 percentage points in tranquil periods.

When crises are expected to last longer (four quarters instead of three, Scenario 3), the optimal policy is to store 28% *less* grain. With a smaller reserve, hunger is on average 52.5% during crises, almost one percentage point above baseline.

		Scenario 1: (baseline)		Scenario 2: $\rho = 3.0$		Scenario 3: $\psi = 4$		Scenario 4: $\phi = 0.05$		Scenario 5: $P_H = 1.60$	
Variable	Stat.	p_L	p_H	p_L	p_H	p_L	p_H	p_L	p_H	p_L	p_H
Tax rate, %	min	1.02	-30.45	1.22	-31.94	0.72	-23.90	0.89	-20.72	0.39	-17.23
	mean	3.23	-11.67	3.75	-12.62	2.02	-7.35	2.07	-6.51	1.41	-5.02
	max	10.83	-0.00	11.91	-0.00	7.35	-0.00	6.70	-0.00	5.07	-0.00
Initial stock	min	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	mean	3.92	1.68	4.49	1.95	2.88	0.98	1.71	0.67	1.50	0.55
	max	5.14	5.14	6.14	6.14	3.65	3.65	2.18	2.18	1.95	1.95
End stock	min	1.29	0.00	1.41	0.00	0.89	0.00	0.80	0.00	0.62	0.00
	mean	4.22	0.42	4.84	0.57	3.06	0.22	1.88	0.01	1.64	0.01
	max	5.14	1.70	6.14	2.46	3.65	1.10	2.18	0.04	1.95	0.05
Food price	min	1.00	1.09	1.00	1.08	1.00	1.13	1.00	1.15	1.00	1.10
	mean	1.01	1.19	1.01	1.19	1.01	1.22	1.01	1.22	1.00	1.16
	max	1.04	1.25	1.04	1.25	1.02	1.25	1.02	1.25	1.02	1.18
Hunger rate, %	min	44.64	48.07	44.66	47.75	44.60	49.43	44.62	50.06	44.55	48.50
	mean	44.93	51.64	45.00	51.46	44.77	52.46	44.78	52.61	44.69	50.57
	max	45.92	53.77	46.05	53.77	45.47	53.77	45.39	53.77	45.17	51.42

Table 3: Policy Case A: Results for All Scenarios

Stocks are normalized as weeks of normal-period imports in "baseline". Columns p_L (p_H) indicate a tranquil period (food crisis). For each scenario, the heading shows the parameter that differs from baseline.

Although counterintuitive, storing less grain in this scenario follows from assuming that the share of periods in crisis remains at $\gamma = 0.2$: if the expected duration of a crisis increases from 3 to 4 quarters, then the expected duration of a tranquil period increases from 12 to 16 quarters. For a tranquil period, this reduces not only the probability of having a crisis the following quarter, but also the expected return of holding grain (equation 20) from 4.4% to 2.7% (quarterly).

According to Wright and Cafiero (2011), while the marginal cost of storing grain is usually modest in regions where humidity is low, modern infrastructure is available, and deterioration unimportant, this may not be the case in hot and humid regions —like Haiti. In Scenario 4 we find that the optimal storage policy is very sensitive to the cost of storing grain: if the unit cost of storage per quarter is 5% instead of 2.5%, then the maximum optimal stock is 2.2 weeks, less than half the amount in the baseline.

The optimal storage policy is also very sensitive to the severity of a crisis. Scenario 5 assumes that the price of grain increases by 60% during a crisis (as compared to 85% in the baseline). With a smaller increase in prices, the hunger rate would reach 51.4% during a crisis. Despite facing a less threatening crisis, which would allow to reduce hunger even more with a given stock of grain, the optimal policy in this case is to have a maximum reserve of only 1.9 weeks.

4.3 Alternative policy approaches

Figure A1 presents histograms of the long term distribution of the hunger rate for all scenarios and policies, conditional on the price of grain. Notice that in none of the cases the storage policy prevents extreme hunger (although it reduces its frequency) nor completely smooths the distribution of hunger. In fact, in all cases the hunger rate during a crisis is higher than during a tranquil period, even when having a full stock of grain.

Cash reserve vs. grain reserve

Figure A2 compares the distribution of initial stock for different scenarios and policies. To facilitate comparisons, all stocks are measured in terms of the weeks of grain imports (from baseline) that can be financed by selling the stock. Notice that for any given size of deposits (in Policy B), the amount of grain that can be purchased is smaller during a crisis.

In the baseline scenario, the optimal deposit is considerably smaller than its grain counterpart. In the long run, the government would hold on average enough deposits to afford 1.8 weeks of imports, compared to the 3.5 weeks when holding a grain reserve.

Both reserves respond similarly to the milder crisis in Scenario 5, with a reduction of approximately 65% on the average reserve. On the other hand, the cash reserve is significantly more responsive to the risk aversion parameter and to the duration of crisis than the grain reserve. While the average grain reserve is 14% higher than in baseline when risk aversion is increased from 2.5 to 3.0 (scenario 2), the average deposit is 52% higher. Similarly, a one-quarter longer crisis (scenario 3) induces a reduction of average stocks, of 28% on grain holdings but 41% on deposits. Furthermore, as expected, the cash reserve is not affected by a change in the cost of storing grain (scenario 4).

An important question here is whether a grain reserve is significantly better at reducing hunger than a simpler deposit account. To answer this question, in Figure A3 we present the value function for these two alternatives, conditional on the price of grain. To better understand the difference between the two policies, the value function is measured in terms of the certainty-equivalent non-hunger rate that each policy can achieve at a given initial reserve. In all five scenarios, the grain reserve seems to outperform the cash reserve, although the difference is relatively small. In scenarios 1 and 2 the grain reserve would afford a hunger rate 0.5 percentage points lower than the cash reserve. For scenarios 3 to 5 the difference is negligible.

Welfare target vs. hunger target

If the government's objective in holding a grain reserve is to maximize social welfare rather than to prevent extreme hunger, the resulting optimal reserve is considerably smaller (see figure A2). For example, in Scenario 1 the long-term average of the grain stock is 55% smaller when the objective is welfare.

In consequence, during crises the hunger rate would be closer to the no-policy rate (figure A1).

4.4 Efficacy of the reserve policy

In this section, we discuss some insights about the efficacy of the storage policy in improving food security. We take the baseline model as reference.

First, the reserve cannot avoid extreme hunger. In many instances, a crisis will hit the country when the reserve is empty. The reserve can at best reduce the frequency of extreme hunger.

Second, a grain reserve has the potential to reduce the expected hunger rate during a crisis (from 53.8% to 48.1%). Yet this reduction is rather modest when put into perspective. For instance, Figure 8 shows the hunger rate as a function of income per capita, for each price state. It follows that the highest protection offered by the reserve can be achieved if income per capita increases 14.4%. Over the course of two average grain price cycles (7.5 years), this would require an annual growth rate of 1.8%.

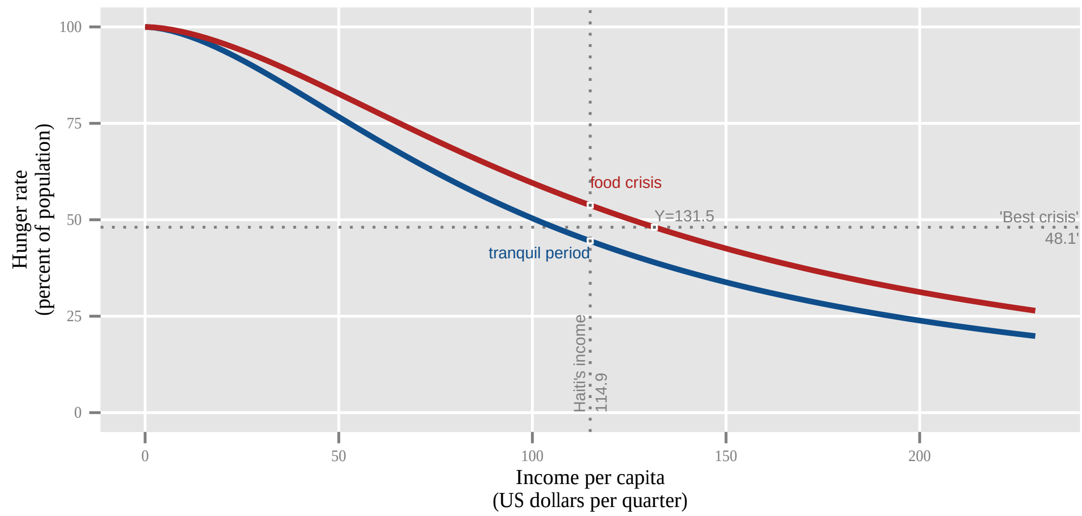

Figure 8: Income Per Capita and Hunger

An increase in income per capita reduces hunger. The "best crisis" hunger rate of 48.1% achieved by the storage policy can also be obtained (without policy) if income per capita increases by 14.4%.

Alternatively, Figure 9 shows that the same protection can be achieved by a redistribution of income, reducing the Gini coefficient from 0.59 to 0.54. This final result deserves consideration: It should be remembered that in this study the policy intervention is neutral with respect to the income distribution, because the import tariff-subsidy rate is the same for all households. The storage policy in our model is ineffective at preventing jumps in the hunger rate , one could argue, because it does not limit the subsidy to only the poorest households. But doing so results in a *redistributive* policy, that is, in a reallocation of resources across households, while a reserve is a tool for *intertemporal* allocation. Following this logic, if the policy objective is to offer protection to vulnerable households, why not do it also during tranquil periods?

5 Conclusions

In this study we propose a model to evaluate the cost and benefit of establishing a grain reserve in a poor, grain-importing country. Given that the main concern about the Global Food Price Crisis is the increased number of people suffering hunger when food becomes expensive, in our model the explicit objective of the reserve is to prevent extreme hunger. The model incorporates a simple mechanism to

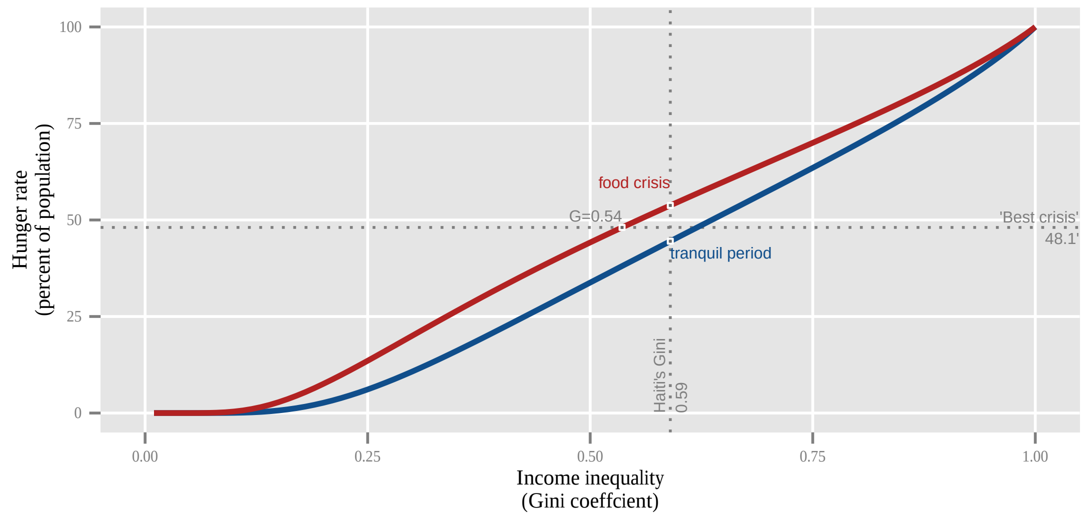

Figure 9: Income Inequality and Hunger

A decline in income inequality reduces hunger. The "best crisis" hunger rate of 48.1% achieved by the policy can also be obtained (without policy) if the Gini coefficient dropped from 0.59 to 0.54.

quantify the transmission from global food prices and local imports tariff-subsidies to national hunger rates. Furthermore, to be sustainable, the policy must raise enough revenue (through tariff) in tranquil periods to afford helping households during crises. We put our model to work by simulating the potential outcomes of a food reserve in Haiti.

Our main results are as follows: Without a government buffer stock, a crisis induces a 25% increase in the food price and raises the hunger rate from 44.5% to 53.8% of the population. To address the possibility of another crisis, the optimal reserve would approximately equal 5.1 weeks of grain imports. This quantity of grain would allow the government to reduce hunger from 53.8% to 48.1% at the peak of the crisis. However, once the reserve is depleted, the government would be unable to further alleviate a crisis that lasts for more than two periods. Once depleted, replenishing the reserve requires an 11% tariff, which would raise the hunger rate from 44.5% to 45.9% during tranquil periods. We find that more often than not the storage policy would fail at avoiding hunger during a crises, because the reserve is below the optimal level due to having been depleted in previous crises. This finding is robust to whether the government accumulates cash instead of grain.

More importantly, our results suggest that rather than storing food, a better approach for a poor country is to focus on fighting poverty directly, since the modest social protection provided by a storage policy could be also be obtained through relatively small improvements in income per capita and income distribution. For example, during crises the storage policy reduces the average hunger rate from 53.8% to 51.6%. Without the storage policy, this result can be achieved by either a 5% increase in income per-capita or by reducing income inequality from 0.59 to 0.57 (Gini coefficient).

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Appendix: Additional Figures

Figures A1 to A4 present results for all five scenarios and three policy stances.

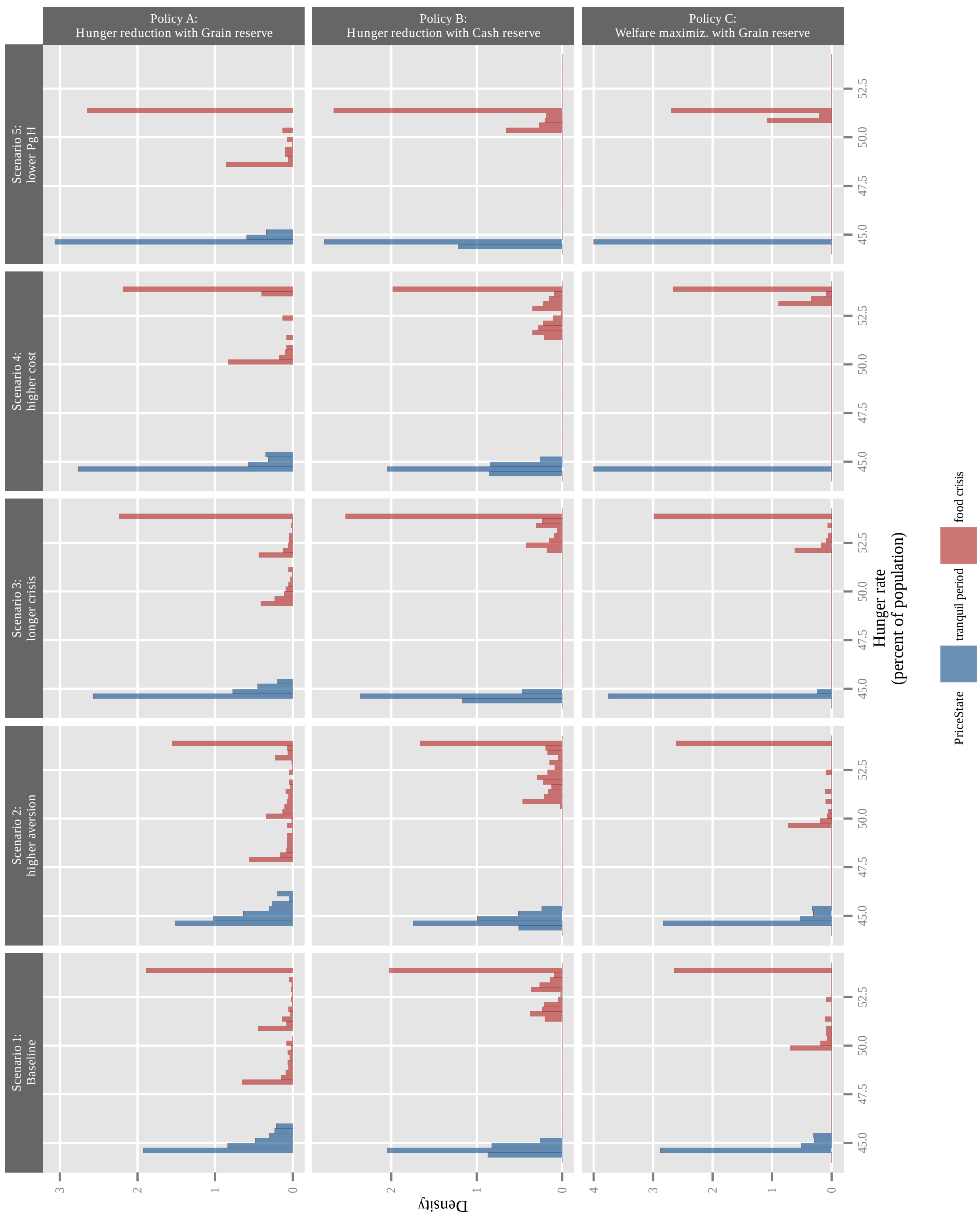

Figure A1: Hunger Histogram

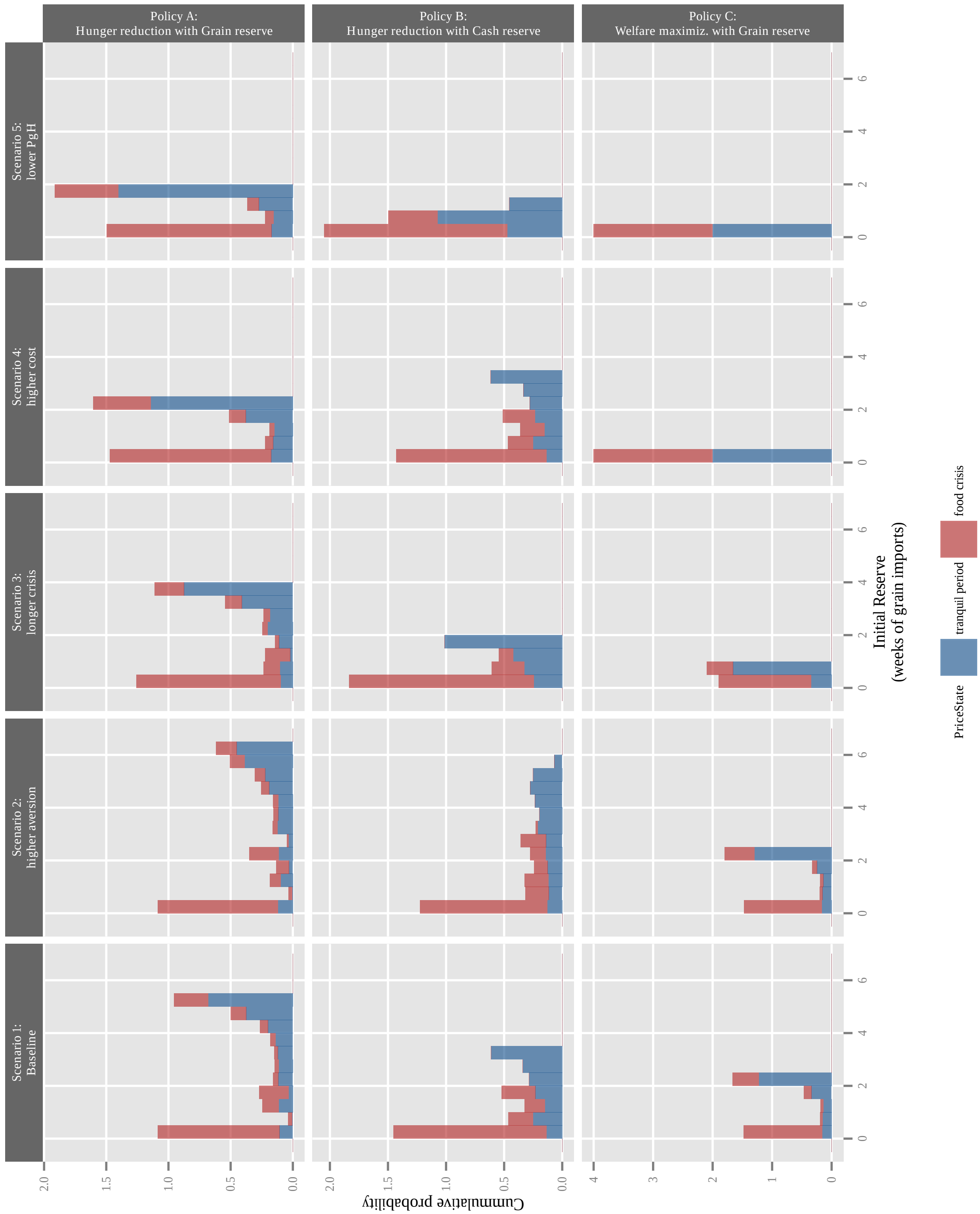

Figure A2: Grain Storage Histogram

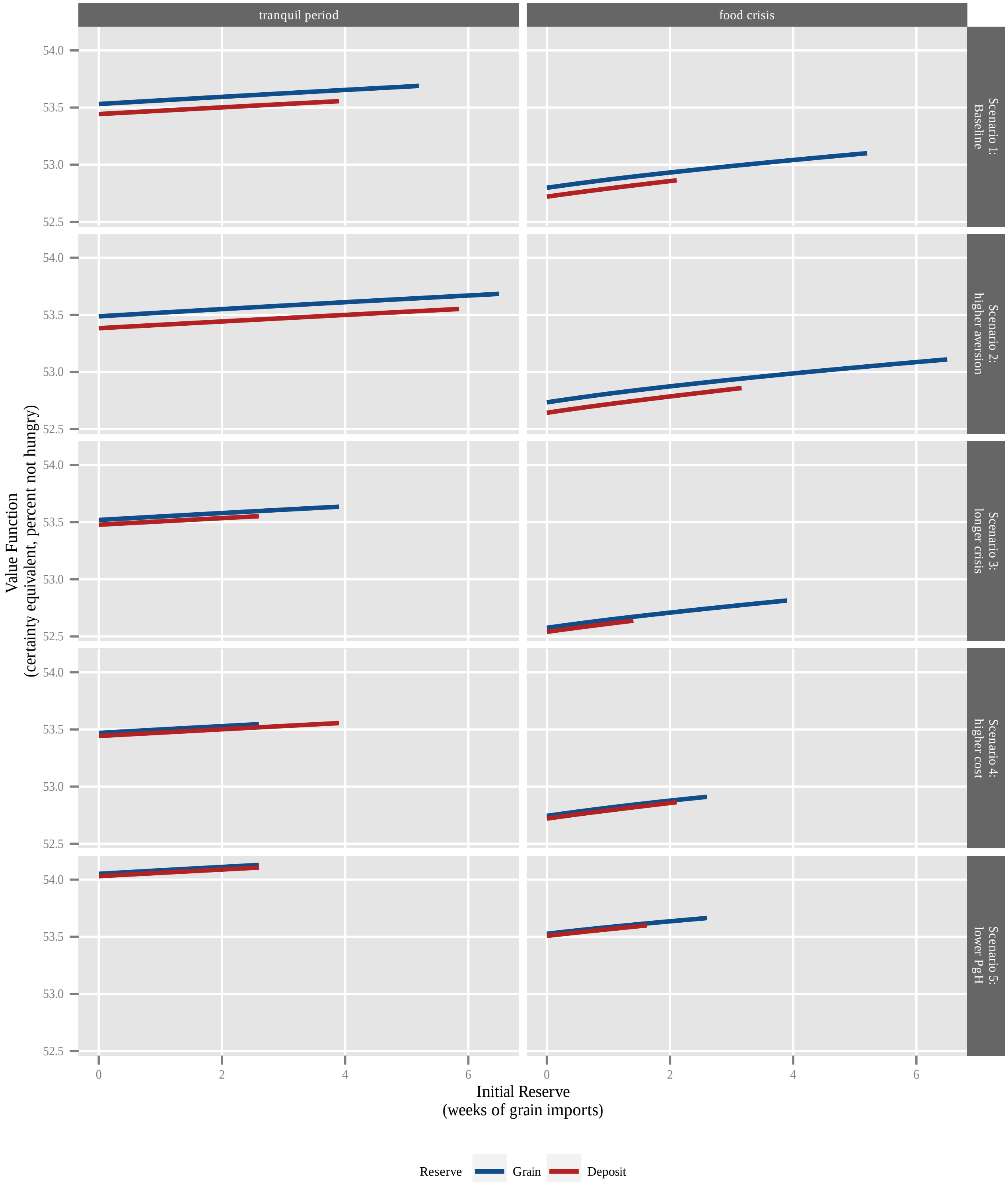

Figure A3: Value Function

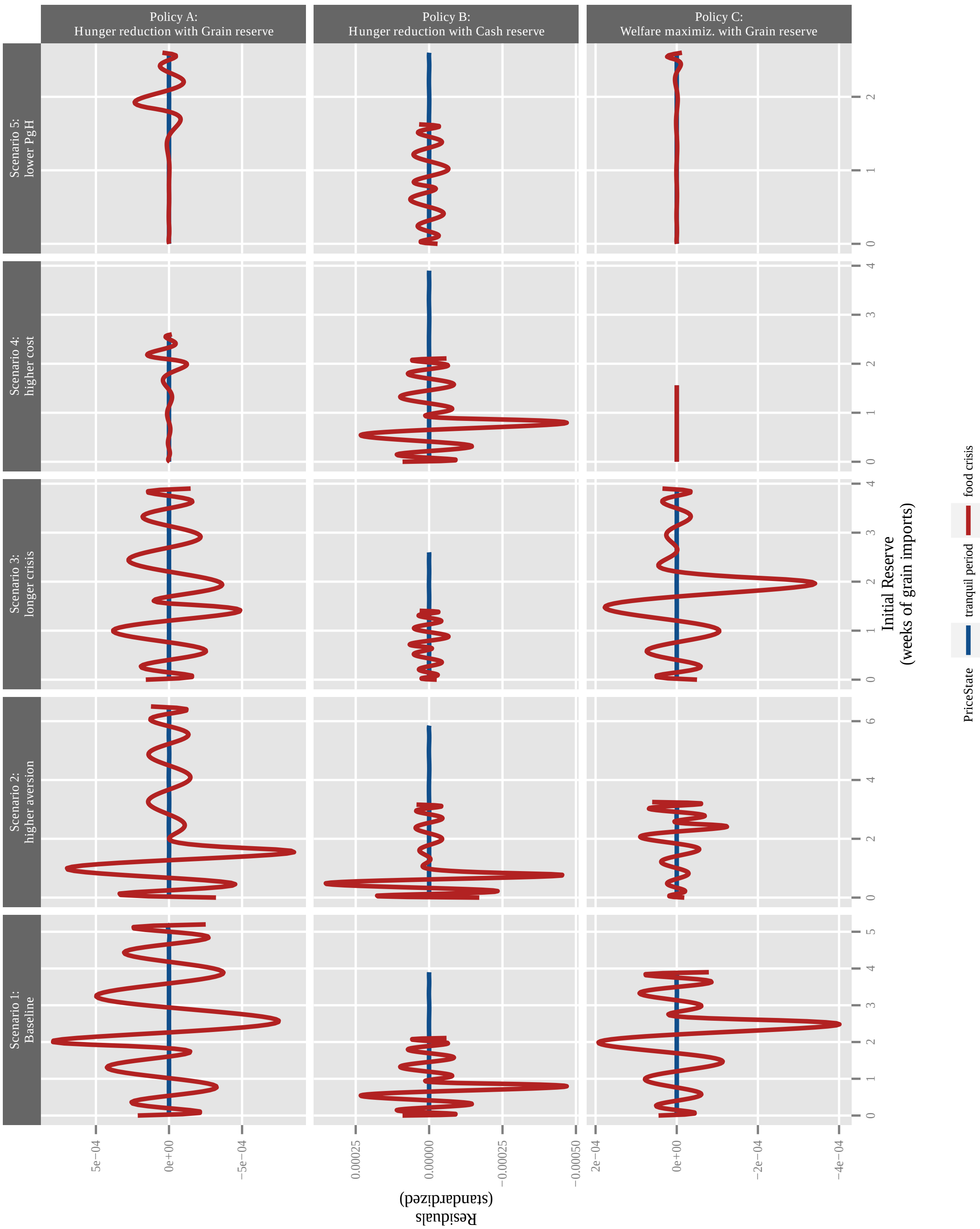

Figure A4: Residuals

List of symbols

PARAMETERS

α	price elasticity of food demand
η	income elaticity of food demand
ϕ	cost of grain storage
π_{ij}	transition probability between food price states
ρ	government's aversion to hunger
σ	elasticity of substitution between ingredients
θ	share of grain in recipe
ζ	food demand scale
a_f	food consumption distribution scale (excluding price effect)
a_y	income distribution scale
b_f	food consumption distribution shape
b_y	income distribution shape
c	critical food consumption
G	income Gini coefficient
p_H	international price of grain, food crisis
p_L	international price of grain, tranquil period
Y	income per capita
Γ	hunger rate

VARIABLES

τ	import tariff rate
Υ	fiscal revenue
D	government's deposits
f	quantity of food
M_i	household i's food budget
P	food price index
p_g	domestic price of grain
p_g^*	international price of grain
p_v	domestic price of vegetable
s	grain stock at beginning of period
x_g	quantity of grain
x_v	quantity of vegetables
y_i	household i's income

FUNCTIONS

$\mathbb{S}$	summation over income distribution
F_y	income distribution (cdf)
F_{food}	food consumption distribution (cdf)
r_H	government reward function, hunger target
r_W	government reward function, welfare target
V	government's value function
W	social welfare