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NATURAL DISASTERS AND MACROECONOMIC PERFORMANCE: THE ROLE OF RESIDENTIAL INVESTMENT

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Natural Disasters and Macroeconomic Performance: The Role of Residential Investment

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Abstract. Recent empirical research has shown that income per capita in the aftermath of natural disasters is not necessarily lower than before the event. Income remains in many cases not significantly affected or, perhaps even more surprisingly, it responds positively to natural disasters. Here, we propose a simple theory, based on the neoclassical growth model, that explains these observations. Specifically we show that GDP is driven above its pre-shock level when natural disasters destroy predominantly residential housing (or other durable goods). Disasters destroying mainly productive capital, in contrast, are predicted to reduce GDP. Insignificant responses of GDP can be expected when disasters destroy about twice as much residential structures as productive capital. We show that disasters, irrespective of whether their impact on GDP is positive, negative, or insignificant, entail considerable losses of aggregate welfare.

Keywords: Natural Disasters; Economic Recovery; Residential Housing; Economic Growth.

JEL: E20, O40, Q54, R31.

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1. Introduction

In this paper we propose an economic theory which deconstructs the macroeconomic impact of natural disasters. We mainly focus on hydro-meteorological disasters (e.g. floods, storms, droughts) and geophysical disasters (e.g. earthquakes, tsunamis) and the physical and monetary damage done. As documented by Cavallo and Noy (2011), these types of disasters are fairly common events across the globe and their incidence is increasing over time. For example, for the Asia-Pacific countries, the most afflicted region, the incidence of natural disasters increased from 11 events per country in the 1970s to 28 events in the 2000s. In Western Europe, events per country and decade increased from 5 to 15 over the same time period.

By now there exists a large and increasing empirical literature investigating the economic impact of natural disasters (e.g. Raddatz, 2007; Noy, 2009; Loyza et al., 2012, Fomby et al, 2013; Cavallo et al., 2013; see Cavallo and Noy, 2011 for a survey). One perhaps surprising conclusion suggested by the literature is that disasters do not necessarily harm macroeconomic performance, measured by GDP per capita, in the aftermath of the event. Loayza et al. (2012), for example, find across all disasters no significant impact on country GDP and on industrial output. When floods are investigated separately, in contrast, they are found to stimulate GDP while droughts are found to harm GDP in developing countries (but not everywhere). Similarly, Fomby et al. (2013) find a negative effect of droughts and a positive effect of floods but no effect of earthquakes and storms on post-disaster GDP in developing countries. In developed countries all types of disasters appear to exert no significant impact on GDP. Using counterfactual analysis, Cavallo et al. (2013) find that disasters exert no significant influence on short- and long-run output when they control for potential post-disaster outbreak of social conflict.

These empirical observations appear to be puzzling against the background of conventional neoclassical growth theory. Once we acknowledge that disasters destroy (potentially severely) productive potential of the economy, we would expect that they harm subsequent economic performance. It is true that the neoclassical growth model predicts that the *growth rate* after an exogenous loss of capital stock (or other productive factors) is positive. This phenomenon is known as catch-up growth from below towards the steady-state. GDP per capita, however, is predicted to fall short of its pre-disaster level according to conventional growth theory.[1]

[1]The disaster literature, confusingly for growth economists, refers sometimes to the differential between pre- and post-shock levels of GDP as GDP growth (e.g. Loayza et al., 2012). This differential is predicted by the standard neoclassical growth model to be unambiguously negative. Moreover there exists also a smaller literature

In this paper we show how a simple extension of the neoclassical growth model can be used to square theory and empirics and how the model can be used to motivate the diverse post-shock macroeconomic outcomes found in the disaster literature. The key ingredients are the introduction of variable labor supply and the distinction between productive capital stock and residential housing (and other durable goods). In line with conventional theory the model predicts that an exogenous loss of capital stock reduces post-disaster GDP. An exogenous loss of residential housing, in contrast, drives GDP above its pre-shock level. The reason is that individuals, suffering from the implied wealth shock, supply more labor in order to (quickly) rebuild the damaged houses (and potentially other damaged durable goods as, for example, cars). Since firm capital remained undestroyed the increased labor supply implies higher GDP per capita during the reconstruction phase.

Considering jointly shocks on both state variables, the model predicts a negative GDP impact for disasters destroying predominantly productive capital and a positive impact on GDP for disasters destroying predominantly residential housing. No significant effect on GDP is predicted when the effects on firm capital is slighty smaller compared to that on residential housing. The theory is not only helpful to explain the frequently insignificant impact of disasters on GDP, it may also be exploited to rationalize the special cases for which the literature finds significant GDP effects. Intuitively, we may expect that droughts exert a negative impact on GDP because they leave residential housing mostly intact and destroy predominantly firm capital, in particular in largely agrarian societies (seeds, livestock). Conversely, we could imagine that floods stimulate GDP because they damage predominantly residential housing (and other durable goods, like furniture or household appliances).

In order to present the mechanics behind the "housing–channel" in the cleanest way we first discuss in Section 3 the case of a small open economy and perfect capital mobility. This exercise shuts down the "capital-channel" because capital stock is pinned down to its steady-state value. In this framework we generally prove that a disaster that damages residential housing leads to higher GDP in the short-run and in the long-run. The reason is the negative wealth effect induced by the disaster, which motivates households to supply more labor and to quickly reconstruct the damaged houses and durable goods.

investigating the association between disaster risk and long-run growth (e.g. Skidmore and Toya, 2002). Here we focus on the short to medium run impact of disasters.

We then turn to the large economy case and show that the main mechanics of the wealth effect are preserved while another, amplifying effect occurs through intertemporal substitution. Households want to reconstruct their damaged houses quickly and increase their residential investments in the aftermath of the disaster. Resources for this purpose are freed by reducing investments in productive capital and by reducing consumption of non-durable goods. In order to mitigate the drop of consumption, households are motivated to raise their labor supply even further, beyond what has already been triggered by the wealth effect.

Our deconstruction of the effect of disasters on firm capital and on residential housing shows that GDP can be a very misleading indicator of the economic damage done by natural disasters. This is most obvious when we compare a disaster that destroys "only" productive capital with another one destroying *additionally* residential housing. The GDP damage is larger for the first one while the induced welfare loss is larger for the second one. At the end of the paper we perform a welfare analysis for a numerically specified version of the model and find large welfare losses from natural diasters that leave GDP more or less unaffected.

The paper is organized as follows. The next section introduces the general model. Section 3 presents the case of a small open economy and Section 4 presents the closed economy case. In the main text we assume that households own their houses. In the Appendix we show robustness of results against an alternative setup in which households rent housing services from firms. In Section 5 we specify the model numerically and investigate post-disaster adjustment dynamics quantitatively. We provide estimates of the incurred welfare loss under varying assumptions about the physical impact of disasters. Throughout the paper we focus on economic or "material" effects and ignore that natural disasters kill people. The welfare estimates should be thus understood as lower bounds of the actual damage done by natural disasters.

2. The Model

2.1. **Households.** The economy is populated by a continuum $(0,1)$ of households who take prices as given, supply ℓ units of labor, and experience utility from consuming nondurable goods c and housing (and other durable goods) d as well as from enjoying leisure $(1-\ell)$. In order to keep the utility function general we abstain from introducing exogenous technological growth. As well-known from the business cycle literature, introducing trend growth would entail severe restrictions on the functional form of the utility function in order to guarantee that leisure is stationary. Our variables (besides leisure) could be interpreted as being measured in terms of deviation from trend growth. In order to derive theoretical results we have to assume that utility is additively separable between nondurable consumption, durable consumption, and leisure.[2] In the quantitative part of the paper we also investigate non-separable utility and demonstrate robustness of the main results.

Households maximize lifetime utility

$$V = \int_0^\infty (u(c) + v(d) + q(1-\ell)) \cdot e^{-\rho t} dt, \tag{1}$$

where u, v, and q denote concave sub-utility functions satisfying the Inada conditions and ρ is the time preference rate. To simplify notation we introduce σ_c, σ_d, and σ_ℓ as the inverse of the elasticity of intertemporal substitution for nondurable goods consumption, durable goods consumption, and leisure, respectively:

$$\sigma_c(c) := -\frac{c\,u''(c)}{u'(c)} \qquad \sigma_d(d) := -\frac{d\,v''(d)}{v'(d)} \qquad \sigma_\ell(\ell) := -\frac{\ell\,q''(\ell)}{q'(\ell)}\,. \tag{2}$$

Household income is spent on non-durable consumption goods c and on residential investment x (including potentially investment in other durable goods). Households earn a wage w per unit of labor supplied and hold assets a, on which they earn a return r, which altogether implies that they face the budget constraint

$$\dot{a} = w\ell + ra - c - px\,, \tag{3}$$

in which p denotes the price of residential investment. We assume that a no-Ponzi-game condition for assets holds.

Durable goods depreciate at rate δ_d and, hence, the stock of durables evolves according to

$$\dot{d} = x - \delta_d d\,, \tag{4}$$

with $x \geq 0$. Households choose c, ℓ, and x to maximize (1) subject to (3) and (4), and the initial conditions $a(0) = a_0$ and $d(0) = d_0$. The first order conditions are

$$u'(c) = \lambda \tag{5}$$

[2]Iacoviello (2005) argues that separability between nondurable and durable goods consumption is supported by empirical evidence; see also Bernanke (1984).

$$\mu = p\lambda \tag{6}$$

$$\lambda w = q'(1-\ell) \tag{7}$$

$$\dot{\lambda} = \lambda\rho - \lambda r \tag{8}$$

$$\dot{\mu} = \mu\rho - v'(d) + \mu\delta\,, \tag{9}$$

where λ denotes the shadow price of one unit of installed capital in terms of marginal utility and μ denotes the shadow price of one unit of residential housing in terms of marginal utility. From the first order conditions we derive the Euler equation for consumption and a relation equating the wage rate to the marginal rate of substitution between consumption of nondurables and leisure:

$$\frac{\dot{c}}{c} = \frac{r-\rho}{\sigma_c} \tag{10}$$

$$w = \frac{q'(1-\ell)}{u'(c)}\,. \tag{11}$$

2.2. **Durable goods producing firms.** There exists a continuum $(0,1)$ of construction firms (durable good producing firms). These firms convert units of final goods into units of housing. Following Iacoviello (2005) and Carlstrom and Fuerst (2010), we assume that firms face convex adjustment costs depending on the amount of housing they produce per unit of time. These costs can be understood as, for example, arising in terms of additional planning costs when sequential tasks have to be preformed in a tight time frame, or inefficient labor input due to fatigue during overtime hours. Since these kind of costs arise when investment and thus the workload is especially high, they explain why marginal costs are increasing in investment per unit of time.

The empirical literature on capital and investment adjustment costs has identified costs arising at the plant level if firms adjust the capital stock or investment (see e.g. Cooper and Haltiwanger, 2006, for a recent study). Similar costs are likely to emerge for firms in the residential construction sector (see Topel and Rosen, 1988). In order to keep the analysis general, we assume that the total costs for installing x units of housing sum up to $x + \psi(x)$ with a convex function ψ satisfying $\psi(0) = 0$. The literature on capital adjustment costs usually assumes that adjustment costs additionally depend on the installed stock. For reasons of tractability we assume that costs depend on investment only. Our quantitative results are robust against alternative specifications with reasonable parametrization of adjustment costs.

Total firm revenue equals px. Each household is assumed to engage one construction firm per unit of time but it can change the contracting party at any point of time. Free entry into the construction sector implies that firms sell x at unit costs:

$$p = 1 + \frac{\psi(x)}{x} \,. \tag{12}$$

Differentiating (12) with respect to time and using (5) – (9) we obtain the law of motion for residential investment as

$$\frac{\dot{x}}{x} = \left(\psi'(x) - \frac{\psi(x)}{x}\right)^{-1} \left[p(r+\delta) - \frac{v'(d)}{u'(c)}\right] \,. \tag{13}$$

2.3. **Final goods producing firms.** The economy is populated by a continuum $(0,1)$ of final goods producing firms. Final goods are used as non-durable consumption goods, for residential investment and for investment in firm capital. Each firm employs capital k and labor ℓ to produce final output $y = Af(k,\ell)$, in which A denotes total factor productivity and $f(k,\ell)$ is a neoclassical production function with positive and diminishing marginal returns. Firm capital depreciates at rate δ_k. Firms hire labor and capital on competitive factor markets and pay them according to their marginal product:

$$r = \frac{\partial Af(k,\ell)}{\partial k} - \delta_k \,, \tag{14}$$

$$w = \frac{\partial Af(k,\ell)}{\partial \ell} \,. \tag{15}$$

Therewith the description of the economy is almost complete. The closing element depends on whether we consider a large economy or a small open one.

3. The Small Open Economy

In case of a small open economy (and perfect capital mobility) firms can borrow on international capital markets and no arbitrage equalizes the domestic interest rate and the world interest rate $\bar{r}$, $r = \bar{r}$. This means that equation (14) pins down the domestic capital labor ratio and that the domestic wage in equation (15) is pinned down by the international wage rate, $w = \bar{w}$. In order to simplify the formal analysis we assume that $\bar{r} = \rho$ such that households prefer a constant time profile of consumption and labor supply, $\dot{c} = \dot{\ell} = 0$ (from equations (10) and (11)).

The demand for non-durable consumption goods and residential investment, as well as household labor supply is determined by the household's intertemporal budget constraint. This means that any shock or new information affecting the intertemporal budget constraint also affects the optimal level of c and ℓ. The implied dynamics of residential investment is then given by equations (4) and (13).

For the small open economy firm capital adjusts via international capital movements. We thus focus the disaster analysis of this section on the effects originating from the destruction of residential housing. For that purpose we assume that the economy rests at a steady state before it is hit by a natural disaster. In order to elaborate how the disaster affects GDP we begin with showing that the destruction of residential housing entails a negative wealth effect. Households respond to the wealth shock by consuming less nondurables and less housing (and other durables) and by supplying more labor. Higher labor supply then lifts GDP above pre-shock level.

Integrating equation (3) provides the households' intertemporal budget constraint,

$$\int_0^\infty c e^{-\bar{r}t} dt = \ell \int_0^\infty \bar{w} e^{-\bar{r}t} dt - \int_0^\infty p(x) x e^{-\bar{r}t} dt + a_0 \,. \tag{16}$$

Using the fact that c and ℓ are constant the budget constraint simplifies to

$$\frac{c}{\bar{r}} = \frac{\ell \bar{w}}{\bar{r}} - \int_0^\infty p(x) x e^{-\bar{r}t} dt + a_0 \,. \tag{17}$$

Finally, substituting $w = v'(1-\ell)/u'(c)$ we obtain

$$\frac{(u')^{-1}\left(\frac{q'(1-\ell)}{\bar{w}}\right)}{\bar{r}} - \frac{\ell \bar{w}}{\bar{r}} = a_0 - \int_0^\infty p(x) x e^{-\bar{r}t} dt \,. \tag{18}$$

Notice that the left hand side of (18) depends negatively on ℓ since $d\left(u'(\cdot)\right)^{-1}/d(\cdot) < 0$. This means that if households experiences a negative wealth effect such that the right hand side of (18) decreases, they respond by supplying more labor.

We show next that an economy resting at a steady state and exposed to a disaster that destroys part of d experiences indeed a negative wealth effect because the disaster raises $\int_0^\infty p(x) x e^{-\bar{r}t} dt$. To do so, we define the net present value of residential investments as

$$X := \int_0^\infty p(x) x e^{-\bar{r}t} dt = \int_0^\infty x \left(1 + \frac{\psi(x)}{x}\right) e^{-\bar{r}t} dt \,. \tag{19}$$

Intuitively, a disaster that destroys parts of d, raises X, because rebuilding the stock of d requires higher temporary investments x, which raises the net present value of future investments. To prove this claim we focus on the dynamics of d and x summarized by

$$\dot{d} = x - \delta_d d \tag{20}$$

$$\frac{\dot{x}}{x} = \left(\psi'(x) - \frac{\psi(x)}{x}\right)^{-1} \left[\left(1 + \frac{\psi(x)}{x}\right)(r + \delta_d) - \frac{v'(d)}{u'(c)}\right] \tag{21}$$

and $d(0) = d_0$. The steady-state of the subsystem (20) and (21) is given by $x = \delta_d d$ and $(1 + \psi(x)/x)\,(\bar{r} + \delta_d) = v'(d)/u'(c)$. Notice that the steady-state of the subsystem depends on c and that c is determined in conjunction with x by the intertemporal budget constraint (18) and the labor supply equation (11). This means that the steady state itself depends on the evolution of the dynamic system towards the steady state. In other words, the steady-state of the dynamic subsystem (20) and (21) depends on the initial situation (c_0, x_0).[3]

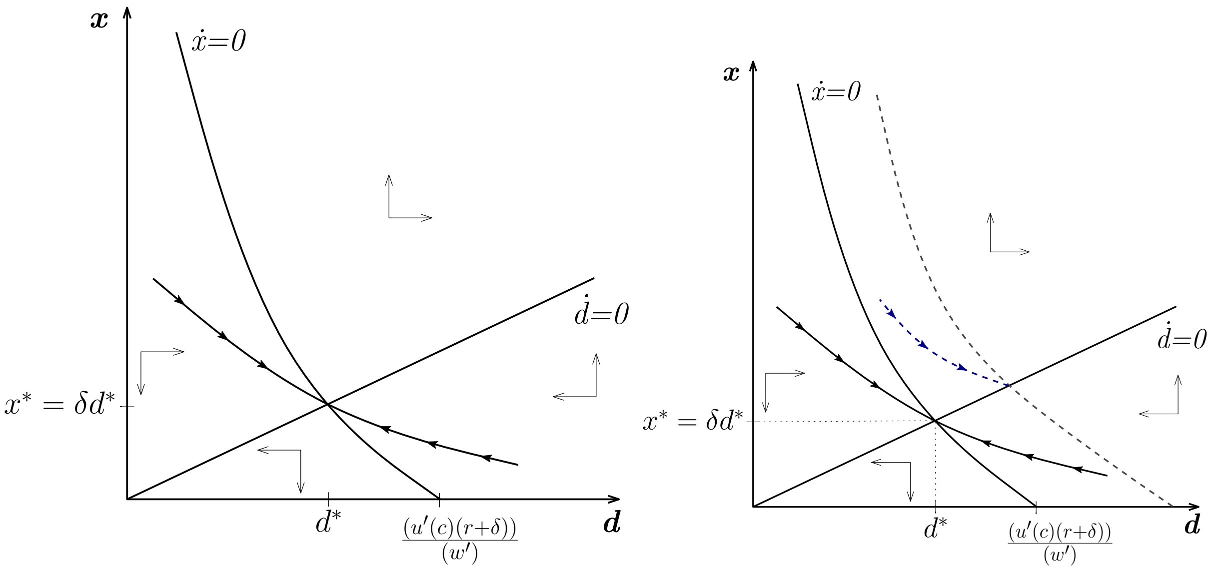
In order to demonstrate that adjustment dynamics towards the steady state are unique we construct a phase diagram, taking c as given and keeping in mind that c depends on X and therefore on the adjustment path of x. The panel on the left hand side of Figure 1 shows the phase diagram with adjustment dynamics towards the steady state. The phase diagram is constructed by first noting that the $\dot{d} = 0$ isocline is a ray with slope δ starting at the origin (from $x^* = \delta d^*$). Above the line, $\dot{d}$ is positive, below the line, $\dot{d}$ is negative. The $\dot{x} = 0$ isocline is downward sloping and intersecting the d axis at $d = (v')^{-1}\left(u'(c)(\bar{r} + \delta)\right)$. On the right hand side of the line, $\dot{x}$ is positive, on the left hand side, $\dot{x}$ is negative. The slopes of the two isoclines have opposite signs, implying that the isoclines intersect exactly once. In conclusion, the steady state is saddlepath-stable. A higher value of c (lower X) shifts the $\dot{x} = 0$ isocline upwards and, hence, the steady state value of d increases. The stable saddlepath towards the steady state is downward sloping. In Appendix A we derive formally, that the subsystem (20) and (21) has a unique and saddle-point stable steady state.

In comparison with conventional growth theory, the usual argument for uniqueness of adjustment dynamics is slightly modified. To see this, consider an economy starting not on the stable saddlepath but somewhere below it. Following the arrows of motion, the economy would always remains below the saddlepath such that aggregate X would also be lower. Then, from

[3] A similar kind of phase diagram for the analysis of dynamic subsystems has been popularized in growth economics by Galor and Weil (2000).

the intertemporal budget constraint (18), consumption c must be higher. This in turn, means that the $\dot{x} = 0$ isocline, and thus the steady state, shifts upwards. An economy starting below the stable arm would thus never arrive at the steady state because x is below the stable arm everywhere during the transition and, secondly, because this very phenomenon shifts the steady state even further upwards. Analogously an economy starting above the saddlepath would never reach the steady state.[4] This reasoning can be exploited to arrive at the following conclusion.

FIGURE 1: PHASE DIAGRAM



Left panel: Phase diagram with stable saddlepath. Right panel: Phase diagram used for for proof of Lemma 1.

LEMMA 1. *If an economy rests at a steady state and residential housing (d) gets destroyed, aggregate expenditure on housing (X) increases compared to the pre-shock steady state level.*

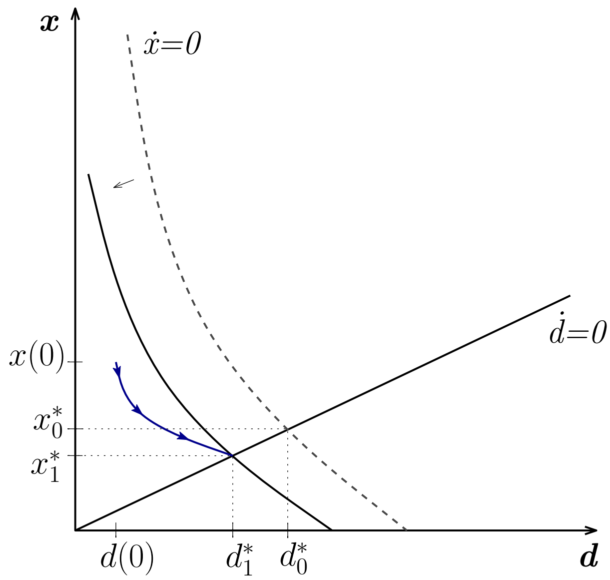
Proof. The lemma is proved by contradiction. The counterfactual phase diagram is shown in the panel on the right hand side of Figure 1. Assume that the destruction of housing d reduces aggregate housing expenditure X. In this case, equations (18) and (11) show that c would increase and, hence, the $\dot{x} = 0$ isocline would shift upwards. This would increase the steady-state value of d. However, along the adjustment path x is strictly larger than at its old steady-state because the stable saddlepath is downward sloping, $x(t) > x^*_{old}$, implying increasing aggregate expenditure X. In other words, reducing X in response to lower d would lead to a

[4]The local uniqueness of the saddlepath can also be proven by analyzing the full dynamic system. Numerical evaluation of the Jacobian matrix for a wide range of parameter values shows that it has one negative and one zero eigenvalue. This indicates that the stable saddlepath is unique and that the steady state to which the economy converges depends on the initial conditions ($a(0) = a_0$ and $d(0) = d_0$).

contradiction. If X would remain constant this would lead to a contradiction in an analogous way. In conclusion, after a destruction of d, X rises compared to it original steady-state level. □

Summarizing, the actual adjustment dynamics triggered by a natural disaster destroying d are shown in Figure 2. Notice that along the adjustment path x is higher compared to the old steady state for an initial period $[0, T]$. During the time interval (T, ∞) x is smaller than x^*_{old}. Yet due to discounting of future expenditures and higher adjustment costs in the initial periods, X increases in net terms. This leads to the following result.

FIGURE 2: PHASE DIAGRAM: ADJUSTMENT DYNAMICS AFTER DISASTER



PROPOSITION 1. *If an economy rests at a steady state and residential housing (d) gets destroyed, only parts of the stock of d are rebuild. The resulting new steady state level of d is lower compared to the pre-shock level.*

Proof. Inspecting the adjustment dynamics derived in Figure 2 confirms that the after-shock steady-state level of d lies below the pre-shock steady-state level. □

The result implies that – without trend growth – an economy never completely rebuilds the housing stock (stock of durables) destroyed by disaster. If there is trend growth, d would grow at the steady state and the post-disaster growth rate of d would be higher than the pre-shock rate. However, the level of d would be lower compared to an economy not experiencing the disaster and growing along the balanced growth path.

The reason for the permanently lower level of residential housing is the negative wealth effect. Households response to the diminished wealth by reducing their consumption of non-durable goods, consumption of housing services (durable goods), and leisure. This leads to our next result.

Proposition 2. *Aggregate welfare falls below its pre-shock level if residential housing gets destroyed in an economy resting at a steady state.*

Proof. According to Proposition 1, the level of residential housing after the disaster falls permanently below the pre-shock level. From Lemma 1 we conclude that consumption of non-durable goods is also permanently lower. Finally, we conclude from equation (18) that labor supply increases. Since instantaneous utility from all three components is strictly below pre-shock level, lifetime utility of households, i.e. aggregate welfare, is below pre-shock level as well. □

Finally, we show that, although aggregate welfare is affected negatively, GDP and GDP growth increase in response to the disaster.

Proposition 3. *If residential housing gets destroyed in an economy resting at a steady state, then aggregate output and thus GDP per capita increase permanently above the pre-shock level. Hence, GDP growth in the aftermath of the disaster is positive.*

Proof. If d gets destroyed, consumption of non-durable goods decreases (see equation (11)) and labor supply increases (see equation (18)). Higher labor supply triggers capital inflows from the rest of the world until the capital labor ratio reaches its pre-shock level and the domestic interest rate equals the world interest rate. Higher labor supply in conjunction with higher capital stock implies higher aggregate output and thus higher GDP per capita. □

4. The Closed Economy Case

4.1. **Setup of the Model.** The closed economy can be best understood as the standard neoclassical growth model augmented by a housing sector and variable labor supply. Households can save only in terms of domestic capital such that $a = k$. The feature of diminishing marginal returns to capital provides a unique steady state.[5]

[5] In the Appendix we show that the dynamic system (22)–(26) has a unique steady state. We also checked by numerically evaluating the eigenvalues that adjustment dynamics are unique for the relevant range of parameter values.

The households' budget constraint (3) can be converted into an equation of motion for aggregate capital by substituting factor prices (equations (14) and (15)) and the price of residential investment (equation (12)). This provides (22). The remaining equations are shared with the small open economy case. For convenience we collect the decisive equations again and obtain the large economy as described by following dynamic system.

$$\dot{k} = Af(k, \ell) - \delta_k k - x - \psi(x) - c \tag{22}$$

$$\dot{d} = x - \delta d \tag{23}$$

$$\frac{\dot{c}}{c} = \frac{r - \rho}{\sigma_c} \tag{24}$$

$$\frac{\dot{x}}{x} = \left(\psi'(x) - \frac{\psi(x)}{x}\right)^{-1} \left[p(r + \delta) - \frac{v'(d)}{u'(c)}\right] \tag{25}$$

$$w = \frac{q'(1 - \ell)}{u'(c)}, \tag{26}$$

together with initial conditions $k(0) = k_0$ and $d(0) = d_0$.

4.2. **Effect of Disasters on GDP: Intuition.** For expositional purposes we distinguish between two polar types of disasters. The first type destroys only residential housing (durable consumption), the second type destroys only productive capital. In reality, of course, disasters usually destroy both, d and k. Real disasters can be conceptualized as a mix of the two polar cases. In the quantitative section we first show results for the two polar types of disasters and then investigate the impact of "mixed disasters".

We begin the analysis again by inspecting the intertemporal budget constraint. Integrating (3) and inserting $a_0 = k_0$ we obtain

$$\int_0^\infty c\, e^{-\int_0^s r(u)du} ds = k_0 + \int_0^\infty w\ell\, e^{-\int_0^s r(u)du} ds - \int_0^\infty p(x)x e^{-\int_0^s r(u)du} ds. \tag{27}$$

The intertemporal budget constraint differs from the open economy case (equation 18) mainly because the wage rate w and the interest rate r are now varying over time. A damaged stock of productive capital entails temporarily lower wages and higher interest rates and these changing factor prices impinge on household wealth. As demonstrated below, these "factor price effects" are quantitatively of second order compared to the wealth effect originating from the loss of productive capital or residential housing.

We start by analyzing a d-shock. As for the small open economy, destroyed houses entail reconstruction costs such that the present value of aggregate residential investment $\int_0^\infty p(x)xe^{-\int_0^s r(u)du}ds$ increases. This, in turn, implies lower household wealth. Households respond to the reduced wealth by lowering consumption of nondurable goods and by supplying more labor. Productive capital, by assumption, was not affected by the disaster, which means that higher labor supply and employment lifts GDP above its pre-shock level.

The impact of a disaster destroying productive capital can be investigated analogously. The k-shock reduces k_0 on the right hand side of equation (27) and thus entails a negative wealth effect as well. Households respond by consuming less nondurable goods, by reducing residential investment, and by supplying more labor. The reason for this joint response lies in the fact that nondurables, durables and leisure are normal goods such that demand of all three components shifts in the same direction after a wealth shock. In contrast to the d-shock higher labor supply is not sufficient to lift output above steady state level for reasonable parameter values, because the lower level of capital after the shock is the dominant force on output. Instead, neoclassical adjustment dynamics are induced: The economy starts at a lower level of output and converges towards the steady state from below. In order to verify this claim and to investigate the quantitative effects of disasters we continue with a numerical specification of the model.

5. Quantitative Analysis

5.1. **Numerical Specification of the Model.** In order to parameterize the model we need to specify the functional form for utility and production technology. We assume that households face an isoelastic utility function

$$\int_0^\infty \left[\frac{c^{1-\sigma_c}-1}{1-\sigma_c} + \beta\frac{d^{1-\sigma_d}-1}{1-\sigma_d} + \eta\frac{(1-\ell)^{1-\sigma_\ell}-1}{1-\sigma_\ell}\right]\cdot e^{-\rho t}dt \tag{28}$$

in which β and η denote the weights of residential housing and leisure, respectively. In Section 5.4 we relax the assumption of separable utility between nondurable and durable consumption goods and verify that the results hold for non-separable utility as well. Firms are assumed to produce according to the Cobb-Douglas technology $y = Ak^\alpha\ell^{1-\alpha}$, in which α denotes the elasticity of output with respect to capital. Adjustment costs for residential investment are assumed to be quadratic, i.e. $\psi(x) = \gamma x^2$.

For the benchmark case we take the values of α, r^*, ℓ^*, and the Frisch elasticity of labor supply from our calibration of the neoclassical growth model for the U.S. economy (Strulik and Trimborn, 2012). Parameter η is set in order to match steady-state labor supply ℓ^*, and ρ is set in order to fit the steady-state interest rate to r^*. For given $\ell^* = 0.25$ and a given Frisch elasticity of unity we obtain $\sigma_\ell = 3$. For depreciation of physical capital and residential housing we take the average depreciation rates measured for the U.S. between 1948 and 2008 (Davis and Heathcote, 2005, Eerola and Määtänen, 2013). We set β and γ in order to match the share of households' housing assets on total assets of (almost) 0.5 in the year 2008, and the average residential investment–GDP ratio of 5%, observed between 1952-2008 (both values according to Iacoviello, 2010 and 2011). The resulting value of γ is 6.5 and it implies an elasticity of house prices with respect to investment of 0.15. When we compare this result with the literature we have, on the one hand, the study by Topel and Rosen (1988), which focusses on adjustment costs in the housing sector and which estimates a long-run (one-year) elasticity of 0.3 and a short-run (one-quarter) elasticity of 1. On the other hand, we have the literature on adjustment costs in general, which comes up with much lower values. The estimates of Cooper and Haltiwanger (2006), for example, would imply an elasticity of 0.0015 for our model and Shapiro's (1986) estimates would imply an elasticity of 0.015. These estimates include all sectors of the economy and the construction sector contributes only with a low weight. Our value for the elasticity of house prices with respect to investment is about in the middle of Topel and Rosen's estimates and the values suggested by the general adjustment cost literature. We respond to the involved uncertainty by providing a sensitivity analysis for the value of γ (see Section 5.3). It turns out that our main results on the quantitative impact of disasters on GDP and on welfare are largely unaffected by the choice of γ.

The inverse of the intertemporal elasticity of substitution for consumption of durables and nondurables, respectively, is set to 2, based on Ogaki and Reinhart (1998). The numerical specification of the benchmark model is summarized in Table 1. A sensitivity analysis with respect to the most decisive parameters is provided below.

Table 1. Parameter Values: Benchmark Model

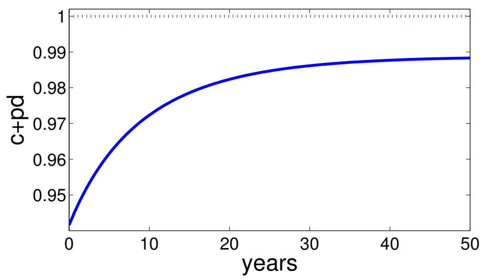
A	α	δ_k	δ_d	r^*	(ρ)	γ	ℓ^*	(η)	Frisch	(σ_ℓ)	σ_c	σ_d	β
1	0.38	0.058	0.015	0.038	0.038	6.5	0.25	3.56	1	3	2	2	1.38

Notation in parenthesis indicates implied values.

5.2. **Quantitative Results.** Quantitative results are calculated by employing the relaxation algorithm (Trimborn et al., 2008). The solution method calculates adjustment dynamics of the non-linear model and provides the exact solution, up to a user-specified error, also for large deviations from the steady-state. It is thus a suitable tool to investigate natural disasters, i.e. big shocks that drive the economy far away from the steady-state. We employ a recently developed numerical method to ensure that non-negativity constraints on capital investment and residential investment hold during the adjustment process (Trimborn, 2013).

We begin with exploring quantitatively the hysteresis effect of the open economy case. Figure 3 shows the impulse response of aggregate consumption (nondurables and housing) following a disaster destroying 20% of the stock of houses. Aggregate consumption jumps down on impact as a reaction to the disaster and recovers afterwards. However, as shown in Proposition 1, the stock of residential housing does not return to its pre-disaster steady state level but converges to a lower new steady state instead. Since nondurable consumption is also lower compared to its pre-disaster level, aggregate consumption falls short of its pre-disaster level. Such a hysteresis in consumption as a response to large disasters has been found by Nakamura et al. (2013).

Figure 3: Hysteresis in Consumption: Small Open Economy

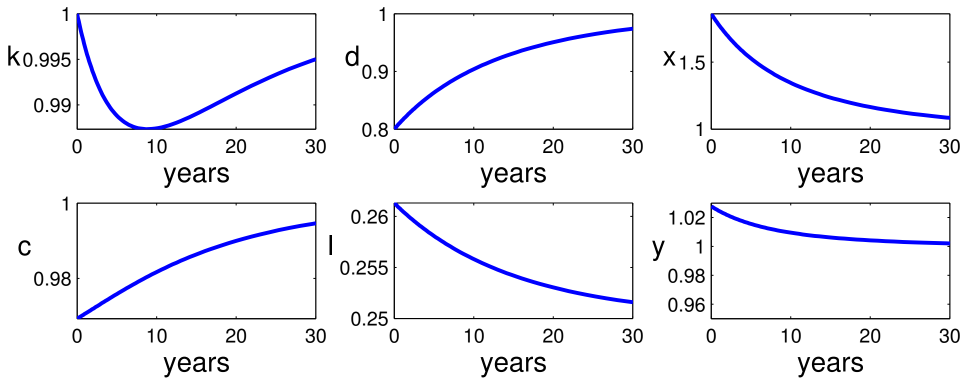


Impulse response of aggregate consumption to the destruction of residential housing by 20%.

We continue with the closed economy case. We investigate three different types of disasters: a d-disaster destroying only residential housing (or other durable goods), a k-disaster destroying only productive capital, and a "mixed disaster" destroying parts of both stocks. We normalize the size of disasters such the value of assets destroyed is equal in all three cases. Recall that our calibration assumed that the value of productive capital and housing is equal at the steady state. This means that the d- and k- disaster are normalized such that they destroy the same proportion of either d or k. For the mixed disaster, we consider a destruction of d and k that adds up to the same loss of wealth as the one-shock disasters.

Figure 4 shows the impulse responses following a reduction of d by 20% of the steady-state level. The response on impact of nondurable consumption, labor supply and output is qualitatively the same as in the open economy case: Households reduce consumption and increase labor supply, thereby lifting GDP above pre-shock level. This response is driven by the wealth effect, which is operative in open and closed economies.

Figure 4: Natural Disaster: Destruction of Residential Housing



Impulse responses to the destruction of residential housing by 20%. The panel shows the response of capital (k), residential housing (d), residential investment (x), nondurable consumption (c), labor supply (ℓ), and output (y).

In the closed economy case there exists, furthermore, an intertemporal substitution effect, which amplifies the positive response of labor supply and GDP. Due to their damaged houses, household experience a high marginal utility from housing, which induces them to rebuild their houses quickly and to incur high residential investments. Since households cannot borrow on international capital markets, resources are scarce in the aftermath of a disaster. In order to free resources, households reduce capital investment and consumption. Then, in order to mitigate the drop of consumption households further increase their labor supply in the aftermath of the disaster. As a consequence, GDP in the initial periods after the disaster rises even further, beyond the increase triggered by the wealth effect.

As a side effect, lower investment in productive capital reduces the capital stock. Only after about nine years – when about half of the houses and other durable goods have been reconstructed – investment in capital is higher than depreciation and the capital stock returns to its steady-state level from below.

In our numerical simulations it turns out that as long as the Frisch elasticity of labor supply is positive, the initial response of labor supply and hence of GDP is positive. The sensitivity analysis conducted in Section 5.3 shows that even for small Frisch elasticities GDP responses positively to disasters destroying residential housing. The sensitivity analysis also reveals that the relative magnitude of the intertemporal elasticity of substitution for nondurable consumption and durable consumption determines the size of the intertemporal substitution effect and therefore much of the quantitative response of output.

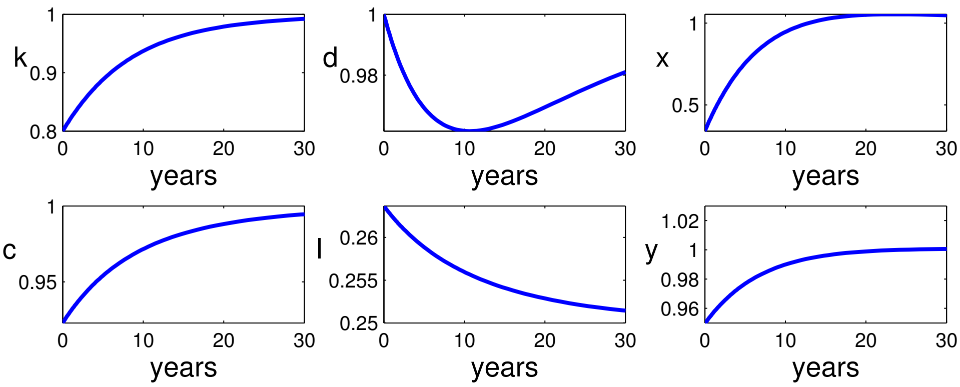
Although the disaster increases GDP per capita, the effect on welfare is clearly negative. Households experience lower utility from housing services as a direct result of the disaster. Furthermore they experience lower levels of nondurable consumption and leisure (as a result of the intertemporal substitution effect and the wealth effect). Hence, all three components of instantaneous utility, i.e. $u(\cdot)$, $v(\cdot)$, and $q(\cdot)$, are affected negatively. In order to make welfare losses comparable we measure them in consumption equivalents of nondurable goods. In the benchmark case the accumulated welfare loss amounts to 4.8% compared to the pre-shock steady-state welfare level (cf. the upper left entries in Table 2). This number means that a household living in the economy struck by the disaster suffers the same welfare loss as a household losing forever 4.8% of nondurable consumption.

We next turn to a shock that destroys physical capital k. In Figure 5 we show the impulse responses caused by a reduction of k by 20%. Consumption and labor supply respond in the same way as for the d-shock. On impact, households consume less nondurable goods and supply more labor because of the negative wealth effect. Similar to the d-shock, there is also an intertemporal substitution effect at work. Since high capital investments are needed in order to rebuild the capital stock, resources are scarce during initial periods. Hence, households react by reducing residential investments, nondurable consumption and increasing labor supply in the initial periods. The intertemporal substitution effect works on top of the wealth effect and thus amplifies labor supply in the aftermath of the disaster.

Although labor supply is higher compared to pre-shock level in the initial periods, GDP decreases after the k-shock. The effect of lower productive capital on output dominates. As already pointed out, this is not a general result but it holds for reasonable parameterizations of the neoclassical growth model. Only when the Frisch elasticity of labor supply is infinity and the share of capital in production implausible low, GDP would response positively to a k-shock (see Strulik and Trimborn, 2014).

For welfare, the intuition developed in conjunction with the standard neoclassical growth model holds for the k-disaster model as well. A lower capital stock unambiguously causes

Figure 5: Natural Disaster: Destruction of Productive Capital



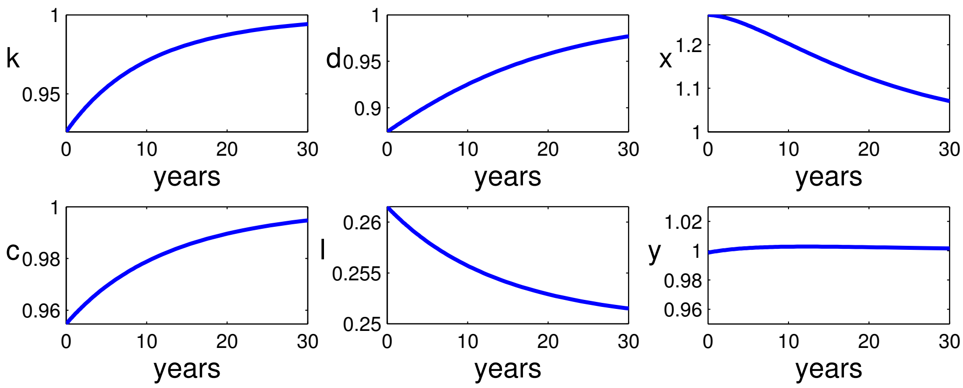
Impulse responses to the destruction of productive capital by 20%.

welfare to decline. This can be seen by inspecting the time path of housing (d), nondurable consumption (c), and labor supply (ℓ). As a response to the negative wealth effect, households enjoy lower levels of nondurable consumption and leisure. In addition, temporarily lower residential investment reduces the stock of housing. Since all three components of utility are affected negatively, overall utility is lower. We calculate a utility loss of 4.3% measured in consumption equivalents.

Finally, we investigate a shock that destroys capital and housing simultaneously. In order to show that disasters destroying productive capital as well as residential housing can have negligible effect on GDP per capital, we focus on a disaster destroying 13% of residential houses and 7% of productive capital. The impulse responses to this "mixed" disaster are shown in Figure 6. The negative effect of the disaster on both stocks entails a negative wealth effect. As a response households decrease consumption and increase labor supply. Similarly to the "pure" shocks discussed before there is an intertemporal substitution effect at work. In the initial periods, final output is needed to reconstruct the stocks of capital and houses, and hence resources are scarce. Households react by decreasing consumption and raising labor supply in addition to what has been caused by the wealth effect. This reconstruction effect raises labor supply and is thus a channel through which, taken for itself, output would increase in the aftermath of the disaster.

In our example the effects of destruction of productive capital and residential housing roughly balance each other. GDP per capita remains largely unaffected. GDP drops by 0.13% as initial

Figure 6: Natural Disaster: Destruction of Productive Capital and Residential Housing



Impulse responses to a simultaneous destruction of residential housing by 13% and productive capital by 7%.

response to this severe disaster and the average response during the first three years after the disaster amounts to a tiny -0.01% of pre-shock GDP.

Nevertheless, the "GDP-neutral" disaster has substantial effects on other economic aggregates and on welfare. Figure 6 shows that all three components of welfare are affected negatively. Households experience lower housing services (as a direct result of the disaster) as well as lower consumption of nondurable goods and lower leisure (as a result of the intertemporal substitution effect and the wealth effect). As a result, the disaster causes aggregate welfare to decline by 5.3%.

5.3. **Robustness Checks.** We conduct a sensitivity analysis with respect to the most decisive parameters of the model. We start with analysing sensitivity of results with respect to the intertemporal elasticity of substitution of nondurables, durables, and the Frisch elasticity of labor supply. We show how a disaster destroying residential housing and other durables (i.e. a d-disaster), a disaster destroying productive capital (k-disaster) and a mixed disaster affect output and welfare. Table 2 reports the effect on average output during the first three years and on welfare measured in consumption equivalents, both compared to pre-shock steady-state level.

We first consider a d-disaster. As a rule, a d-disaster increases GDP and entails large negative effects on aggregate welfare. A low intertemporal elasticity of substitution for nondurables or durables (high σ_c or σ_d) implies are large after-shock increase of GDP because households strongly prefer to smooth consumption and therefore respond strongly with increasing labor

TABLE 2. Sensitivity Analysis: preference parameters

	d-disaster	k-disaster	mixed-disaster
benchmark	$\Delta y = +2.3\%$ $\Delta W = -4.8\%$	$\Delta y = -4.1\%$ $\Delta W = -4.3\%$	$\Delta y = -0.01\%$ $\Delta W = -4.5\%$
$\sigma_c = 4$	$\Delta y = +2.9\%$ $\Delta W = -4.6\%$	$\Delta y = -3.1\%$ $\Delta W = -4.2\%$	$\Delta y = +0.7\%$ $\Delta W = -4.3\%$
$\sigma_c = 1$	$\Delta y = +1.7\%$ $\Delta W = -5.0\%$	$\Delta y = -5.2\%$ $\Delta W = -4.3\%$	$\Delta y = -0.8\%$ $\Delta W = -4.6\%$
$\sigma_d = 4$	$\Delta y = +3.0\%$ $\Delta W = -5.3\%$	$\Delta y = -3.8\%$ $\Delta W = -4.3\%$	$\Delta y = +0.5\%$ $\Delta W = -4.7\%$
$\sigma_d = 1$	$\Delta y = +1.6\%$ $\Delta W = -4.6\%$	$\Delta y = -4.4\%$ $\Delta W = -4.3\%$	$\Delta y = -0.5\%$ $\Delta W = -4.3\%$
Frisch = 2	$\Delta y = +3.4\%$ $\Delta W = -4.8\%$	$\Delta y = -2.9\%$ $\Delta W = -4.3\%$	$\Delta y = +1.1\%$ $\Delta W = -4.5\%$
Frisch = 0.5	$\Delta y = +1.4\%$ $\Delta W = -4.8\%$	$\Delta y = -5.2\%$ $\Delta W = -4.3\%$	$\Delta y = -1.0\%$ $\Delta W = -4.5\%$

Δy denotes the average percentage deviation of GDP compared to pre-shock level during the first three years, ΔW denotes the percentage deviation of welfare compared to pre-shock steady state level, measured in non-durable consumption equivalents. A d-disaster is a 20% reduction of residential housing compared to steady-state level, a k-disaster is a 20% reduction of productive capital, and a mixed disaster is a 13% reduction of residential housing and a 7% reduction of productive capital.

supply. Likewise, a high Frisch elasticity implies a large increase of GDP because it diminishes the disutility from working such that households respond to a disaster with strongly increasing labor supply. Altogether, GDP rises between 1.4 and 3.4 percent for the considered range of elasticities. At the same time, variations of the intertemporal elasticity of substitution for non-durables or durables as well as variations of the Frisch elasticity have a relatively small impact on the estimated welfare loss, which is always around 5 percent.

A k-disaster (column two of Table 2) exerts always a negative effect on GDP during the first three years and a drastic negative effect on aggregate welfare. A lower intertemporal elasticity of substitution for nondurables or durables (higher σ_c or σ_d) reduces the initial response of GDP because households prefer to smooth consumption more strongly and therefore increase their labor supply more strongly. Likewise, households increase labor supply in the aftermath of a disaster particularly strongly when the Frisch elasticity is high. Again, the size of the preference parameters has a relatively small impact on the estimated welfare loss.

A mixed disaster (column three of Table 2) has a negligible impact on GDP but a significantly negative impact on welfare. The effect on welfare is comparable in magnitude to the one obtained for the d-disasters and k-disasters. The effect on GDP is mildly positive when preferences imply a high response of labor supply (i.e. for high σ_c, σ_c, or Frisch elasticity), and mildly negative otherwise Notice, however, that it is always possible to identify a "GDP-neutral" disaster for any choice of the preference parameters. In other words, there exists always a disaster for which the positive labor supply effect and the negative effect on productive capital balance each other.

Finally, Table 3 shows results with respect to a sensitivity analysis for the adjustment cost parameter γ. The first row reiterates the benchmark case, the second and third row show results when the of value of γ increases or declines by factor 2. The results demonstrate that the response of GDP is fairly robust against variations of γ. The reason is that higher adjustment costs of residential investment entail two opposing effects on GDP, which roughly balance each other. A higher value of γ raises reconstruction costs through higher house prices, i.e. $p = 1+\gamma x$. On the one hand these higher reconstruction costs amplify the negative wealth effect, leading to more labor supply in the aftermath of the disaster. On the other hand, households respond to a higher value of γ by raising residential investment by less during the reconstruction phase. As a consequence, adjustment dynamics after the shock are prolonged. The slower adjustment towards the steady state attenuates the intertemporal substitution effect and leads to a smaller response of labor supply on impact. In our numerical experiments it turns out that the expansive and contractive forces roughly balance each other such that the response of GDP is largely unaffected by the size of γ.

TABLE 3. Sensitivity Analysis: adjustment costs

		d-disaster	k-disaster	mixed-disaster
$\gamma = 6.5$	$\epsilon = 0.15$	$\Delta y = +2.3\%$ $\Delta W = -4.8\%$	$\Delta y = -4.1\%$ $\Delta W = -4.3\%$	$\Delta y = -0.01\%$ $\Delta W = -4.5\%$
$\gamma = 13$	$\epsilon = 0.26$	$\Delta y = +2.3\%$ $\Delta W = -5.3\%$	$\Delta y = -4.0\%$ $\Delta W = -4.3\%$	$\Delta y = +0.03\%$ $\Delta W = -4.8\%$
$\gamma = 3.2$	$\epsilon = 0.09$	$\Delta y = +2.4\%$ $\Delta W = -4.5\%$	$\Delta y = -4.1\%$ $\Delta W = -4.3\%$	$\Delta y = -0.02\%$ $\Delta W = -4.3\%$
$\gamma = 0.49$	$\epsilon = 0.015$	$\Delta y = +2.1\%$ $\Delta W = -4.1\%$	$\Delta y = -4.4\%$ $\Delta W = -4.3\%$	$\Delta y = -0.06\%$ $\Delta W = -4.1\%$
$\gamma = 0.05$	$\epsilon = 0.0015$	$\Delta y = +1.5\%$ $\Delta W = -3.9\%$	$\Delta y = -4.5\%$ $\Delta W = -4.3\%$	$\Delta y = -0.06\%$ $\Delta W = -4.0\%$

ϵ is the implied price elasticity of housing investment. See Table 2 for further explanatory notes.

Table 3 also demonstrates that variations in the size of γ only mildly affect the estimated welfare loss. The effect of k-disasters on welfare is insignificantly influenced by the choice of γ. For d-disasters and mixed disaster we obtain a somewhat larger welfare loss for high values of γ.

The reason is, again, that large adjustment costs prolong adjustment dynamics. A higher value of γ leads to a slower and more costly reconstruction of houses. This means that the stock of houses is farther below its long-run optimal value for a longer period of time, an outcome that causes the welfare loss to be larger.

Interestingly, these conclusions remain valid when we further reduce γ towards values close to zero, implying a price elasticity of residential investment equal to what have been suggested by Shapiro (1986) and Cooper and Haltiwanger (2006) (see discussion in Section 5.1). Results are documented in row 4 and 5 of Table 3. In particular our main result of substantial welfare losses from GDP-neutral disasters turns out to be also quantitatively robust against the size of adjustment costs.

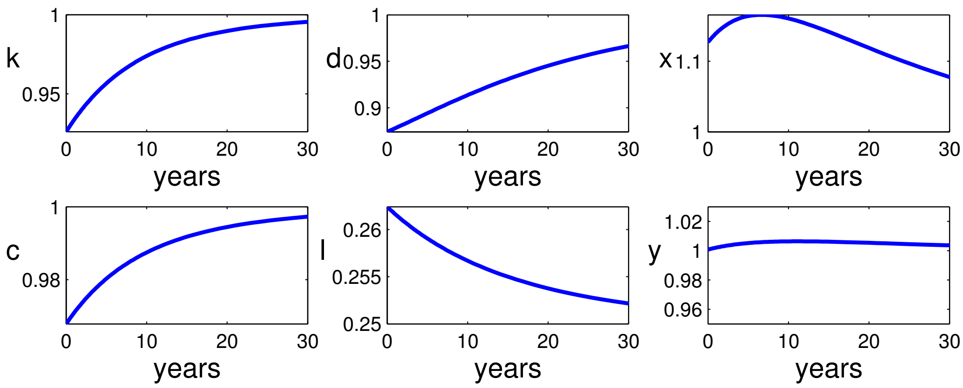
5.4. **Non-Separable Utility.** The assumption of a separable utility function tremendously simplifies the model analysis and, naturally, most of the related literature assumes like us that utility experienced from housing and non-durable goods consumption is separable. The study by Ogaki and Reinhart (1998), however, suggests that utility between nondurable and durable consumption is nonseparable. In order to demonstrate robustness of our main results with respect to non-separability we adopt the utility function suggested by Ogaki and Reinhart (1998) and extend it by utility experienced from leisure. This means that households maximize

$$\int_0^\infty \left(\frac{\left[\left(c^{1-\epsilon} + \beta d^{1-\epsilon}\right)^{\frac{1}{1-\epsilon}}\right]^{1-\sigma} - 1}{1-\sigma} + \eta \frac{(1-\ell)^{1-\sigma_\ell} - 1}{1-\sigma_\ell} \right) e^{-\rho t} \tag{29}$$

subject to the budget constraints (3) and (4). We adopt the parameter estimates from Ogaki and Reinhart for ϵ and σ, i.e., $\epsilon = 1.167$ and $\sigma = 2.2$, and take over all other parameter values from our benchmark calibration. As a result, we mildly deviate from our calibration targets for asset holdings and residential investment. The share of housing assets as part of total assets is now 0.49 instead of 0.5, and the average residential investment-GDP ratio is now 4.9% instead of 5%.

Figure 7 shows the impulse responses of economic aggregates for a shock destroying 13% of residential housing and 7% of productive capital. The quantitative results differ only mildly from those obtained for separable utility (cf. Figure 6). Over the first three years after the disaster GDP is +0.25% above steady-state level instead of -0.01% below steady-state level in case of

Figure 7: Non-Separable Utility: Destruction of Productive Capital and Residential Housing



Impulse responses to a simultaneous destruction of residential housing by 13% and productive capital by 7%.

separable utility. Considering the huge destruction of stocks, however, it seems appropriate to conclude that GDP remains almost unaffected in both cases. The welfare loss is computed as 4.3% in the non-separable case compared to 4.5% for separable case. Table 4 summarizes the results for the three different types of disaster. The first row reiterates results for separable utility and the second row shows results for non-separable utility. Apparently, the conclusions from the benchmark model are robust against the assumption of non-separable utility.

Table 4. Robustness: Separable vs. Non-Separable Utility

	d-disaster	k-disaster	mixed-disaster
separable utility	$\Delta y = +2.3\%$ $\Delta W = -4.8\%$	$\Delta y = -4.1\%$ $\Delta W = -4.3\%$	$\Delta y = -0.01\%$ $\Delta W = -4.5\%$
non-separable utility	$\Delta y = +2.7\%$ $\Delta W = -4.6\%$	$\Delta y = -4.0\%$ $\Delta W = -4.3\%$	$\Delta y = +0.25\%$ $\Delta W = -4.3\%$

6. Conclusion

In this paper we have developed a theory that offers an explanation for the puzzling empirical finding that GDP in the aftermath of natural disasters is not necessarily lower than before the event, and in some cases even higher than before. We have shown that disasters destroying predominantly residential housing (or other durable goods) drive GDP above pre-disaster steady-state level and that disaster destroying mainly productive capital are predicted to reduce GDP. Insignificant responses of GDP can be expected when disasters destroy about twice as much residential structures as productive capital. The theory explains why the welfare losses entailed by GDP-neutral disasters are substantial and of about the same order of magnitude as those entailed by one-shock-only disasters. As a rule of thumb we estimate that a disaster destroying 20 percent of total assets entails a welfare loss of about 4 to 5 percent irrespective of its highly variable and disaster-type specific impact on GDP. This result turned out to be very robust against the type of the disaster and the assumed preferences of citizens.

Our study suggests that GDP is an inferior and misleading indicator of the damage done by natural disasters. A better proxy would be the lost stock of housing and/or productive capital or the discounted aggregate investment expenditure needed to reconstruct the lost stocks.

Our results are insignificantly influenced by the assumed absolute size of the disaster. This fact allowed us to focus the quantitative analysis exemplarily on disasters leading to a loss of 20 percent of total assets. For larger or smaller disasters the estimated welfare loss and – in case of one shock disasters – the estimated GDP responses vary in proportion with the size of the disaster. Likewise, we can always find a shock composition implying zero disaster impact on GDP, irrespective of disaster size. This quantitative outcome is an artefact of iso-elastic utility and an iso-elastic, constant-returns-to-scale production function, the usual ingredients of quantitative macroeconomics.

For very large shocks, however, it seems reasonable to abandon the constant elasticity assumption. In particular, labor supply is likely to be bounded from above. The work day is limited by 24 hours and for most occupations physiological limits are reached by far earlier. Humans cannot sustain a physical activity level (PAL) of more than 2.4 of basal metabolism for an extended period of time (Westerterp, 2001). For example, activities like 'loading sacks on a truck' and 'carrying wood' are associated with PAL values of 6.6 (FAO, 2001) implying that a worker's energy needs would be 6.6 times his basal metabolic rate if he were occupied with these activities for 24 hours. Such a "heavy construction worker" could only manage to exert effort for $2.4 \cdot 24/6.6 = 8.7$ hours per day. Less energy consuming activities are, of course, sustainable for longer hours. In any case, upper limits to daily labor supply would help to explain why large disasters are more frequently found to exert a negative impact on GDP than small disasters (see Loayza et al., 2012). Extending our model by physiologically-constrained labor supply, for example based on Dalgaard and Strulik (2011), could be a promising task for future research on the macroeconomic implications of natural disasters.

Appendix A

We analyze the phase diagram for subsystem (20) and (21), and show that it has a unique and saddle-point stable steady state. To do this we show that the $\dot{x} = 0$ isocline and $\dot{d} = 0$ isocline intersect exactly once in the positive quadrant. Saddle-point dynamics can then be inferred from the phase diagram.

The $\dot{d} = 0$ isocline is given by $x = \delta_d d$. Hence, it is linear with positive slope $\delta_d > 0$. The $\dot{x} = 0$ isocline is given by

$$\left(1 + \frac{\psi(x)}{x}\right)(\bar{r} + \delta_d) = \frac{v'(d)}{u'(c)}\,. \tag{30}$$

Both isoclines intersect in the positive quadrant. To see this notice first that $\lim_{x\to 0}\psi(x)/x = 0$ and $\lim_{x\to\infty}\psi(x)/x = \infty$ because ψ is convex and $\psi(0) = 0$. Hence, for $d \to 0$ the right hand side of equation (30) converges towards infinity implying that $x \to \infty$, and for $d \to 0$ the right hand side of equation (30) converges to 0 implying that the $\dot{x} = 0$ isocline intersects the d axis at a finite point. An illustration of both isoclines is shown in Figure 1.

In order to prove that the intersection point of the isoclines is unique we begin with showing that the slope of the $\dot{x} = 0$ isocline is always negative. By implicit differentiation of (30) we obtain

$$\frac{\mathrm{d}x}{\mathrm{d}d} = \frac{\frac{v''(d)}{u'(c)}}{\frac{1}{x}\left(\psi'(x) - \frac{\psi(x)}{x}\right)(r + \delta_d)} < 0. \tag{31}$$

The numerator is negative, because v is convex, and the denominator is positive, because the convexity of ψ together with $\psi(0) = 0$ implies that $\psi'(x) > \psi(x)/x$. Together this implies that the sign of the derivative is negative. Hence, the slopes of the isoclines have opposite signs and the intersection point is unique.

The isoclines divide the phase diagram into four areas. Saddle-point stability follows from the dynamics within these areas: Above the $\dot{d} = 0$ isocline $\dot{d}$ is positive and below $\dot{d}$ is negative; on the right hand side of the $\dot{x} = 0$ isocline $\dot{x}$ is positive and on the left hand side $\dot{x}$ is negative.

Appendix B

Here, we present an alternative setup in which households rent housing services from firms. We show that the results of Section 3 are robust against the alternative setup. Furthermore, we show that the alternative setup is equivalent to the social planner's solution. The only difference between the basic setup and the alternative setup is the law of motion for x (equation (21)).

Households solve

$$\max_{c,d,\ell} \int_0^\infty (u(c) + v(d) + q(1-\ell)) \cdot e^{-\rho t} dt, \tag{32}$$

subject to

$$\dot{a} = w\ell + ra - c - p_d d + \pi\,, \tag{33}$$

where p_d denotes the price for hiring one unit of durable consumption good (houses) d for one unit of time, and π denotes profits of firms offering housing services to consumers. The first order conditions are

$$u'(c) = \lambda \tag{34}$$

$$v'(d) = \lambda p_d \tag{35}$$

$$\lambda w = q'(1-\ell) \tag{36}$$

$$\lambda r = \lambda\rho - \dot{\lambda}\,. \tag{37}$$

We derive an equation for p_d:

$$p_d = \frac{v'(d)}{u'(c)}\,. \tag{38}$$

Firms construct houses d and rent them to households. Hence, firms maximize

$$\pi = \int_0^\infty (p_d d - x - \psi(x))\, e^{-rt} dt \tag{39}$$

$$\text{s.t.} \quad \dot{d} = x - \delta d \tag{40}$$

The first order conditions are

$$1 + \psi'(x) = \nu \tag{41}$$

$$p_d - \nu\delta = \nu r - \dot{\nu} \tag{42}$$

with ν denoting the shadow price of one installed unit of d in terms of marginal revenues. Differentiating equation (41) with respect to time, equating with (42) and substituting for p_d

yields

$$\dot{x} = \frac{1}{\psi''(x)} \left[\left(1 + \psi'(x)\right)(r + \delta_d) - \frac{v'(d)}{u'(c)} \right]. \tag{43}$$

We discuss the implications of equations (40) and (43) using phase diagram analysis. The phase diagram is similar to the one the main text. It only differs with respect to the slope of the $\dot{x} = 0$ isocline. The slope is given by

$$\frac{\mathrm{d}x}{\mathrm{d}d} = \frac{\frac{v''(d)}{u'(c)}}{\psi''(x)(r + \delta_d)} < 0. \tag{44}$$

The slope is negative, because v is concave and ψ is convex. Hence, the propositions of the main text hold true also for the alternative setup.

Finally, we show that the social planner's solution is equivalent to the solution for the alternative setup. We focus on the open economy case. The social planner solves

$$\max_{c,i,x,\ell} \int_0^\infty (u(c) + v(d) + q(1 - \ell)) \cdot e^{-\rho t} dt \tag{45}$$

subject to

$$\dot{b} = Af(k, \ell) + rb - c - i - x - \psi(x) \tag{46}$$

$$\dot{k} = i - \delta_k k \tag{47}$$

$$\dot{d} = x - \delta_d d \tag{48}$$

and $b(0) = b_0$, $k(0) = k_0$. b denotes international bond holdings such that the total assets a are equal to $a = k + b$. The Hamiltonian reads

$$H = (u(c) + v(d) + q(1 - \ell)) + \lambda(Af(k, \ell) + rb - c - i - x - \psi(x)) + \phi(i - \delta_k k) + \mu(x - \delta_d d)$$

and the first order conditions are

$$\frac{\partial H}{\partial c} = 0 \quad \Leftrightarrow \quad u'(c) = \lambda \tag{49}$$

$$\frac{\partial H}{\partial i} = 0 \quad \Leftrightarrow \quad -\lambda + \phi = 0 \tag{50}$$

$$\frac{\partial H}{\partial x} = 0 \quad \Leftrightarrow \quad -\lambda(1 + \psi'(x)) + \mu = 0 \tag{51}$$

$$\frac{\partial H}{\partial \ell} = 0 \quad \Leftrightarrow \quad -q'(1 - \ell) + \lambda \frac{\partial Af(k, \ell)}{\partial \ell} = 0 \tag{52}$$

$$\frac{\partial H}{\partial b} = \lambda\rho - \dot{\lambda} \qquad \Leftrightarrow \qquad \lambda r^* = \lambda\rho - \dot{\lambda} \tag{53}$$

$$\frac{\partial H}{\partial k} = \phi\rho - \dot{\phi} \qquad \Leftrightarrow \qquad \lambda\frac{\partial Af(k,\ell)}{\partial k} - \phi\delta_k = \phi\rho - \dot{\phi} \tag{54}$$

$$\frac{\partial H}{\partial d} = \mu\rho - \dot{\mu} \qquad \Leftrightarrow \qquad v'(d) - \mu\delta = \mu\rho - \dot{\mu} \tag{55}$$

We assume that $\bar{r}$ is given on international capital markets and $\bar{r} = \rho$ holds. Therefore from equations (53), (49), and (50) it follows that $\frac{\dot{\lambda}}{\lambda} = \frac{\dot{\phi}}{\phi} = \frac{\dot{c}}{c} = 0$. From equation (54) we can derive that $\partial Af(k,\ell)/\partial k - \delta_k = \bar{r}$. The capital-labor ratio is pinned down by the international interest rate. Equation (52) shows that $\dot{\ell} = 0$ and that ℓ depends on the level of c. We obtain the intertemporal budget constraint of the economy by noting that $i = \delta_k k$ and integrating equation (46):

$$\int_0^\infty ce^{-\bar{r}t}dt = \int_0^\infty Af(k,\ell) - \delta_k ke^{-\bar{r}t}dt - \int_0^\infty x\left(1 + \frac{\psi(x)}{x}\right)e^{-\bar{r}t}dt + b_0\,. \tag{56}$$

Note further that $k_0 = \int_0^\infty \left(\frac{\partial Af(k,\ell)}{\partial k} - \delta_k k\right)e^{-\bar{r}t}dt$ holds and thus the equation can be modified to

$$\int_0^\infty ce^{-\bar{r}t}dt = \int_0^\infty \ell\frac{\partial Af(k,\ell)}{\partial \ell}e^{-\bar{r}t}dt - \int_0^\infty x\left(1 + \frac{\psi(x)}{x}\right)e^{-\bar{r}t}dt + a_0\,, \tag{57}$$

which is equivalent to equation (18). Finally we obtain equation (43) by differentiating equation (51) with respect to time and substituting equations (49), (53), and (55).

Appendix C

We show that the steady state of the large economy described by system (22) - (26) is unique. We begin with noticing that the capital-labor ratio is pinned down by equation (24). Second, we exploit the analysis of subsystem (23) and (25) from Section 3. From the analysis above we know that a higher steady state value of c leads to a higher steady state of x and d. We can express this insight as a steady-state relationship $x = s(c)$ with $s'(\cdot) > 0$. This means that by substituting for x and rearranging equation (22) we obtain

$$k\left(\frac{Af(k,\ell)}{k} - \delta_k\right) = c + s(c) + \psi(s(c))\,. \tag{58}$$

The equation states a positive relationship between k and c at the steady state.

Next we show that equation (26) constitutes a negative steady state relation between k and c, taking the capital-labor ratio as given. We do this by evaluating the derivative at the steady state for a constant capital-labor ratio:

$$\left.\frac{\mathrm{d}k}{\mathrm{d}c}\right|_{KRR} = \left.\frac{\mathrm{d}k}{\mathrm{d}l}\right|_{KRR} \cdot \frac{\mathrm{d}l}{\mathrm{d}c} = 1 \cdot \frac{-\frac{u''(c)}{u'(c)}}{q''(1-\ell)} < 0\,. \tag{59}$$

The overall derivative is negative, because $u''(\cdot) < 0$, $q''(\cdot) < 0$, and $u'(\cdot) > 0$. Equations (58) and (26) both imply a steady-state relationship between k and c. Finally, noticing that the slopes of the steady-state equations (26) and (58) are of opposite sign, we conclude uniqueness of the steady state.

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