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. In many cases, income is not significantly affected and surprisingly, can even respond 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 equally residential structures and productive capital. We also 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 to analyze the macroeconomic effects 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 caused by these disasters. As documented by Cavallo and Noy (2011), these types of disasters are fairly common events across the globe, and occur with increasing frequency. For example, in the Asia-Pacific region, 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.

To date, 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 decrease GDP per capita in the aftermath of the event. Loayza et al. (2012), for example, find no significant impact on a country's GDP and industrial output across all disasters. In contrast, when floods are investigated separately, 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 positive effect of floods and a negative effect of droughts 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 seem puzzling when analyzed within the context of conventional neoclassical growth theory. Once we acknowledge that disasters destroy (potentially severely) the productive potential of an economy, we would expect that they then harm the 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]

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[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 investigating

In this paper, we show how a simple extension of the neoclassical growth model can be used to reconcile theory with 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 other damaged durable goods such as cars). Since firm capital remained undestroyed, the increased labor supply implies higher GDP per capita during the reconstruction phase.

Considering simultaneous shocks on both state variables, the model predicts a negative impact on GDP 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 slightly smaller compared to that on residential housing. The theory is not only helpful to explain the frequently insignificant impact of disasters on GDP, it can also rationalize those 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. This is in particularly the case 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). Furthermore, some authors find positive employment effects of disasters supporting our proposed mechanism through which output might increase in the aftermath of a disaster (see Leiter et al., 2009, Ewing et al., 2009).

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 with 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 disasters damaging residential housing lead to higher output in the short and long-run and we state conditions under which the response of GDP is also positive. The reason for the positive effect on GDP is that disasters reduce the wealth

the association between disaster risk and long-run growth (e.g. Skidmore and Toya, 2002; and Crespo Cuaresma et al., 2008). Here, we focus on the short- to medium-run impact of disasters.

of households, which motivates them to supply more labor in order to quickly reconstruct the damaged houses and durable goods.

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 nondurable goods. In order to mitigate the drop in consumption, households are motivated to raise their labor supply even further, beyond what has already been triggered by the wealth effect.

Our analysis of the individual effects of disasters on firm capital and on residential housing shows that GDP can be a very misleading indicator of the economic damage caused 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 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 the fact that natural disasters kill people. The welfare estimates should thus be understood as lower bounds of the actual damage caused 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.[3]

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 the 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 nondurable consumption goods c and on residential investment x (including potential 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; hence, the stock of durables evolves according to

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

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

[3]In this paper, we also neglect the influence of population growth and transportation costs on the economy and in particular, on housing prices (see Knoll et al., 2014).

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

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

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

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

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

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

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 with 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 (firms producing durable goods). These firms convert units of final goods into units of housing (durable goods). 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 performed in a tight time frame, or when there is inefficient labor input due to fatigue during overtime hours. Since such 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 only on investment. 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 firms producing final goods. Final goods are used as nondurable 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:

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

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

2.4. **Output and GDP.** In most macroeconomic models, aggregate output equals GDP. Here, in a model with durable consumption goods, we have to distinguish between these aggregates. The reason is that the System of National Accounts (SNA) requires counting the service flow from already installed residential houses as part of consumption, and thus, it is part of GDP (see EC, IMF, OECD, UN & World Bank, 2009, pp. 466-467). In particular, SNA states that houses leased to other households are supposed to be treated equivalently to owner-occupied houses. A newly

constructed house raises output and GDP according to its construction costs. In the following years, the house contributes to GDP – but not to output – according to the rent paid by its tenant (if it is leased) or according to an imputed rent (if it is owner occupied). Houses are the only durable goods from which a service flow enters GDP calculations. For example, service flows from cars used for consumption purposes are not included as part of GDP.

In terms of our model, newly constructed houses are immediately part of output and GDP since construction costs are paid from final output. Because houses are owner-occupied in our benchmark model, we introduce an imputed rent in order to account for the contribution of housing services to GDP. In Appendix B, we set up an alternative model in which houses are leased to households by real estate firms. We show that the alternative setup is equivalent to the benchmark model, and that the equilibrium rental price p_d for renting one unit of d for one unit of time is equal to

$$p_d = \frac{v'(d)}{u'(c)}. \tag{16}$$

Intuitively, the price ratio between durable consumption goods and nondurable consumption goods, $p_d/1$, is equal to the marginal rate of substitution between durable consumption goods and nondurable consumption goods, $v'(d)/u'(c)$. In the following, we use (16) as the imputed price for GDP accounting.

If durable goods d referred only to residential housing, GDP would be equal to output plus the service flow from houses, $GDP = y + p_d \cdot d$. Here, we keep the analysis more general and leave it open as to whether d refers only to housing or whether other durables such as cars, furniture, and household appliances are included as well. We denote the share of housing in durable goods by μ, $0 \leq \mu \leq 1$. This means that GDP is defined as

$$GDP = y + \mu \cdot p_d d. \tag{17}$$

The notation comprises two limiting cases: For $\mu = 1$, durable goods consumption consists of only housing and for $\mu = 0$, durable goods consumption does not include any housing. Notice that the latter case would capture as well countries deviating from the SNA rules by not including the service flow of housing in their GDP accounts. We allow μ to take any number between zero and one but mainly report results for the limiting cases $\mu = 0$ and $\mu = 1$. In other words, we provide the upper and lower bounds for our GDP estimates.

3. The Small Open Economy

In a small open economy (and given perfect capital mobility) firms can borrow at the world interest rate $\bar{r}$, $r = \bar{r}$. This means that equation (14) pins down the domestic capital labor ratio and that the international wage rate, $w = \bar{w}$, pins down the domestic wage in equation (15). 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 nondurable consumption goods and residential investment, as well as household labor supply is determined by the 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).

In a 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 (and other durable goods). For this 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 by showing that the destruction of residential housing entails a negative wealth effect. Households respond to the wealth shock by consuming fewer nondurables and housing (and other durables) and by supplying more labor. Higher labor supply then lifts GDP above the pre-shock level.

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

$$\int_0^\infty c e^{-\bar{r}t} dt = \ell \int_0^\infty \bar{w} e^{-\bar{r}t} dt - \int_0^\infty p(x) x e^{-\bar{r}t} dt + a_0 \,. \tag{18}$$

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

$$\frac{c}{\bar{r}} = \frac{\ell \bar{w}}{\bar{r}} - \int_0^\infty p(x) x e^{-\bar{r}t} dt + a_0 \,. \tag{19}$$

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

$$\frac{(u')^{-1}\left(\frac{q'(1-\ell)}{\bar{w}}\right)}{\bar{r}} - \frac{\ell \bar{w}}{\bar{r}} = a_0 - \int_0^\infty p(x) x e^{-\bar{r}t} dt \,. \tag{20}$$

Notice that the left-hand side of (20) depends negatively on ℓ since $d\left(u'(\cdot)\right)^{-1}/d(\cdot) < 0$. This means that if households experience a negative wealth effect such that the right-hand side of (20) decreases, the household will respond by supplying more labor.

We next show that an economy initially situated at a steady-state experiences indeed a negative wealth effect when it is exposed to a disaster that destroys part of d. For that purpose we define the net present value of residential investments as

$$X := \int_0^\infty p(x) x e^{-\bar{r}t} dt = \int_0^\infty x \left(1 + \frac{\psi(x)}{x}\right) e^{-\bar{r}t} dt\,. \tag{21}$$

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. In order to verify this claim we focus on the dynamics of d and x summarized by

$$\dot{d} = x - \delta_d d \tag{22}$$

$$\frac{\dot{x}}{x} = \left(\psi'(x) - \frac{\psi(x)}{x}\right)^{-1} \left[\left(1 + \frac{\psi(x)}{x}\right)(r + \delta_d) - \frac{v'(d)}{u'(c)}\right] \tag{23}$$

and $d(0) = d_0$. The steady-state of the subsystem (22) and (23) 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 (20) 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 (22) and (23) depends on the initial situation (c_0, x_0).[4]

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; and below the line, $\dot{d}$ is negative. The $\dot{x} = 0$ isocline is downward sloping and intersects the d axis at $d = (v')^{-1}(u'(c)(\bar{r} + \delta))$. On the right-hand side of the line, $\dot{x}$ is positive; and 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; hence, the steady-state value of d increases. The stable saddlepath towards the steady-state is downward

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

sloping. In Appendix A we formally derive, that the subsystems (22) and (23) have a unique and saddle-point stable steady-state.

FIGURE 1: PHASE DIAGRAM

Left panel: Phase diagram with stable saddlepath. Right panel: Phase diagram used for proof of Lemma 1.
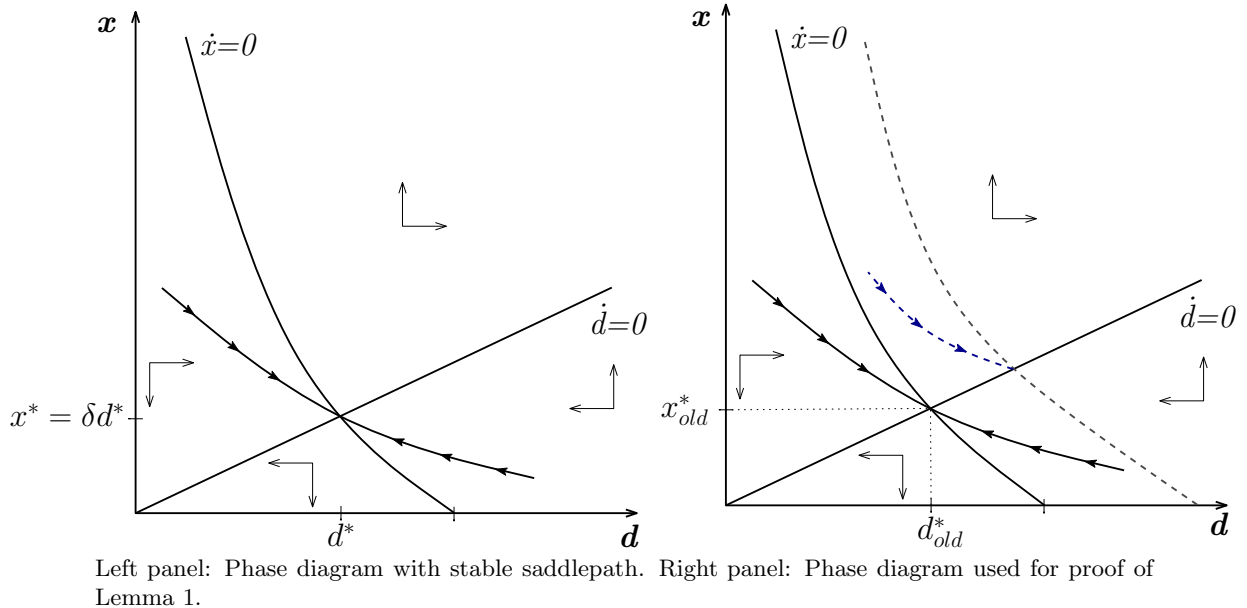
In comparison with conventional growth theory, the usual argument for uniqueness of adjustment dynamics is slightly modified. To see this, consider an economy starting somewhere below the stable saddlepath. Following the arrows of motion, the economy would always remain below the saddlepath such that aggregate X would also be lower. Then, from the intertemporal budget constraint (20), 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 saddlepath would thus never arrive at the steady-state because x is below the stable saddlepath 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.[5] This reasoning can be exploited to arrive at the following conclusion.

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

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[5]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 $d(0) = d_0$).

aggregate housing expenditure X. In this case, equations (20) and (11) show that c would increase; thus 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 its former 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 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. $\square$

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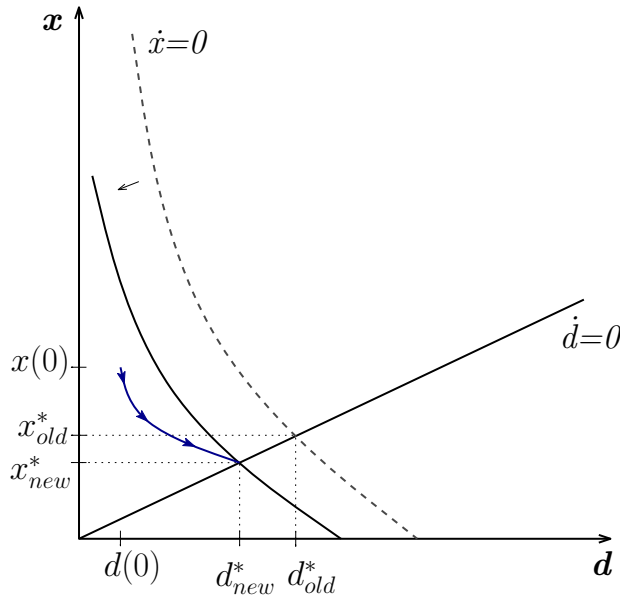
PROPOSITION 1. *If an economy rests at a steady-state and residential housing (d) gets destroyed, only parts of the stock of d are rebuilt. The resulting new steady-state level of d is lower compared to the pre-shock level.*

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. $\square$

The result implies that without trend growth, an economy never completely rebuilds the housing stock (stock of durables) destroyed by a 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 nondurable 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 nondurable goods is also permanently lower. Finally, we conclude from equation (20) that labor supply increases. Since instantaneous utility from all three components is strictly below pre-shock level, the lifetime utility of households, i.e. aggregate welfare, is below the pre-shock level as well. □

Finally, we show that, although aggregate welfare is affected negatively, output and output growth increase in response to the disaster, and we derive conditions under which GDP also responds positively.

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

Proof. If d gets destroyed, consumption of nondurable goods decreases (see equation (11)) and labor supply increases (see equation (20)). 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 per capita. □

The response of GDP in the aftermath of a disaster is equivalent to the response of output only if $\mu = 0$, i.e. if durable goods do not include residential housing. For $\mu > 0$, GDP is also affected by the service flow from residential housing, $p_d d$, since $GDP = y + \mu \cdot p_d d$. To evaluate

the full impact of disasters on GDP we need to show how the price of housing services p_d responds in relation to the destruction of residential houses d. Intuitively, the price of nondurable goods relative to durable goods (and thus p_d) increases when a disaster destroys the stock of durables. Formally, the price is pinned down by (16). As long as we keep the utility function general, the combined effect of disasters on $p_d d$ remains indeterminate. However, if the share of residential housing in durables, μ, is sufficiently small, the effect of the disaster on output dominates the service flows of housing. This leads to our final result.

PROPOSITION 4. *If residential housing gets destroyed in an economy resting at a steady-state, then aggregate GDP per capita increases permanently above the pre-shock level if the share of residential housing on durables, μ, is sufficiently small. In this case, GDP growth in the aftermath of the disaster is positive.*

Proof. We already verified that output responds positively in the aftermath of a disaster. If the service flow of housing, $p_d \cdot d$, also responds positively, the result holds for any μ, $0 \leq \mu \leq 1$. If $p_d \cdot d$ responds negatively it is always possible to find a μ^* such that the response of output is equal to the response of $\mu \cdot p_d d$ in absolute terms, i.e. $|\Delta y| = \mu^* \cdot |\Delta p_d \cdot \Delta d|$. Then, for any $\mu < \mu^*$, GDP responds positively in the aftermath of a disaster. $\qquad\square$

4. THE CLOSED ECONOMY CASE

4.1. **Setup of the Model.** The closed economy model can be best understood as the standard neoclassical growth model augmented by a housing sector and variable labor supply. In a closed economy, households save only in terms of domestic capital such that $a = k$. The feature of diminishing marginal returns to capital provides a unique steady-state.[6]

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 (24). The remaining equations are shared with the small open economy case. For convenience we again collect the decisive equations and obtain the large economy as described by the following dynamic system

$$\dot{k} = Af(k, \ell) - \delta_k k - x - \psi(x) - c \tag{24}$$

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[6]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.

$$\dot{d} = x - \delta d \tag{25}$$

$$\frac{\dot{c}}{c} = \frac{r - \rho}{\sigma_c} \tag{26}$$

$$\frac{\dot{x}}{x} = \left(\psi'(x) - \frac{\psi(x)}{x} \right)^{-1} \left[p(r + \delta) - \frac{v'(d)}{u'(c)} \right] \tag{27}$$

$$w = \frac{q'(1 - \ell)}{u'(c)}, \tag{28}$$

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

4.2. **Effect of Disasters on GDP: Intuition.** To illustrate out argument, we distinguish between two polar types of disasters. The first type destroys only residential housing (durable consumption) while 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

$$\int_0^\infty c\, e^{-\int_0^s r(u)du} ds = k_0 + \int_0^\infty w\ell\, e^{-\int_0^s r(u)du} ds - \int_0^\infty p(x)x e^{-\int_0^s r(u)du} ds. \tag{29}$$

The intertemporal budget constraint differs from the open economy case (equation 20) 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 $\int_0^\infty p(x)x e^{-\int_0^s r(u)du} ds$ 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 output above its pre-shock level. This also lifts GDP above its pre-shock level, because the service flow from housing responds either positively or only slightly negatively as we show below.

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 (29) 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 the demand for 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 the 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.

The effect of a k-shock on the service flow of housing is also negative, amplifying the negative response of output. Intuitively, lower output forces households to reduce consumption of nondurables in the aftermath of a k-disaster, which raises the marginal utility from nondurable consumption. Since marginal utility from durable goods is not affected immediately after the disaster, the rental price of durables p_d declines. GDP responds negatively to the disaster because output as well as service flows from housing decline. 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 form of the utility function and the production technology. We assume that households face an isoelastic utility function

$$\int_0^\infty \left[\frac{c^{1-\sigma_c} - 1}{1 - \sigma_c} + \beta \frac{d^{1-\sigma_d} - 1}{1 - \sigma_d} + \eta \frac{(1-\ell)^{1-\sigma_\ell} - 1}{1 - \sigma_\ell} \right] \cdot e^{-\rho t} dt \tag{30}$$

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 production 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. $\psi(x) = \gamma x^2$.

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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 4.5%, observed between 1952-2008 (both values according to Iacoviello, 2010 and 2011). The resulting value of γ is 2.9 and implies an elasticity of housing prices with respect to residential investment of 0.09. 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 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, whereas 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 slightly. Our value for the elasticity of housing 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). We set the share of houses in total durables μ to one and report results for output y and GDP separately. For any other real-world value of μ, GDP can be directly inferred from the reported results because it would be a linear combination of the reported values of output and GDP. 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.

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

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	μ
1	0.38	0.058	0.015	0.038	0.038	2.9	0.25	3.56	1	3	2	2	1.51	1

Notation in parenthesis indicates implied values.

non-linear model and provides the exact solution, up to a user-specified error, and 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).

Because we already showed analytically that disasters destroying residential houses exert an unambiguously positive effect on output in the small open economy case, we focus on the closed economy case and 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 that the value of assets destroyed is equal in all three cases. Recall that our calibration assumed that the values of productive capital and housing are 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 3 shows the impulse responses following a reduction of d by 20% of the steady-state level. As a reaction to the disaster, households increase residential investment above the steady-state level in order to rebuild the damaged stock of houses. The resulting negative wealth effect causes households to reduce nondurable consumption and to increase labor supply on impact. Higher labor supply in the aftermath of the disaster then lifts output above steady-state level. Later, when the economy recovers and the damaged stock of durables is rebuilt, economic aggregates return to their pre-shock steady-state levels.

There exists, on top of the wealth effect, an intertemporal substitution effect, which amplifies the positive response of labor supply and output. Due to their damaged houses, households 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

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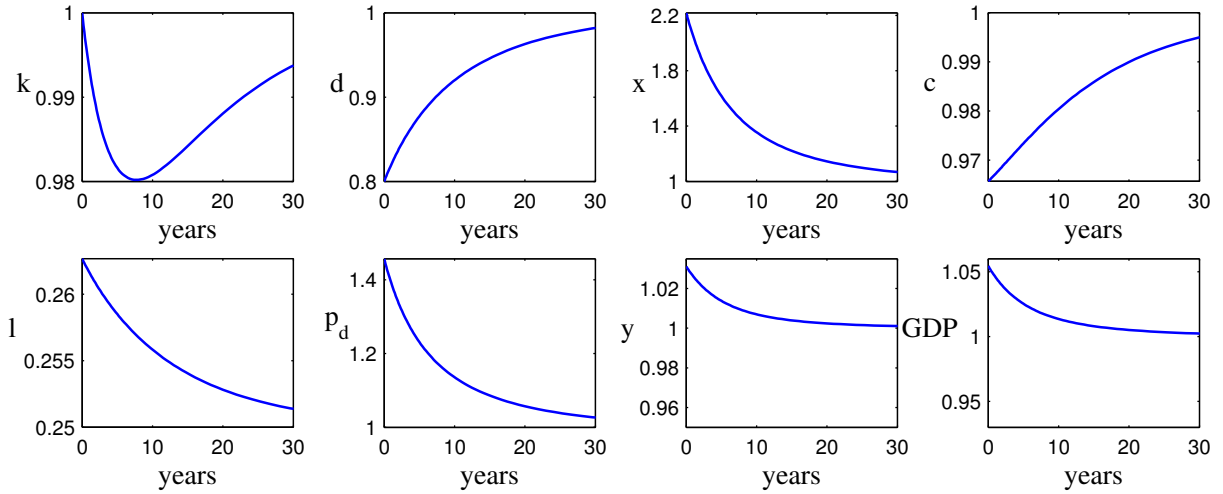
Impulse responses to the destruction of residential housing by 20%. The panel shows the response of capital (k), residential housing (d), residential investment (x), nondurable consumption (c), labor supply (ℓ), rental price of durables (p_d), output (y), and GDP (for $\mu = 1$).

reduce capital investment and consumption. Then, in order to mitigate the drop in consumption, households further increase their labor supply in the aftermath of the disaster. As a consequence, output in the initial periods after the disaster rises even further, beyond the increase triggered by the wealth effect.

To assess the impact on GDP, recall that GDP equals output plus the service flow from housing, $p_d \cdot d$. A smaller stock of housing in the aftermath of the disaster has a negative impact on GDP, whereas a higher price of housing services, p_d, has a positive impact. For our numerical specification of the model it turns out that the price effect dominates the quantity effect such that GDP reacts even more strongly than output (see panel for p_d, y, and GDP in Figure 3).

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 output and GDP is positive. The sensitivity analysis conducted in Section 5.3 shows that even for small Frisch elasticities, GDP responds 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. As a rule, the positive response of output is stronger when the intertemporal elasticity of substitution for nondurable consumption and durable consumption is low (high σ_c and σ_d), respectively. We explain the mechanism behind this finding in more detail in the next section.

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 4.6% 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 permanently losing 4.6% of nondurable consumption.

We next turn to a shock that destroys physical capital k. In Figure 4, 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 the pre-shock level in the initial periods, output 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 holds for reasonable parameterizations of the neoclassical growth model. Only when the Frisch elasticity of labor supply is infinite and the share of capital in production is implausibly low, output would response positively to a k-shock (see Strulik and Trimborn, 2014).
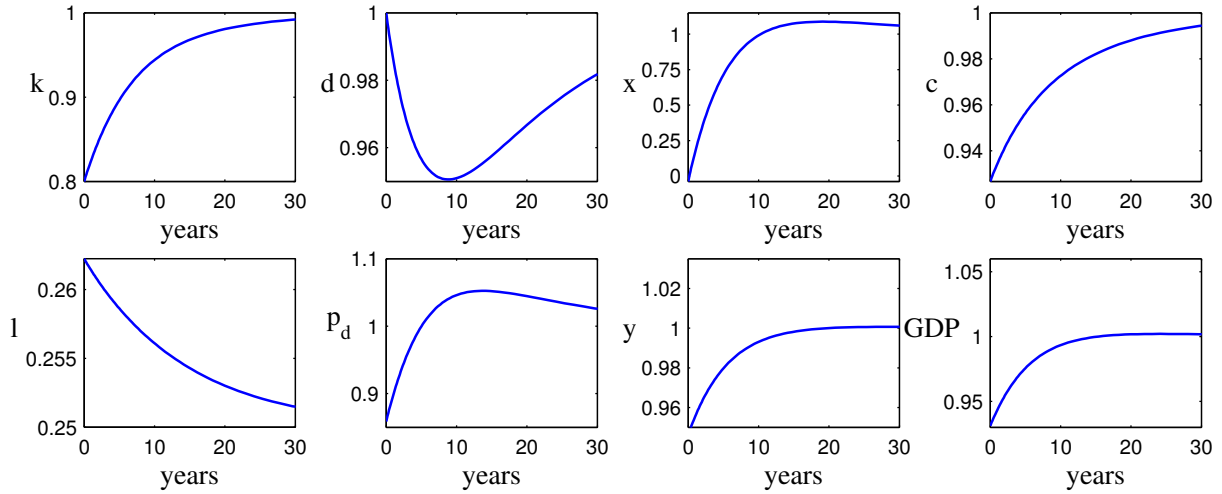
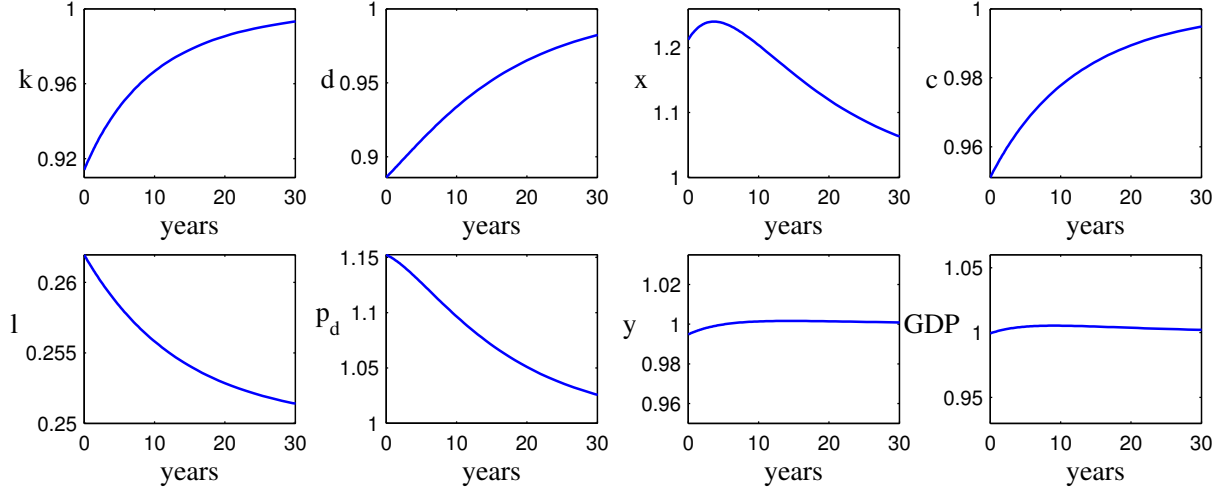Impulse responses to the destruction of productive capital by 20%.

The effect of the shock on GDP is again amplified by the response of service flows from housing. A negative price effect diminishes the service flow from housing such that GDP responds more strongly and negatively to the shock than aggregate output.

For welfare, the intuition developed in conjunction with the standard neoclassical growth model holds for the k-disaster as well. A lower capital stock unambiguously causes 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 both capital and housing simultaneously. In order to show that disasters destroying productive capital as well as residential housing can have a negligible effect on GDP per capita, we focus on a disaster destroying 11% of residential houses and 9% of productive capital. The impulse responses to this "mixed" disaster are shown in Figure 5. 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; hence, resources are scarce. Households react by consuming less and raising their 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.

FIGURE 5: NATURAL DISASTERS: DESTRUCTION OF PRODUCTIVE CAPITAL AND RESIDENTIAL HOUSING

Impulse responses to a simultaneous destruction of residential housing by 11% and productive capital by 9%.

In our example, the effects of destruction of productive capital and residential housing roughly balance each other out. Output per capita and GDP per capita remain largely unaffected. Output drops by 0.5% as the initial response to this severe disaster and the average response during the first three years after the disaster amounts to -0.3% of pre-shock output. GDP drops by 0.06% on impact and the average response during the first three years amounts to a tiny +0.15% of pre-shock GDP. Thus, for this type of "mixed" disaster the effect on GDP would be virtually zero for any value of μ, i.e. for any share of residential housing on total durable goods.

Nevertheless, the "GDP-neutral" disaster has substantial effects on other economic aggregates and on welfare. Figure 5 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 4.4%.

5.3. **Robustness Checks.** We conduct a sensitivity analysis with respect to the most decisive parameters of the model. We start with analyzing the sensitivity of results with respect to the intertemporal elasticity of substitution for durables and nondurables and for 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, GDP, and welfare. Table 2 reports the effect on average output during the first three years, average GDP during the first three years (with $\mu = 1$), and on welfare measured in consumption equivalents, all compared to the pre-shock steady-state level.

TABLE 2. Sensitivity Analysis: Preference Parameters

	d-disaster	k-disaster	mixed-disaster
benchmark	$\Delta y = +2.5\%$ $\Delta GDP = +4.3\%$ $\Delta W = -4.6\%$	$\Delta y = -4.1\%$ $\Delta GDP = -5.3\%$ $\Delta W = -4.3\%$	$\Delta y = -0.3\%$ $\Delta GDP = +0.2\%$ $\Delta W = -4.4\%$
$\sigma_c = 4$	$\Delta y = +3.0\%$ $\Delta GDP = +4.6\%$ $\Delta W = -4.4\%$	$\Delta y = -3.3\%$ $\Delta GDP = -4.9\%$ $\Delta W = -4.2\%$	$\Delta y = +0.4\%$ $\Delta GDP = +0.5\%$ $\Delta W = -4.2\%$
$\sigma_c = 1$	$\Delta y = +1.7\%$ $\Delta GDP = +4.0\%$ $\Delta W = -4.7\%$	$\Delta y = -5.2\%$ $\Delta GDP = -5.7\%$ $\Delta W = -4.4\%$	$\Delta y = -1.2\%$ $\Delta GDP = -0.2\%$ $\Delta W = -4.4\%$
$\sigma_d = 4$	$\Delta y = +2.9\%$ $\Delta GDP = +11.7\%$ $\Delta W = -5.0\%$	$\Delta y = -3.8\%$ $\Delta GDP = -4.7\%$ $\Delta W = -4.4\%$	$\Delta y = +0.09\%$ $\Delta GDP = +4.0\%$ $\Delta W = -4.5\%$
$\sigma_d = 1$	$\Delta y = +1.8\%$ $\Delta GDP = +0.8\%$ $\Delta W = -4.4\%$	$\Delta y = -4.6\%$ $\Delta GDP = -5.7\%$ $\Delta W = -4.3\%$	$\Delta y = -0.8\%$ $\Delta GDP = -1.9\%$ $\Delta W = -4.3\%$
Frisch $= 2$	$\Delta y = +3.7\%$ $\Delta GDP = +5.5\%$ $\Delta W = -4.6\%$	$\Delta y = -3.0\%$ $\Delta GDP = -4.2\%$ $\Delta W = -4.3\%$	$\Delta y = +0.8\%$ $\Delta GDP = +1.2\%$ $\Delta W = -4.4\%$
Frisch $= 0.5$	$\Delta y = +1.4\%$ $\Delta GDP = +3.3\%$ $\Delta W = -4.6\%$	$\Delta y = -5.1\%$ $\Delta GDP = -6.2\%$ $\Delta W = -4.3\%$	$\Delta y = -1.3\%$ $\Delta GDP = -0.8\%$ $\Delta W = -4.4\%$

Δy denotes the average percentage deviation of output compared to the pre-shock level during the first three years, ΔGDP denotes the percentage deviation of GDP compared to the pre-shock level during the first three years for the case of $\mu = 1$, ΔW denotes the percentage deviation of welfare compared to the pre-shock steady-state level, measured in nondurable consumption equivalents. A d-disaster is a 20% reduction of residential housing compared to the steady-state level, a k-disaster is a 20% reduction of productive capital, and a mixed disaster is a 11% reduction of residential housing and a 9% reduction of productive capital.

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 a large after-shock increase of GDP because households strongly prefer to smooth consumption and therefore respond strongly to increasing labor supply. Likewise, a high Frisch elasticity implies a large increase in GDP because it diminishes the disutility from working such that households respond to a disaster with strongly increasing labor supply.

Altogether, output rises between 1.4 and 3.7 percent and GDP rises between 0.8 percent and 11.7 percent for the considered range of elasticities. At the same time, variations of the intertemporal elasticity of substitution for nondurables and 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) always exerts 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, thereby increasing 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 an insignificant impact on output and 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 output 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 an "output-neutral" and a "GDP-neutral" disaster for any choice of the preference parameters. In other words, there is always a disaster for which the positive labor supply effect and the negative effect on productive capital balance each other out.

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 a factor of 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, which roughly balance each other in their impact on GDP. A higher value of γ increases reconstruction costs through higher housing prices, i.e. $p = 1 + \gamma x$. On the one hand, these higher reconstruction costs amplify the negative wealth effect, leading to greater labor supply in the aftermath of the disaster. On the other hand, households respond to a higher value of γ by increasing residential investment by smaller amounts 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 out such that the response of GDP is largely unaffected by the size of γ. Only for very small values of γ does the average response of GDP during the first three years become less pronounced, while at the same time, the response on impact becomes very large (not shown in Table 3).

TABLE 3. Sensitivity Analysis: Adjustment Costs

		d-disaster	k-disaster	mixed-disaster
$\gamma = 2.9$	$\epsilon = 0.09$	$\Delta y = +2.5\%$ $\Delta GDP = +4.3\%$ $\Delta W = -4.6\%$	$\Delta y = -4.1\%$ $\Delta GDP = -5.3\%$ $\Delta W = -4.3\%$	$\Delta y = -0.3\%$ $\Delta GDP = +0.2\%$ $\Delta W = -4.4\%$
$\gamma = 5.7$	$\epsilon = 0.17$	$\Delta y = +2.4\%$ $\Delta GDP = +5.2\%$ $\Delta W = -5.0\%$	$\Delta y = -4.1\%$ $\Delta GDP = -4.9\%$ $\Delta W = -4.3\%$	$\Delta y = -0.04\%$ $\Delta GDP = +0.8\%$ $\Delta W = -4.5\%$
$\gamma = 1.5$	$\epsilon = 0.05$	$\Delta y = +2.4\%$ $\Delta GDP = +3.7\%$ $\Delta W = -4.4\%$	$\Delta y = -4.1\%$ $\Delta GDP = -5.3\%$ $\Delta W = -4.3\%$	$\Delta y = +0.1\%$ $\Delta GDP = +0.4\%$ $\Delta W = -4.3\%$
$\gamma = 0.45$	$\epsilon = 0.015$	$\Delta y = +2.2\%$ $\Delta GDP = +2.7\%$ $\Delta W = -4.2\%$	$\Delta y = -3.6\%$ $\Delta GDP = -4.7\%$ $\Delta W = -4.3\%$	$\Delta y = +0.1\%$ $\Delta GDP = +0.02\%$ $\Delta W = -4.2\%$
$\gamma = 0.05$	$\epsilon = 0.0015$	$\Delta y = +1.0\%$ $\Delta GDP = +1.0\%$ $\Delta W = -4.1\%$	$\Delta y = -1.9\%$ $\Delta GDP = -2.5\%$ $\Delta W = -4.3\%$	$\Delta y = +0.00\%$ $\Delta GDP = -0.3\%$ $\Delta W = -4.2\%$

ϵ is the implied price elasticity of housing investment. See Table 2 for further 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 disasters, 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 below its long-run optimal value for a longer period of time, an outcome that increases the welfare loss.

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 the 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. Naturally, like us most of the related literature assumes that utility experienced from the consumption if housing and nondurable goods is separable. The study by Ogaki and Reinhart (1998), however, suggests that utility between nondurable and durable consumption is non-separable. 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 with utility experienced from leisure. This means that households maximize

$$\int_0^\infty \left(\frac{\left[(c^{1-\epsilon} + \beta d^{1-\epsilon})^{\frac{1}{1-\epsilon}} \right]^{1-\sigma} - 1}{1-\sigma} + \eta \frac{(1-\ell)^{1-\sigma_\ell} - 1}{1-\sigma_\ell} \right) e^{-\rho t} \tag{31}$$

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 4.4% instead of 4.5%.

FIGURE 6: NON-SEPARABLE UTILITY: DESTRUCTION OF PRODUCTIVE CAPITAL AND RESIDENTIAL HOUSING
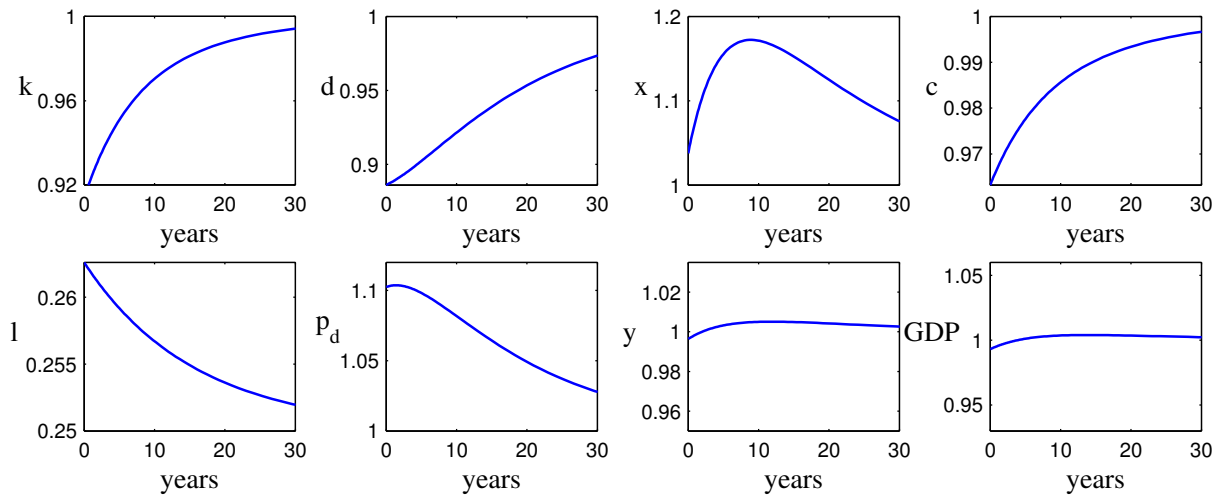
Impulse responses to a simultaneous destruction of residential housing by 11% and productive capital by 9%.

Figure 6 shows the impulse responses of economic aggregates for a shock destroying 11% of residential housing and 9% of productive capital. The quantitative results differ only mildly from those obtained for separable utility (cf. Figure 5). In the first three years after the disaster, GDP is 0.4% below the steady-state level, instead of 0.2% above the steady-state level in case

of 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 4.2% in the non-separable case compared to 4.4% for the separable case. Table 4 summarizes the results for the three different types of disasters. 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	$\Delta y = +2.5\%$ $\Delta GDP = +4.3\%$ $\Delta W = -4.6\%$	$\Delta y = -4.1\%$ $\Delta GDP = -5.3\%$ $\Delta W = -4.3\%$	$\Delta y = -0.3\%$ $\Delta GDP = +0.2\%$ $\Delta W = -4.4\%$
non-separable utility	$\Delta y = +2.8\%$ $\Delta GDP = +2.7\%$ $\Delta W = -4.4\%$	$\Delta y = -4.0\%$ $\Delta GDP = -4.5\%$ $\Delta W = -4.3\%$	$\Delta y = -0.1\%$ $\Delta GDP = -0.4\%$ $\Delta W = -4.2\%$

For a description, see Table 2.

6. Conclusion

In this paper, we 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 the pre-disaster steady-state level and that disasters destroying mainly productive capital are predicted to reduce GDP. Insignificant responses of GDP can be expected when disasters destroy about equally residential structures and 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 caused 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 stock.

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 a natural consequence 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 far earlier. Humans cannot sustain a physical activity level (PAL) of more than 2.4 times the basal metabolic rate 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 (22) and (23), 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

$$\left(1 + \frac{\psi(x)}{x}\right)(\bar{r} + \delta_d) = \frac{v'(d)}{u'(c)}. \tag{32}$$

Both isoclines intersect in the positive quadrant. To see this, notice 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 (32) converges towards infinity implying that $x \to \infty$, and for $d \to 0$ the right-hand side of equation (32) 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 intersect of the isoclines is unique, we begin by showing that the slope of the $\dot{x} = 0$ isocline is always negative. By implicit differentiation of (32), we obtain

$$\frac{\mathrm{d}x}{\mathrm{d}d} = \frac{\frac{v''(d)}{u'(c)}}{\frac{1}{x}\left(\psi'(x) - \frac{\psi(x)}{x}\right)(r + \delta_d)} < 0. \tag{33}$$

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 $\dot{d}$ 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 this setup is equivalent to the model in Section 2. The alternative setup allows us to derive a rental price for durables, p_d.

Households solve

$$\max_{c,d,\ell} \int_0^\infty \left(u(c) + v(d) + q(1 - \ell) \right) \cdot e^{-\rho t} dt, \tag{34}$$

subject to

$$\dot{a} = w\ell + ra - c - p_d d, \tag{35}$$

where p_d denotes the price for hiring one unit of a durable consumption good (a house) d for one unit of time. The first order conditions are

$$u'(c) = \lambda \tag{36}$$

$$v'(d) = \lambda p_d \tag{37}$$

$$\lambda w = q'(1 - \ell) \tag{38}$$

$$\lambda r = \lambda \rho - \dot{\lambda}. \tag{39}$$

We derive an equation for p_d by combining equation (36) and (37):

$$p_d = \frac{v'(d)}{u'(c)}. \tag{40}$$

Furthermore, substituting equation (36) into (38) yields equation (11), and differentiating equation (36) with respect to time and combining with equation (39) yields the Keynes-Ramsey rule (10).

There exists a continuum $(0, 1)$ of firms buying installed units of houses x from construction firms at price p_x and renting houses d to households. These firms can best be seen as real estate firms whose only role is to buy installed houses and rent them to households. Hence, these firms maximize

$$\pi = \int_0^\infty \left(p_d d - p_x x \right) e^{-rt} dt \tag{41}$$

$$\text{s.t.} \quad \dot{d} = x - \delta d \tag{42}$$

The first order conditions are

$$p_x = \nu \tag{43}$$

$$p_d - \nu\delta = \nu r - \dot{\nu} \tag{44}$$

with ν denoting the shadow price of one installed unit of d in terms of marginal revenues.

There exists a continuum $(0,1)$ of construction firms converting final goods into housing. These firms face adjustment costs $\psi(x)$ for installing x units of housing. Each real estate firm 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:

$$p_x = 1 + \frac{\psi(x)}{x}. \tag{45}$$

Substituting equation (43) into (45), differentiation with respect to time, and substituting (44) and (40) yields

$$\frac{\dot{x}}{x} = \left(\psi'(x) - \frac{\psi(x)}{x} \right)^{-1} \left[\left(1 + \frac{\psi(x)}{x} \right) (r + \delta_d) - \frac{v'(d)}{u'(c)} \right], \tag{46}$$

which is equal to equation (23). Hence, the alternative setup for households renting durable goods d from real estate firms is equivalent to the benchmark setup.

APPENDIX C

We show that the steady-state of the large economy described by system (24) - (28) is unique. We begin by noticing that the capital-labor ratio is pinned down by equation (26). Second, we exploit the analysis of subsystem (25) and (27) 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 (24) we obtain

$$k \left(\frac{Af(k,\ell)}{k} - \delta_k \right) = c + s(c) + \psi(s(c)). \tag{47}$$

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

Next, we show that equation (28) 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:

$$\left. \frac{\mathrm{d}k}{\mathrm{d}c} \right|_{KRR} = \left. \frac{\mathrm{d}k}{\mathrm{d}l} \right|_{KRR} \cdot \frac{\mathrm{d}l}{\mathrm{d}c} = 1 \cdot \frac{-\frac{u''(c)}{u'(c)}}{q''(1-\ell)} < 0. \tag{48}$$

The overall derivative is negative because $u''(\cdot) < 0$, $q''(\cdot) < 0$, and $u'(\cdot) > 0$. Equations (47) and (28) both imply a steady-state relationship between k and c. Finally, noticing that the slopes

of the steady-state equations (28) and (47) are of opposite sign, we conclude uniqueness of the steady-state.

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