The Long Shadow of a Major Disaster: Dynamic Impacts of the HayWired Earthquake Scenario on California's Economy*

Ian Sue Wing[a], Adam Rose[b], Dan Wei[c], and Anne Wein[d]

February 12, 2022

* This research was funded by the U.S. Geological Survey Land Change Science Program. The authors wish to thank the many members of the HayWired project research team for their underlying contributions, including the engineering damage estimates of the earthquake hazards and ancillary fires, analyses of population movement, and estimates of transportation system disruptions. However, the authors are solely responsible for any errors or omissions in this paper.

[a] Professor, Department of Earth and Environment, Boston University, 675 Commonwealth Ave., Boston, MA 02215, USA. E-mail: isw@bu.edu

[b] Research Professor, Sol Price School of Public Policy, University of Southern California, 230 RGL, 650 Childs Way, Los Angeles, CA 90089, USA. E-mail: adam.rose@usc.edu

[c] Research Associate Professor, Sol Price School of Public Policy, University of Southern California, Center for International and Public Affairs 379C, Los Angeles, CA 90089, USA. (corresponding author) E-mail: danwei@usc.edu

[d] Operations Research Analyst, Western Geographic Science Center, U.S. Geological Survey, 345 Middlefield Rd., Menlo Park, CA 94025, USA. E-mail: awein@usgs.gov

Abstract

We develop and apply a dynamic economic simulation model to analyze the multi-regional impacts of, and mechanisms of recovery from, a major disaster, the HayWired scenario — a hypothetical Magnitude 7.0 earthquake affecting California's San Francisco Bay Area. The model integrates loss pathways: capital stock damage, labor supply shocks due to short-term population displacement and longer-run out-migration from damaged areas, and the exacerbating effects of damage to transportation infrastructure capital, as well as various aspects of static and dynamic economic resilience. With input substitution-based static inherent resilience and dynamic resilience in the form of optimal intertemporal and spatial investment allocation, gross output losses range from 0.5% to 6% across regions, welfare losses are 0.4% statewide but can be ten times as large in hardest-hit areas, and large-scale reconstruction investment is supported by substantial interregional transfers of resources through intra-state trade. Increased output via firms engaging in the key adaptive resilience tactic of production recapture can alleviate a substantial fraction of losses—but only if upstream and downstream barriers to recovery can be lowered quickly.

Keywords: disaster recovery, dynamic multi-regional CGE modeling, economic resilience, HayWired earthquake scenario

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1. Introduction

Earthquakes have been among the costliest natural disasters world-wide over the past 30 years. This includes the events centered in Northridge USA (1994), Kobe Japan (1995), Wenchuan China (2008), and Tohuku Japan (2011). Moreover, similar larger earthquakes are distinct possibilities for many parts of the world, as for example a Southern San Andreas Fault, event often referred to as the "Big One", just east of Los Angeles (see, e.g., Porter et al., 2011; Rose et al., 2011).

Estimating long-run impacts of disasters has typically been one of the thorniest aspects of research in this field (Skidmore and Toya, 2002; Chang and Rose, 2012; Botzen et al., 2019). While the direct property damage from earthquakes is readily observable, estimating losses of associated economic activity is more difficult because they are not directly observable and because their duration is difficult to determine given the mounting number of other factors affecting the economy over time. Most studies of actual and hypothetical earthquakes only address the short-run economic impacts of a few years, and the analysis becomes more difficult for longer periods in part because of the vagaries of insurance payments and government and private philanthropic assistance, as well as recovery policy in general.

We model the long-term economic recovery of a major hypothetical but realistically plausible earthquake on the Hayward Fault in Northern California. The "HayWired" scenario characterizes and simulates the impacts of a hypothetical magnitude (M) 7.0 earthquake (mainshock) and its aftershocks. The fault is along the east side of San Francisco Bay and is among the most active and dangerous in the United States, because it runs through a densely urbanized and interconnected region with a population of more than 7 million people (Hudnut et al., 2018). Three overarching objectives of the HayWired scenario are to: 1) improve the communication and use of earthquake-hazard science in decision-making, 2) advance basic knowledge of earthquake risks and to inform actions to reduce earthquake risks, and 3) help build community capacity to respond to and recover from earthquakes (Hudnut et al., 2017). The scenario was co-produced by government, academic and private researchers and practitioners including engineers and emergency managers in critical infrastructure organizations, urban planners, and regional economists.

Our model incorporates the initial level of property damage, infrastructure disruptions, population/labor supply adjustments, and shifts in economic activity. It simulates the efficient use of resources to recover from input supply disruptions in the short-term (static resilience) and efficient use of investment for repair and reconstruction of capital assets in the long-term (dynamic resilience). This is done in the context of a multi-regional model that allows for spatial shifts of population, investment funds and commodity flows.

The paper offers several advances in the modeling of disaster losses. Foremost is that it analyzes the trajectory of an economy and its recovery over a 20-year period, much longer than most research to-date. Second, it integrates inputs from several disciplines and societal domains, including engineering damage estimates of earthquake hazards and ancillary fires, demographic aspects of population movement, transportation planning considerations, disaster assistance, and static and dynamic resilience. It does so through the formulation of a sophisticated economic growth model capable of incorporating all of these features. While the analysis is oriented toward earthquakes, the model is sufficiently general to address impacts of and recovery to most types of natural and man-made disasters.

This study breaks out complex interactions of economic impact pathways and illustrates effects on spatiotemporal patterns of economic recovery within a region. Policy development can be informed by insights into: 1) the impacts of capital stock losses, transportation infrastructure degradation, supply-chain interruptions, population movements, and the relations among them, and 2) the effects of the amount, timing, and allocation of disaster assistance to repair and replace capital stocks for economic recovery. Furthermore, the effectiveness of microeconomic resilience tactics can be evaluated in the context of supply-chain constraints.

The paper is divided into six sections. In Section 2, we provide an overview of the HayWired scenario, highlighting the innovations of its economic analysis as compared with previous USGS disaster studies, the channels through which the earthquake shifts the baseline trajectory of regional economies, and considerations of economic resilience. Section 3 introduces the dynamic simulation model of the California's regional economies, and discusses its input data, numerical calibration and the specification of HayWired scenario shocks. Simulation results are presented and interpreted in Section 4, starting with the baseline California economy, continuing with impacts of the HayWired scenario with and without resilience, and culminating with a discussion of the model's sensitivity to key parameters. Section 5 summarizes the implications of the results for policy and planning, and discusses caveats to the analysis. Section 6 concludes with a brief outline of future research needs.

2. The HayWired Earthquake Scenario

2.1 Overview

The foundation of the HayWired scenario is a simulation of a M 7.0 earthquake on the Hayward fault with an epicenter in Oakland in the Bay Area Region. Detweiler and Wein (2017) details the scenario earthquake fault rupture, shaking, liquefaction, landslides, and fire following for the mainshock and an aftershock sequence. Interdisciplinary analyses translate the earthquake hazards into structural engineering damages and societal consequences including economic impacts (see Detweiler et al., 2018, 2021).

Innovations of the HayWired scenario prior to the economic analysis include: 1) integrated damage assessments for all hazards and 2) water supply and telecommunications service restorations dependencies on other lifeline infrastructure systems. Building and content damage and loss from shaking, liquefaction and landslides were estimated using Hazus, FEMA disaster modeling tool (Seligson et al., 2018). These damages were integrated with fire following damage (Scawthorn, 2018, in Johnson et al. (2021). In a new model, the restoration of water-distribution systems that supply homes and workplaces factored in the restoration of other utilities and transportation routes and the availability of labor and material resources (Porter, 2018). Wein et al. (2021) modeled dependence of telecommunications restorations on electric power services and surges in demand for information and communication after a large earthquake.

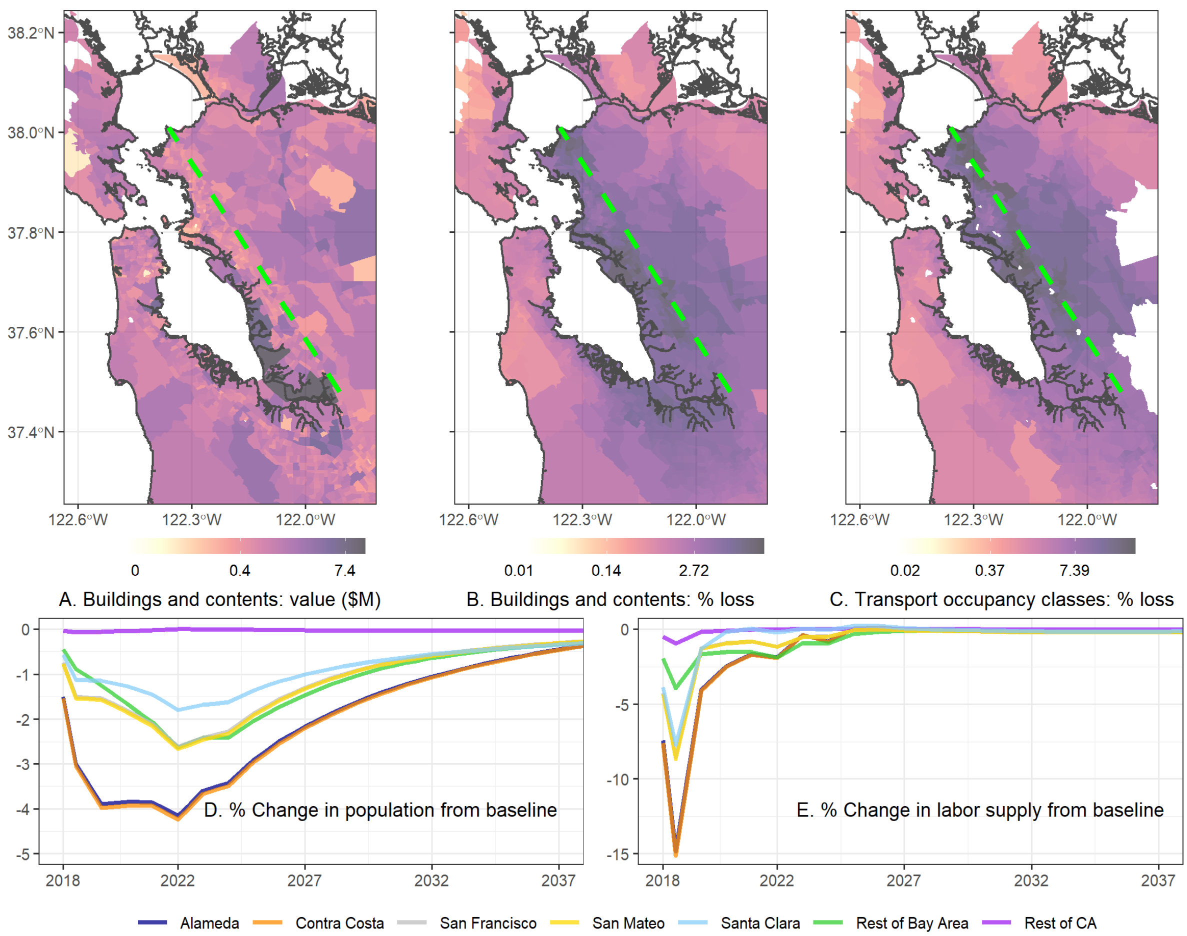
An economic analysis of the HayWired scenario was performed with the multi-regional CGE model utilizing estimates of physical damage to buildings and infrastructure, with the estimation being performed with and without resilience tactics (Sue Wing et al., 2021). This and related analyses span micro- and macro-economic perspectives including characteristics of businesses (for example, small size or minority owned) disrupted by building damage, spatial and temporal impacts on industrial sectors, and estimations of gross state product losses, also with and without economic resilience adjustments (Levy et al., 2020). Another macroeconomic analysis studied the gross regional product (GRP), employment, and population losses compared to the Association of Bay Area Government's socio-economic forecast through 2040 using the REMI PI+ Model (Kroll et al., 2020). This analysis considered output losses from building damages and commute disruptions from damages to transportation systems of highway-bridge and Bay Area rapid transit.

2.2 Pathways of regional economic impact

There are numerous pathways by which the effects of a disaster affect the functioning of the economy and result in forgone output (Rose et al. 2011; Sue Wing and Rose 2021). For the case of an earthquake the process usually begins with property damage, which reduces the capacity to produce. Similarly, death and injury, reduces labor inputs, as do other impingements on labor supply, such as caring for the injured or for children who are not able to go to school. Another major pathway is the disruption of utility, telecommunications, and transportation services, which can stunt the ability to produce, but this also generalizes to the disruption of any critical intermediate input.

Here we consider the HayWired scenario's dynamic effects on the economy through three channels. The primary pathway of impact is unanticipated destruction of a portion of the economy's endowment of productive capital (see Akao and Sakamoto 2018;Douenne 2020, for theoretical appraisals of the long-run growth impacts). Such losses directly reduce output and the supply of commodities to satisfy contemporaneous demand for final and intermediate goods, in addition to constraining the investment necessary for reconstruction of the capital stock. Heavily damaged areas will likely experience transitory declines in the productivity of gross investment spending in the immediate aftermath of the disaster, reflecting the need to allocate resources to demolishing irreparably damaged structures and removing debris before new capital formation can proceed.

A second impact pathway is changes in the population and labor supply, which incorporates a mix of direct and indirect effects. For example, it took days to months for employees to be ready for work after the 2011 Christchurch earthquake (Donnelly and Proctor-Thomson, 2013) (for other examples, see Li et al., 2013; Koks et al., 2015; Zhang et al., 2019). Earthquake-related deaths and injuries in the HayWired scenario (Seligson et al. 2018) directly reduce the population and economy's labor endowment, and indirectly, building damage induces short-term displacement of populations from their homes and businesses away from their pre-disaster locations (Johnson et al., 2021; Wein et al., 2021), while damage to transportation infrastructure makes travel more difficult. In severely damaged areas, the latter phenomena increase spatial mismatch, with workers and/or businesses relocating beyond the maximum feasible commuting distance, or severed transportation links precluding workers traveling to their jobs altogether (Kroll et al., 2020; Wein et al., 2021). The upshot is a temporary net reduction in the supply of labor until populations are able to return to their places of residence and transportation lifelines' functionality is restored. Over longer time-frames some residents may choose to permanently relocate out of affected areas, shifting those regions' populations from their long-run baseline trajectories, with the potential for additional adverse effects on local labor supplies.



Sources: Panels A and B use Census tract-level data from Seligson et al. (2018) to map the value of buildings and contents, summed across HAZUS occupancy classes, and the value of building and content losses, similarly aggregated and expressed as fractions of census tract totals. Panel C uses the same data to map the value of building and content losses as fractions of census tract totals, but only for HAZUS occupancy classes corresponding to transportation sectors (COM2 and COM4). Panels C and D reproduce Kroll et al. (2020) Figures 6B and 5B, respectively.

Figure 1. Effects of the HayWired Scenario on the San Francisco Bay Area: Capital Stock, Direct Earthquake Damage on Buildings/Contents and Transportation Sector, and Dynamic Population and Labor Supply Impacts

Third, disruption of transportation lifelines is associated with transitory disequilibrium due to a breakdown of commodity market intermediation (Yonson et al., 2020). The timing of lifeline restoration has a large impact on social welfare, but is adversely affected by lack of coordination among lifeline firms' decisions and activities. In the aftermath of a large-scale disaster, repairs may take several months, and spatial heterogeneity in the speed of restoration can impose considerable costs on firms and households in different regions. (e.g., six months to restore Los Angeles' road network to pre-condition of 1994 Northridge earthquake—Casari and Wilkie 2005). Over the period of restoration, commodity supplies may not be able to satisfy demands despite having the operational capacity to do so. In particular, only a fraction of the output that can be produced can be conveyed to domestic users and exporters, and only a fraction of the potential supply of domestic and imported commodities can be conveyed to intermediate users and final consumers.

The foregoing shocks induce a further chain reaction of indirect effects through forward and backward linkages in the economy's input-output system. The former is exemplified by firms cutting back on orders for inputs because of inability to use them, which then ripples upstream to decrease in activity of the many rounds of input supplier. Analogously, if directly affected firms suffer reductions in output, their customers (both direct and indirect) will have to curtail their production. Additional curtailment of economic activity will arise from reduced household income and subsequent reductions in expenditure on consumption and investment. Such indirect effects are often modeled explicitly as in the use of a computable general equilibrium model (see, e.g., Rose et al., 2016; Sue Wing and Rose, 2021), but are modeled implicitly in the context of our partial equilibrium economic growth model.

Figure 1 illustrates the three channels. Geographically, capital stocks (the value of buildings and their contents) are concentrated in the south and east of the region, close to the southern end of the Hayward fault, indicated by the dashed green line. Direct damage to capital stocks, both in aggregate and for occupancy classes corresponding to transportation sectors, are most severe in the east and southeastern portions of the San Francisco Bay (Contra Costa, Alameda, and Santa Clara counties). Impacts on population are modest but persist over the long run, converging to losses of one-half of one percent in affected regions. Transitory reductions in labor supply are three times as large in the year after the earthquake, and rapidly converge thereafter to the population shock. Similar to the pattern of capital stock losses, population and labor supply impacts are most severe in Alameda and Contra Costa, and about half as large in San Francisco and San Mateo. Interestingly, labor markets are responsible for geographic transmission of the effects of capital stock losses to mildly damaged North Bay counties (Marin, Napa, Solano, and Sonoma counties).

2.3 Resilience

There are many definitions of resilience, but Rose (2009), Alexander (2013) and others have found more commonalities than differences. We offer the following general definitions of resilience, which capture the essence of the concept, and then follow them up with definitions that adapt them to economic considerations. Following Rose (2004b, 2009), we distinguish two major categories of resilience.

Static resilience: generally, the ability of the system to maintain a high level of functioning when shocked. *Static economic resilience* is the efficient use of remaining resources at a given point in time. It pertains to the core economic concept of coping with resource scarcity, which is exacerbated under disaster conditions.

Dynamic resilience: generally, the ability and speed of the system to recover. *Dynamic economic resilience* is the efficient use of resources over time for investment in repair and reconstruction. Investment is a time-related phenomenon—the act of setting aside resources that could potentially be used for current consumption in order to reestablish productivity in the future. Static economic resilience does not restore damaged capacity and is therefore not likely to lead to complete recovery.

Economic resilience manifests itself at three levels:

Micro: the operation of individual businesses, households, and government agencies; for example, conservation of or substitution for critical inputs, use of inventories or excess capacity, relocation, and production rescheduling

Meso: the operation of industries and markets; for example, the resource-allocating mechanism of the price system

Macro: the operation of the economy; for example, supply-chain adjustments, importation of critical inputs, and fiscal and monetary policy

Another important delineation in economic resilience, and resilience in general, is the distinction between inherent and adaptive resilience (Rose and Liao, 2005; Tierney, 2007; Cutter, 2016). Inherent resilience refers to capacity already built into a system or that can be enhanced by "pre-positioning" before the disaster strikes, such as the ability to use more than one type of fuel in an electric-power generating unit, purchasing a portable electricity generator, or stockpiling critical materials at the micro level. At the meso and macro levels it pertains to the the workings of the price system to provide signals of increased resource scarcity after disaster struck. At the macro level it pertains to substituting domestically disrupted goods and services by imports, and the use of established government policy levers. The working of the price system and such responses as input substitution, substitution of imports for locally produced goods, and regional shifts in economic activity are intrinsic to our model (see also Wei et al., 2020).

Adaptive resilience is exemplified by ordinary and improvisational actions after a disaster strikes. Examples include recapturing lost production by working overtime and extra shifts, conservation that was not previously thought possible, changing technology, devising market mechanisms where they might not previously existed, and devising new government post-disaster assistance programs.

Economic resilience can also be defined from both the customer-side and supplier-side (Rose, 2009, 2017). Customer-side resilience primarily refers to demand-side resilience tactics, by which the businesses and households cope with the disruption (quantity and timing) of the delivery of primary and intermediate production inputs or final goods and services, respectively, using resilience tactics such as conservation, input substitution, import substitution, use of inventories, and production recapture. In contrast, supplier-side resilience is concerned with delivering outputs to customers and could include the establishment of system redundancy in the production process (a form of static resilience); it also involves the repair or reconstruction of critical inputs (dynamic resilience).

3. Methods

3.1 A dynamic model of California's regional economy

A large literature has developed investigating the impact of disasters on economic growth (see, e.g., Botzen et al., 2019). Of the many simulation studies, a number adopt intertemporal partial equilbirum (PE) or computational general equilibrium (CGE) formulations (see, variously, droughts—Pande et al., 2014, floods—Grames et al., 2016, earthquakes—Xie et al., 2018, tornados—Attary et al., 2020, endogenous catastrophic climate damages— van der Ploeg and de Zeeuw 2019). Perhaps the closest study to ours is Shibusawa (2020), who applies dynamic CGE models to assess the regional economic consequences of earthquakes, focusing on the spatial scale of Chinese provinces. Our approach is to abstract from regions' detailed input-output structure in order to transparently highlight the effects of impact pathways on key margins of producer and consumer adjustment, and the ultimate consequences for economic growth.

We specify a multiregional PE Ramsey growth model, which divides the state of California into $r \in \mathcal{R}$ regions whose economic activity is simulated over $t \in \{0, \dots, T\}$ time periods. A social planner[1] allocates each region's consumption (C), investment (I), exports (X), imports (M), and intermediate commodity uses (Z) across regions and time periods to maximize welfare (W), given exogenous trajectories of regional population (N), labor supply (L), and total factor productivity (Φ^Y). The model (including list of variables/parameters and equations) is summarized in Table 1. Welfare is specified as the weighted present value of discounted instantaneous utility of regional households (1), which is based on their per capita consumption (2). Regions' producers generate aggregate output (Y) from quantities of labor, capital (K) and intermediate inputs, (3) and (4), using nested constant elasticity of substitution (CES) technology that combines labor and capital into a value-added composite (KL), which in turn substitutes for intermediate input. Each region's output satisfies demand for domestic uses and exports (5). Interregional trade follows the Armington (1969) specification, in which exports are aggregated into a statewide CES supply composite that satisfies regions' import demands (6). In (7), each region's imported and domestic goods are combined into a CES Armington supply composite (A) that satisfies domestic households' consumption and investment demands, and domestic producers' intermediate input demands (8). The primary engine of regional economies' growth is investment-driven accumulation of capital according to the perpetual inventory equation (9), which captures the effects of time-to-build lags on the dynamics of new capital formation.

Regional economies' baseline trajectories are determined by exogenously-expanding populations (10) and labor supplies (11), as well as exogenous total factor productivity (TFP) growth (12). The model's counterfactual simulations compute deviations from the baseline, driven by the

[1] The model is intended to replicate market interactions, but the convention of a "social planner" is used to connote that a social optimum allocation of resources will be achieved in the process (i.e., perfect foresight and no market failures or frictions).

three channels of impact described in section 2.2. Capital destruction is assumed to occur at the beginning of the planning horizon, and is represented by the capital shock factor, $\Phi^K < 1$, applied to regions' initial capital stocks (13). Transitory labor market disruption is captured by the labor supply shock factor, $\Phi^L < 1$, while longer-run impacts due to out-migration are represented via the population shock factor, $\Phi^N < 1$. We represent temporary breakdown of market intermediation via the assumption of "iceberg costs", whereby only a fraction of produced output can be transformed into domestic use and exports, and only a fraction of a region's Armington supply composite can satisfy demands for consumption, investment and intermediate input. Both fractions are approximated by the transport disruption shock factor, $\Phi^T < 1$. Due to insufficient data from prior HayWired analyses, we did not consider the potential dependence of the productivity of investment on the magnitude of capital destruction, e.g. early in the planning horizon, specifying κ as declining with Φ^K.

The model also incorporates several dimensions of resilience discussed in section 2.3. For individual regions, the dynamic margin of adjustment is allocation of investment to determine the trajectory of the capital stock. Dynamic economic resilience is inherent in the model's Ramsey formulation: investment is allocated so as to maximize intertemporal welfare, subsuming the issue of the optimal time-path of recovery that has arisen in many prior studies (e.g., Rose et al., 1997; Sue Wing et al., 2016; Xie et al., 2014, 2018). Given the character of the shocks to the economy, early in the simulation horizon, adjustments that facilitate mobilization of resources for reconstruction by sustaining output, and barriers that might dissipate resources or obstruct their mobilization, are critical to determining the subsequent dynamics of recovery. We offer a formal consideration of investment allocation in an appendix.

Static economic resilience is incorporated via the inherent resilience margins of input substitution, import substitution, and interregional shift of economic activity. At each time step the regional supplies of capital and labor are determined, and therefore the margin of short-run adjustment available to firms in each region is substitution of intermediate input for value-added (governed by the elasticity, σ^Y) to determine the quantity of output. Further intra-region static margins are reallocation of output between domestic use and exports, subsequent substitution of imports for the domestic component of output (governed by the elasticity, σ^A) to determine the quantity of Armington supply, and reallocation of the latter among consumption, investment and intermediate input. Broader market-mediated resilience of the regional system arises from reallocation of flows of exports (governed by the elasticity, σ^X) and imports among jurisdictions. Along each of the aforementioned adjustment margins the ease with which substitution can occur implicitly reflects firms' excess production capacity during stable periods of normal economic functioning.

Table 1. Summary of the Numerical Simulation Model

*A. Variables**

C	Consumption	I	Investment	X	Exports	M Imports	W Welfare
Y	Gross output	KL	Value added	K	Physical capital	K^{Eff}	Effective capital
D	Domestic use	Z	Intermediate input	A	Armington composite	L	Labor

B. Parameters

η	Discount factor	δ	Depreciation rate	γ	TFP growth rate	ω	Welfare weight
κ	Investment maturation coefficient			ν	Population growth rate		

α_{KL}, α_Z	Gross output CES distribution parameters: value-added, intermediate input
α_K, α_L	Value-added CES distribution parameters: labor, capital
β_X	Regional export aggregation CES distribution parameters
β_D, β_M	Armington aggregation CES distribution parameters: domestic uses, imports
σ_Y, σ_{KL}	Production elasticities of substitution: value-added-intermediate, capital-labor
σ_X, σ_A	Armington elasticities of substitution: interregional trade, domestic-imports
N, L, Φ^Y	Exogenous inputs: county population, labor supply, total factor productivity
Φ^K, Φ^N, Φ^L, Φ^T	Earthquake shocks: capital, population, labor supply, transport disruption
R, Φ^R, π	Resilience: recaptured production capacity, recapture factors, disaster funds

C. Equations

Aggregate welfare: $$\max_{C_{r,t},I_{r,t},X_{r,t},M_{r,t},Z_{r,t}} W = \Sigma_r \omega_r \{\Sigma_{t=0}^T \eta_t N_{r,t} U_{r,t}\} \quad (1)$$

Regional consumers' utility: $$U_{r,t} = \log(C_{r,t}/N_{r,t}) \quad (2)$$

Production: $$Y_{r,t} = \Phi^Y_{r,t}\bar{Y}_r\left(\alpha_{KL,r}\left(KL_{r,t}/\overline{KL}_r\right)^{(\sigma_Y-1)/\sigma_Y} + \alpha_{Z,r}\left(Z_{r,t}/\bar{Z}_r\right)^{(\sigma_Y-1)/\sigma_Y}\right)^{\sigma_Y/(\sigma_Y-1)} \quad (3)$$

Value-added: $$KL_{r,t} = \overline{KL}_r\left(\alpha_{K,r}\left(K^{\mathrm{Eff}}_{r,t}/\bar{K}_r\right)^{(\sigma_{KL}-1)/\sigma_{KL}} + \alpha_{L,r}\left(\Phi^L_{r,t}L_{r,t}/\bar{L}_r\right)^{(\sigma_{KL}-1)/\sigma_{KL}}\right)^{\sigma_{KL}/(\sigma_{KL}-1)} \quad (4)$$

Product disposition: $$\Phi^T_{r,t}Y_{r,t} \geq D_{r,t} + X_{r,t} \quad (5)$$

Statewide trade balance: $$(\Sigma_r \bar{X}_r)\cdot\left(\Sigma_r \beta_{X,r}\left(X_{r,t}/\bar{X}_r\right)^{(\sigma_X-1)/\sigma_X}\right)^{\sigma_X/(\sigma_X-1)} \geq \Sigma_r M_{r,t} \quad (6)$$

Armington composite: $$A_{r,t} = \bar{A}_r\left(\beta_{D,r}\left(D_{r,t}/\bar{D}_r\right)^{(\sigma_A-1)/\sigma_A} + \beta_{M,r}\left(M_{r,t}/\bar{M}_r\right)^{(\sigma_A-1)/\sigma}\right)^{\sigma_A/(\sigma_A-1)} \quad (7)$$

Absorption: $$\Phi^T_{r,t}A_{r,t} \geq C_{r,t} + I_{r,t} + Z_{r,t} \quad (8)$$

Capital accumulation: $$K_{r,t+1} = \Sigma_\ell \kappa_{r,t-\ell}(I_{r,t-\ell} + \pi_{r,t-\ell}) + (1-\delta)K_{r,t} \quad (9)$$

Exogenous population: $$N_{r,t} = \Phi^N_{r,t}\bar{N}_r(1+\nu_r)^t \quad (10)$$

Exogenous labor supply: $$L_{r,t} = \bar{L}_r N_{r,t}/\bar{N}_r \quad (11)$$

Exogenous total factor productivity: $$\Phi^Y_{r,t} = (1+\gamma_r)^t \quad (12)$$

Shock to initial capital: $$K_{r,0} = (1-\Phi^K_r)\bar{K}_r \quad (13)$$

Effective capacity due to recapture: $$K^{\mathrm{Eff}}_{r,t} = K_{r,t} + \Phi^R_{r,t}\Phi^K_r\bar{K}_r \quad (14)$$

* An overline indicates variables' benchmark 2018 values derived from economic accounts.

Resilience is also factored into the magnitude and duration of labor supply and transport disruption impacts, via the parameters Φ^L and Φ^T. Kroll et al. (2020) incorporate several adjustments that account for the moderating effects of road redundancy and the possibility for the commuters to use alternative routes or modes to cope with destructions of the transportation system, as well as the effects of telework and flexible commuting and working schedules on shocks to regional labor supplies. Additionally, we introduce adaptive resilience via production recapture, R, which represents the functionality of damaged productive capital that can be temporarily recouped via capacity stretching, overtime work and reconfiguration of business processes and production lines. In eq. (14) the latter is determined by the factor, $\Phi^R < 1$, the recaptured fraction of lost initial productive capacity. Additional resilience is provided by exogenous infusions of financial resources into the regional system from federal disaster assistance payments, $\pi > 0$, which we describe in section 3.3, below.

3.2 Numerical calibration

The model is formulated as a nonlinear program in GAMS (GAMS Development Corp., 2021) and numerically calibrated and solved using the CONOPT solver (DRUD 1994). Seven regions were specified: the five counties most affected by the earthquake (Alameda, Santa Clara, Contra Costa, San Francisco, San Mateo), an aggregate of the remaining counties in the Bay Area (Marin, Napa, Solano, Sonoma) which sustained slight to moderate damage, and an aggregate of the remaining 49 counties in the state which were largely undamaged. These economies were simulated on a six-month time-step over the 2018 January-June to 2040 July-December horizon (45 periods). Values of the CES distribution parameters and the benchmark values of the variables are calculated based on IMPLAN county-level social accounting matrices (SAMs) for 2012 IMPLAN (2014), scaled to the year 2018 according to the 2012-18 rates of growth of real county GDP recorded by the Bureau of Economic Analysis regional accounts (Sue Wing et al., 2021). Values for the elasticities of substitution were adapted from Sue Wing et al. (2021). These are small ($\sigma^Y = 0.05$, $\sigma^{KL} = 0.25$, $\sigma^A = 0.5$, $\sigma^X = 2$), reflecting the challenges faced by economic actors in accurately perceiving and appropriately responding to price signals the over the short semi-annual time-step on which the model solves. Regions' initial populations and 2018-2040 growth rates were taken from Caltrans' (2020) Long-Term Socio-Economic Forecasts by County. Welfare weights were calculated as regions' shares of the statewide sum of utilities, calculated by evaluating eq. (2) at 2018 benchmark values of per capita consumption. We assumed per-period rates of depreciation of 2.5% (5% per annum), and discount of 2.3% (based on the 2018 Jan-Jun unseasoned Moody's Baa corporate bond yield of 4.6%). We also assumed that one-third of the investment in any period matures into new capital in that and succeeding time steps, for a total maturation lag of 18 months ($\kappa_t = \kappa_{t-1} = \kappa_{t-2} = 1/3$). Initial values of capital stocks and investment, and long-run TFP growth rates, were calibrated so that the model's simulated increase in baseline regional output approximated Caltrans (2020) 2018-35 real industrial production trends.

3.3 Simulation Inputs

HayWired mainshock and aftershock damages to buildings and contents (Seligson et al. 2018), and fire damage (Scawthorn 2018) integrated with the Hazus damage assessment (Johnson et al. 2021), were spatially aggregated and expressed as a percentage of the benchmark property value by county and Hazus occupancy classes. These percentage losses were mapped to sectors in the IMPLAN county SAMs and further aggregated to calculate all-sector total and percentage losses in the value of capital input to each of the model regions. The resulting values (first numerical column in Table 2) were taken to be the shock to initial capital, Φ^K. Long-run shocks to population, and short and long-run shocks to labor supply (Φ^N and Φ^L) were calibrated based on Kroll et al. (2020)—see Figure 1, panels D and E. Transportation disruption shocks (Φ^T) were calibrated based on Kroll et al. (2020; Table 11). We note that these authors make adjustments to limit potential double counting of the output impacts of damage to capital stocks generally and transport infrastructure specifically. This ensures that the effects of transportation disruption are additional to those of capital stock losses, rather than independent and oaverlapping. Production recapture factors (Φ^R), declining over time, were taken from Sue Wing et al. (2021), weighted by the gross output of industries in each region.

Table 2 summarizes the values for these inputs. Alameda, Contra Costa and Santa Clara counties are hardest hit in terms of capital stock losses. These impacts are exacerbated by a sharp contraction in the labor supply, followed by less severe but persistent knock-on effects of population declines (Figure 1), which are for the most part concentrated in heavily damaged regions. These labor-market impacts peak in the 6-month period following the disaster. The effects of transport disruption are largest in Alameda. This impact pathway also triggers degradation of commodity market functioning in the less directly damaged San Francisco, San Mateo and Contra Costa, especially in the 6-month post-earthquake period, hampering reconstruction. Offsetting these effects is producers' adaptive resilience through their ability to engage in recapture, which reduces the loss of effective production capacity by around 35-40% in the immediate aftermath of the disaster, and 15-20% over the subsequent six months, but cannot be sustained thereafter.

Assumptions about the availability of disaster assistance funding, and the interregional and intertemporal allocation of payments, were based on Kroll et al. (2020). They estimated that 85% of aggregate building damage-related losses would be uninsured. They further assumed that assistance from all levels of government covers two-thirds of uninsured losses, with two-thirds of the resulting amount actually spent on rebuilding (as opposed to administrative functions), of which three quarters is accounted for by Federal spending from outside the Bay Area. In aggregate, 29% of the losses estimated by Seligson et al. (2018) are attributable to building contents. Assuming content losses are uninsured, the total exogenous infusion of resources works out to 20% of the initial capital stock damage. Finally, Kroll et al. (2020) hypothesize a 9-year spending trajectory in which between five and 20 percent of the total aid package is disbursed in a given year, apportioned among regions according to their shares of aggregate damage. Linearly interpolating the resulting path of spending yields exogenous reconstruction investment series for each region (π). We assume that disaster payments are subject to the same maturation lags as domestic investment, and that their timing and regional distribution are fully anticipated by the social planner, who factors them into the optimal program of interteporal allocation.

Table 2. Simulation Inputs: Capital Stock and Transportation Disruption Loss Fractions and Production Recapture Factors

	Capital Stock	Transport Disruption		Production Recapture	
	2018 Jan-Jun	2018 Jan-Jun	2018 Jul-Dec	2018 Jan-Jun	2018 Jul-Dec
Alameda	-0.296	-0.025	-0.074	0.374	0.161
Santa Clara	-0.133	-0.010	-0.030	0.395	0.170
Contra Costa	-0.139	-0.013	-0.039	0.393	0.169
San Francisco	-0.034	-0.016	-0.048	0.367	0.158
San Mateo	-0.098	-0.015	-0.046	0.384	0.165
Rest of Bay Area	0.000	-0.002	-0.007	0.366	0.158
Rest of California	-0.022	-0.005	-0.015	0.371	0.160

4. Results

4.1 California's baseline economy

We begin with a brief presentation of the baseline trajectory of regional economies simulated by the model. Projected baseline values of economic variables for the year 2035 for each of the five most affected counties, rest of the Bay Area region, and rest of California are shown in Table 3. To facilitate ccomparison we normalize each variable's 2035 value as a percentage changes from the 2018 initial year. The model is calibrated so that regions' 18-year percentage changes in gross output are within 1% of growth rates forecast by Caltrans (2020). Capital stocks grow fastest in San Mateo (41.4%), followed by San Francisco and Santa Clara (30%), with the rest of the Bay Area and rest of the state growing more slowly (22% and 18%, respectively). San Mateo also exhibits the highest rate of growth of other indicators, including consumption, gross output, intermediate input and value added, all of which increase faster than capital. However, in terms of the growth rate of Investment, Contra Costa and rest of the Bay Area are projected to have the largest growth (nearly tripling by 2035) than other regions in the state.

Table 3. California's Baseline Economy in 2035
(% change in variables from 2018 level)

	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of Bay Area	Rest of California
Population	10.3	0.4	13.5	17.4	4.0	5.7	7.4
Consumption	31.7	16.5	36.4	45.4	26.8	25.0	15.7
Investment	105.7	187.3	62.4	31.1	13.2	190.0	110.1
Exports	50.3	40.4	46.3	73.7	66.6	46.5	4.4
Imports	27.0	15.9	30.6	35.5	21.2	23.7	24.9
Gross Output	40.6	31.8	40.3	62.8	49.9	36.5	13.5
Intermediate Input	16.1	8.9	18.8	24.8	13.1	12.4	11.4
Capital Stock	27.2	21.0	31.4	41.4	30.2	22.3	18.0
Domestic Use	33.1	19.5	36.0	47.3	30.4	28.9	19.5
Armington Use	30.4	17.4	34.6	41.7	25.8	26.4	21.8
Value-Added	14.7	6.9	17.5	23.1	11.1	11.0	10.9

4.2 Impacts of the HayWired mainshock and aftershocks and the consequent recovery

This section presents and describes our main results, namely the dynamic economic consequences of the three pathways of impact, excluding the moderating effects of resilience due to production recapture and disaster assistance payments. Figure 2 indicates that, with intertemporally optimizing economic agents, perfect markets, and an absence of frictions, California's economy will substantially recover over a period as short as a decade. Damage from earthquake sequence hazards and fire reduces the size of the initial aggregate capital stock by nearly 30 percent in Alameda, 14 percent in Santa Clara and Contra Costa counties, and 10 percent in San Mateo, whereas the remaining Bay region counties sustain damage to their capital stocks of less than 5 percent (panel A). Interestingly, in the 6-month period immediately following this economic shock, capital stocks in the largely unaffected remainder of the Bay region and the State also decrease relative to the baseline. The reason is reallocation of investment toward the most severely damaged counties (panel B). Statewide, the earthquake reduces initial capital by 4 percent. This in turn stimulates an increase in investment that initially covers the capital loss and then reverts slowly to the long-run baseline level over the simulation horizon. This behavior arises from the fact that the quantity of investment is smaller than the capital stock, so that damage to the latter can only be offset by a sustained increase in the rate of accumulation of the former. Relative to baseline levels of investment, increases of 160 percent in Alameda and 80 percent in Santa Clara and Contra Costa drive rapid accumulation of capital, with these counties' stocks recovering to 95 percent of their baseline levels less than 5 years after the earthquake, and 99 percent after a decade. In less-affected and undamaged regions, investment and capital stocks—which are larger in magnitude—recover more slowly, attaining 98 percent and 99 percent of their baseline levels after 5 years and a decade, respectively.

In response to the departure of regional capital stocks from their baseline trajectories, gross output, value-added, and intermediate commodity use all exhibit qualitatively similar dynamics (panels C-E). The interregional pattern of initial declines and subsequent patterns of recovery mirrors that of capital stocks in panel A. This is not surprising given the within-period determination of value-added (cf., eq. (4)) and low values of the elasticities of substitution, both of which limit the ability of firms to offset the impact of capital damage on production by increasing the quantity of intermediate commodity inputs. The consequent complementarity between capital and intermediate goods means that inputs of the latter decrease as well, but by a smaller fraction than value-added. The upshot is that the economy experiences a slightly larger reduction in value-added than gross output, and both quantities decrease by a much smaller amount than capital. California's aggregate gross output and value-added experience decrease by about 2 percent initially, after which they slowly return to their long-run baseline levels over the simulation horizon. Despite the social planner's objective's attempt to preserve the level of households' utility, consumption rebounds more slowly to its baseline level (panel F), because of the need to allocate resources to capital stock reconstruction.

Especially in the most affected counties, the need to allocate larger quantities of final goods to increased investment results in precipitous decreases in exports, coupled with increases in imports (panels G and H). The result is a reorganization of commodity trade and a shift in counties' trade balances. Along the baseline trajectory, Rest of California is a net importer, San

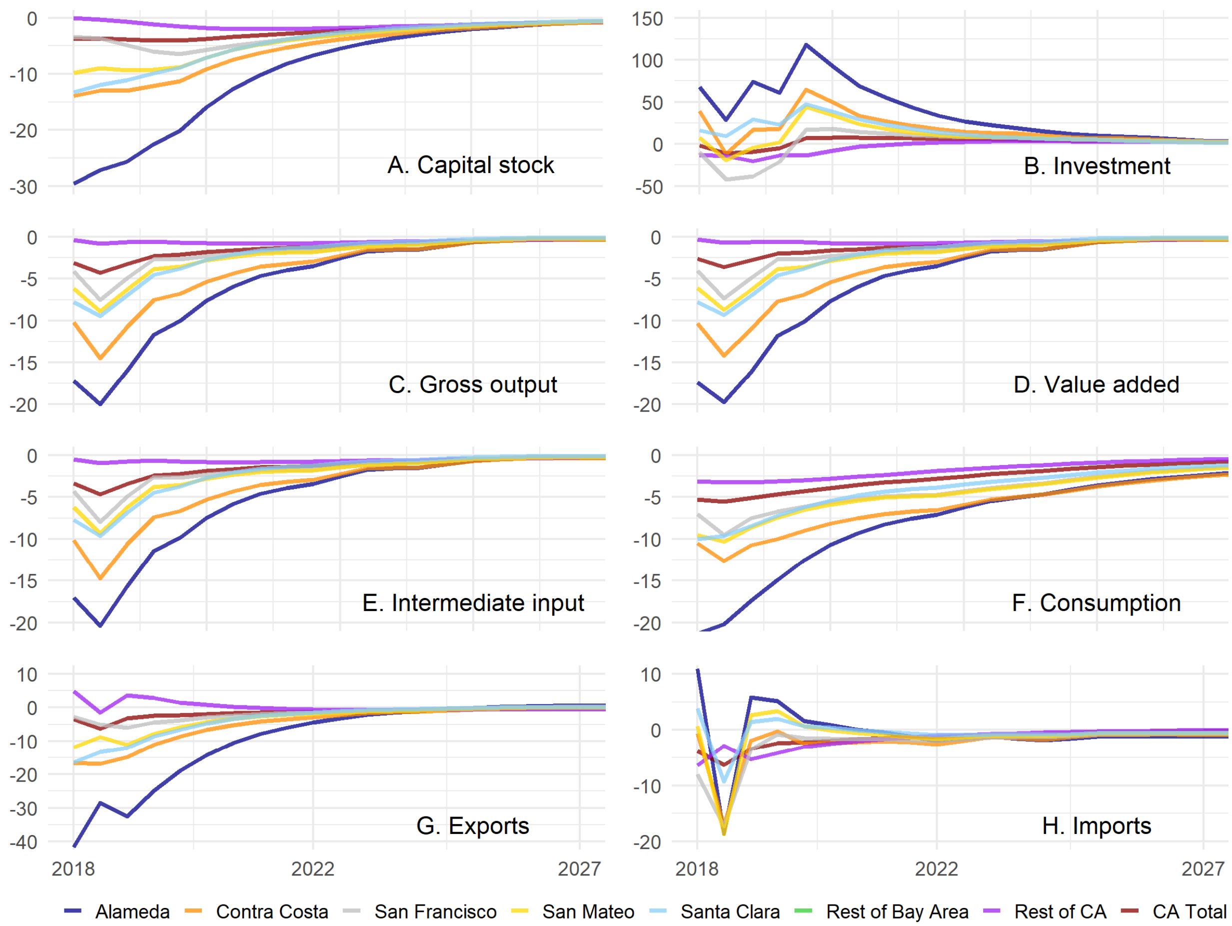


Figure 2. Impacts of the HayWired Scenario (Without Adaptive Resilience or Disaster Assistance), 2018-27: % Change Relative to Baseline Regional Trajectories

Francisco, San Mateo and Santa Clara are net exporters, Alameda, Contra Costa and Rest of the Bay Area are initially net importers that subsequently become net exporters. Overall, the shock induces severely impacted counties to slash exports and, to a lesser extent, increase imports, which substantially delays Alameda's and Contra Costa's transition to net exports.

With the exception of capital stocks and consumption, the trajectories of all variables indicate the exacerbating but transitory effects of shocks to labor supplies and disruptions to commodity conveyance, whose impacts are largest in the latter half of 2018. These impacts are small (on the order of 1-5 percent) but significant enough to temporarily reverse the process of recovery. Finally, regions' long-run recovery trajectories are affected by the impacts of induced population change on their intertemporal allocation of consumption (via regional consumers' utility in eq. (2)) and endowments of labor. Consistent with Figure 1, panel D, these influences are modest within the first five years, and very slight thereafter.

Table 4 summarizes the HayWired scenario's impacts over the immedate post-earthquake decade, expressed as the change in the present discounted value of economic variables, evaluated at the discount rate, ρ. California sustains losses of gross output and value added of $500 Bn and $2 Tn, respectively, both of which represent reductions from the present discounted baseline of around 1.5%. The change in aggregate welfare is much smaller due to consumption smoothing, with the value of the model maximand declining by 2.3%. The only variable to experience increases is investment, whose aggregate quantity rises by $103 Bn or 2.7%. Interregionally, declines in most variables, and increases in investment, follow the patterns of severity of the shocks, and are concentrated in Alameda and Contra Costa. New capital formation to rapidly reconstruct the worst affected regions comes at the expense of investment in less damaged northern Bay Area counties and the rest of the state.

Table 4. Impacts of the HayWired Scenario (Base Case Without Adaptive Resilience or Disaster Assistance), 2018-27: Change in Present Discounted Value of Variables Relative to Baseline ($ Bn, % in parentheses)

	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of Bay Area	Rest of California	California Total
Consumption	-78.6	-32.5	-34.7	-24.3	-71.2	-28.2	-234.4	-503.8
	(-8.9)	(-6.7)	(-4.7)	(-5.0)	(-4.5)	(-4.1)	(-2.0)	(-3.0)
Investment	72.3	24.1	1.1	15.4	74.9	-2.2	-82.3	103.3
	(40.7)	(18.7)	(0.5)	(9.2)	(16.1)	(-1.5)	(-3.2)	(2.7)
Exports	-80.7	-49.2	-15.3	-32	-95.9	-6.0	33.0	-246.0
	(-10.5)	(-5.3)	(-1.9)	(-3.4)	(-3.9)	(-1.1)	-0.4	(-1.7)
Imports	-3.5	-21.5	-10.1	-6.3	-7.8	-18.8	-182.2	-250.3
	(-0.5)	(-2.4)	(-2.7)	(-1.3)	(-0.5)	(-3.0)	(-1.8)	(-1.7)
Gross Output	-103.6	-66.1	-38.6	-38.2	-108.4	-24.6	-129.2	-508.6
	(-6.0)	(-4.3)	(-2.0)	(-2.4)	(-2.4)	(-2.0)	(-0.6)	(-1.5)
Intermed. Input	-38.7	-38.8	-11.0	-12.1	-43.0	-9.9	-52.1	-205.7
	(-6.1)	(-4.4)	(-2.1)	(-2.5)	(-2.5)	(-2.0)	(-0.6)	(-1.6)
Capital Stock	-660.7	-292.2	-207.1	-231.4	-741.1	-148.7	-1221.1	-3502.3
	(-11.2)	(-6.3)	(-3.3)	(-4.7)	(-5.1)	(-2.9)	(-1.3)	(-2.6)
Domestic Use	-30.6	-20.9	-29.7	-10.9	-21.5	-19.9	-173.9	-307.4
	(-3.2)	(-3.4)	(-2.7)	(-1.7)	(-1.1)	(-2.8)	(-1.4)	(-1.6)
Armington Use	-35.0	-42.5	-39.8	-17.2	-29.2	-38.7	-356.1	-558.5
	(-2.1)	(-2.8)	(-2.7)	(-1.5)	(-0.8)	(-2.9)	(-1.6)	(-1.7)
Value-Added	-401.4	-217.1	-144.2	-136.3	-396.1	-109.4	-603.5	-2007.9
	(-6.2)	(-4.4)	(-2.1)	(-2.5)	(-2.6)	(-2.0)	(-0.6)	(-1.4)
Welfare	-11.3	-0.4	-7.8	-3.0	-2.4	-4.6	-14.5	-2.3
	(-3.9)	(-3.6)	(-2.2)	(-2.2)	(-1.6)	(-2.0)	(-0.2)	(-0.4)

The results have several important implications for the interregional nature of recovery from a major natural disaster. They indicate that, as in the case of the direct and indirect consequences themselves, the pattern of recovery reveals further departures from simple direct assessments of investment in repair and reconstruction, after considering various types of dynamic interregional general equilibrium effects. Those counties implementing the higher levels of repair and reconstruction investment benefit the most, but these effects spill over onto neighboring counties as well. The spillover effect is greater than in ordinary circumstances because the less-affected counties have greater productive capacity relative to the directly affected counties than in the baseline case, and they are relied upon as the sources of supplies of direct and indirect inputs into recovery. Thus, the lightly damaged counties gain from picking up the slack of lost capacity in the core of the damaged region and also provide valuable inputs to all affected counties during the recovery process.

Table 5 summarizes how the three categories of shocks contribute to the total losses in each region. The patterns of effects of the impact pathways on gross output and value added are similar. Transportation disruptions exert the smallest impacts by a wide margin. In regions

Table 5. Contribution of Impact Pathways, 2018-27:
Changes in Present Discounted Value of Variables Relative to Baseline

	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of Bay Area	Rest of California	California Total
				Gross Output				
Capital stock	-3.36	-1.77	-0.46	-0.93	-1.48	-0.64	-0.41	-0.80
Labor/population	-2.58	-2.41	-1.38	-1.32	-0.83	-1.21	-0.12	-0.62
Transportation	-0.36	-0.35	-0.25	-0.23	-0.23	-0.14	-0.08	-0.15
Sum of Impacts	-6.30	-4.52	-2.09	-2.48	-2.54	-1.99	-0.62	-1.57
Combined Impacts	-5.97	-4.28	-2.03	-2.43	-2.44	-1.96	-0.61	-1.51
Difference (Sum vs. Combined Impacts)	-0.33	-0.24	-0.06	-0.05	-0.10	-0.02	0.00	-0.05
				Value Added				
Capital stock	-3.54	-1.87	-0.47	-0.97	-1.57	-0.64	-0.40	-0.74
Labor/population	-2.66	-2.51	-1.41	-1.38	-0.88	-1.23	-0.12	-0.54
Transportation	-0.34	-0.32	-0.24	-0.22	-0.22	-0.13	-0.08	-0.13
Sum of Impacts	-6.54	-4.69	-2.12	-2.57	-2.67	-2.00	-0.60	-1.41
Combined Impacts	-6.19	-4.44	-2.06	-2.52	-2.56	-1.98	-0.59	-1.37
Difference	-0.35	-0.25	-0.06	-0.06	-0.10	-0.02	0.00	-0.04
				Welfare				
Capital stock	-0.45	-0.20	-0.19	-0.23	-0.24	-0.19	-0.17	-0.07
Labor/population	-3.37	-3.36	-1.88	-1.88	-1.33	-1.78	-0.02	-0.30
Transportation	-0.13	-0.06	-0.10	-0.09	-0.06	-0.05	-0.04	-0.02
Sum of Impacts	-3.95	-3.62	-2.18	-2.20	-1.62	-2.02	-0.23	-0.38
Combined Impacts	-3.93	-3.61	-2.17	-2.19	-1.62	-2.02	-0.23	-0.38
Difference	-0.02	-0.01	-0.01	-0.01	-0.01	-0.01	0.00	0.00

experiencing the most severe direct damage to capital (Alameda and Santa Clara counties), the effects of capital stock losses dominates, with labor supply impacts being a close second. This pattern also arises in the rest of California, despite the small amount of direct damage suffered by regions outside the Bay Area. In less directly affected regions (San Fancisco, San Mateo, and the remaining northern counties in the Bay Area), changes in labor supply and population drive output and value added losses twice as large as those due to destruction of capital. Contra Costa exhibits this pattern as well, despite sustaining substantial capital stock damage. Summing present discounted losses generated by the three separate pathways yields total losses that are uniformly larger than the combined impacts of the shocks in Table 4. These differences, which account for approximately one-tenth of the present discounted losses in the variables considered, suggest the moderate importance of the long-run influences of static resilience via intra-period substitution and dynamic resilience via intertemporal investment allocation.

4.3 Benefits of adaptive economic resilience

We now consider how production recapture (a static adaptive resilience tactic) and disaster assistance (a dynamic resilience tactic) further ameliorate the HayWired scenario's losses.[2] Trajectories of recovery are shown in the Appendix (Table A.1). Initial impacts follow the same patterns as in Figure 2, with slight attenuation of the tendency for value added, intermediate inputs and gross output to worsen before recovery, and reductions in attendant worst-case contemporaneous losses 6-12 months post-earthquake. Given the limited extent of substitutability on the supply side of the economy, gross output is able to increase by a percentage slightly larger than the product of the recapture factor and the absolute magnitude of the shock to capital.[3] Increases in investment early in the planning horizon are smaller as capacity stretching by firms substitutes for the need to sustain production by immediately ramping up capital formation, and smaller near-term output declines alleviate pressure on budget constraints. Although the maximum change in investment still occurs 3 years post-earthquake, its peak magnitude is reduced by about 10%.

Table 6, panel A summarizes the effectiveness of production recapture and disaster assistance in moderating the HayWired scenario's impacts. The two resilience tactics reduce losses in value-added, intermediate inputs, and gross output by approximately 0.6% in Alameda and between 0.05% and 0.25% in other counties and regions. The moderations in long-run declines in consumption and investment tend to be larger than the previous three indicators in all regions, and, interregionally, are largest for Alameda, Rest of California and Contra Costa. The latter regions' higher levels of investment also translate into expedited recovery of capital stock losses. Finally, reduced pressure to allocate final goods to investment result in reductions in the previous declines in exports and increases in imports.

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[2] Note that the major inherent resilience tactics, such as input and import substitution, are intrinsic to the model and cannot readily be separated (c.f., Wei et al., 2020).

[3] To see this, assume the fixed-proportions technology, $Y = aK^{\text{Eff}}$. In the event of a capital loss, Φ^K, eqs. (9), (13) and (14) imply that in the absence of recapture output is $Y' = a(1 - \Phi^K)K$, but with recapture it is $Y'' = a(1 - \Phi^K + \Phi^R\Phi^K)K$, for a fractional saving of $Y''/Y' - 1 = \Phi^R\Phi^K/(1 - \Phi^K)$. Applying numbers in Table 2 for Alameda suggests an increase in 0.296 x 0.296 / (1 - 0.296) = 12.4% of output relative to a no-recapture scenario, which is comparable to the 0.6 / 5.97 = 10% present discounted improvement in Table 6.

Table 6. Moderating Effects of Production Recapture and Disaster Assistance, 2018-27: Difference in % Change in Present Discounted Value of Variables from Base Case (No Resilience Case)

	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of Bay Area	Rest of California	California Total
	A. Production Recapture and 9-Year Disaster Assistance Payments							
Consumption	0.78	0.43	0.33	0.30	0.33	0.41	0.47	0.35
Investment	0.98	0.57	0.40	0.38	0.31	0.39	0.51	0.42
Exports	1.45	0.45	-0.02	-0.18	0.02	0.29	0.51	0.11
Imports	-0.52	-0.12	0.17	0.25	0.10	-0.16	-0.21	0.12
Gross Output	0.60	0.26	0.07	0.04	0.05	0.14	0.24	0.11
Intermed. Input	0.60	0.27	0.07	0.05	0.05	0.14	0.25	0.12
Capital Stock	0.40	0.19	0.12	0.10	0.10	0.15	0.19	0.13
Domestic Use	-0.11	-0.03	0.14	0.18	0.08	-0.10	-0.10	0.11
Armington Use	-0.28	-0.08	0.16	0.21	0.08	-0.13	-0.16	0.11
Value-Added	0.63	0.28	0.07	0.04	0.05	0.14	0.26	0.10
Welfare	0.09	0.04	0.03	0.03	0.04	0.04	0.04	0.04
	B. Production Recapture and 6-Month Restoration Investment							
Consumption	0.87	0.53	0.33	0.26	0.52	0.50	0.48	0.34
Investment	1.55	0.92	0.51	0.37	0.61	0.67	0.76	0.52
Exports	1.42	0.81	0.19	0.00	0.50	0.54	0.58	0.29
Imports	0.71	0.51	0.28	0.23	0.32	0.37	0.42	0.30
Gross Output	1.07	0.65	0.19	0.07	0.31	0.39	0.47	0.24
Intermed. Input	1.11	0.68	0.20	0.08	0.33	0.42	0.50	0.25
Capital Stock	0.90	0.46	0.22	0.13	0.33	0.41	0.43	0.23
Domestic Use	1.04	0.64	0.25	0.16	0.37	0.43	0.49	0.28
Armington Use	0.91	0.57	0.26	0.19	0.36	0.40	0.46	0.29
Value-Added	1.10	0.68	0.19	0.07	0.31	0.40	0.49	0.21
Welfare	0.10	0.04	0.03	0.03	0.06	0.05	0.05	0.05

Overall, the effects of the resilience tactics we have modeled are modest, generating long-run improvements of between two and ten percent, depending on the variable and region. Crucially, recapture is a temporary phenomenon operationalized over time-frames that coincide with other disruption pathways. Lack of fungibility between capital and labor in the production process thus limits the extent to which firms are able to translate the increment to effective capacity generated by recapture into additional output when labor is scarce. Moreover, because of iceberg transport disruption losses, final and intermediate consumers do not end up reaping the full benefit of the incremental output that firms do manage to produce. Disaster assistance has a more direct impact on investment, capital accumulation and output. However, due to our disbursement scenario's protracted time-horizon, this measure does little to stimulate investment in the crucial post-disaster period when the demand for reconstruction to rapidly kick-start increases in output and capital accumulation is highest (Attary et al. 2020). Taken together, these results suggest that isolated resilience tactics may not achieve anywhere near their full welfare-improving potential due to lack of coordination in the face of simultaneous upstream and downstream barriers—upstream labor shortages obviating the benefits of producers' ability to stretch capacity, and firms being able to produce more output than damaged transport links have the capacity to convey to downstream customers.

4.4 Sensitivity analysis

To highlight the implications of the timing and targeting of disaster assistance, we simulate an alternative resilience scenario in which external disaster funds are disbursed quickly, and are coordinated to provide temporary shelter and business places (e.g., FEMA trailers), restore utility services such as electricity, gas, water/sewerage and telecommunications/internet, and repair passenger and commodity transport linkages. The key assumption is that these investments are effective in lowering simultaneous upstream and downstream impediments to recovery. In particular, they moderate short-run labor supply reductions and disruptions to commodity transport by 50% of their worst-case values in the 6 month post-earthquake period. Capital stock destruction and production recapture both remain unchanged.

The results are summarized in Table 6, panel B and Appendix Figure A.2. Relative to the entries in Table 6 panel A, improvements in the variables are markedly amplified, illustrating how the removal of barriers allows recapture to achieve its full potential. Value added, intermediate input and gross output losses are further moderated by 60% to a factor of six, investment declines are moderated by a further 25% to almost double, increases in the long-run value of the capital stock of 30% to a factor of three, and amelioration of welfare impacts of between 11% and 50%. Figure A.2 illustrates the origin of these effects. Compared to Figure 2, the departures of value add, intermediate input and gross output from their baseline trajectories that occur early in the planning horizon are now only two-thirds as large, and their convergence to the long-run baseline is slightly faster. In particular, peak increases in investment relative to the baseline are smaller and shift earlier, reflecting increased availability of resources, even in the presence of consumption smoothing.

In this section, we also report the results of analyses to evaluate the sensitivity of our base-case results in section 4.2 to key model parameters. The results are presented in Table 7. Output, value added and welfare losses are relatively insensitive to the values of the various substitution elasticity parameters displayed in Table 1. Doubling them moderates the present discounted values of the HayWired scenario's reductions in these variables by less than 15% of the impacts in Table 4, despite the fact that increased elasticity values would seem to imply greater economic flexibility in adjusting to the shocks. This result arises from the fact that base-case values of the elasticities are small, reflecting limited options for substitution over the course of the short six-month time step on which the model solves. Increasing the ease with which exports can be reallocated, and, to a lesser extent, reducing the time to maturation of investment, have the most significant moderating effects. Of the three variables considered, changes in welfare exhibit the lowest sensitivity. This is unsurprising, given that, in the model's structure, consumption responds to market adjustments that are only indirectly affected by the substitution elasticities (e.g., allocation of output between domestic uses and exports, and Armington supply among consumption, investment and intermediate goods). Interestingly, more elastic adjustment to the earthquake's effects does not always result in improved long-run outcomes. Doubling the capital-labor substitution elasticity results in a very slight exacerbation of value added and output losses, while doubling the Armington trade elasticity worsens value added, output and welfare impacts in the rest of California.

Table 7. Sensitivity of HayWired Scenario Impacts to Parameters: Change in Present Discounted Value of Variables Relative to Baseline (%)*

	Alameda	Contra Costa	San Francisco	San Mateo	Santa Clara	Rest of Bay Area	Rest of California	California Total
				Gross Output				
$2 \times \sigma_{KL}$	***-6.11***	***-4.53***	***-2.21***	***-2.68***	***-2.79***	***-2.07***	***-0.64***	***-1.64***
$2 \times \sigma_{Y}$	-5.51	-4.13	-2.01	-2.35	-2.34	-1.94	-0.60	-1.46
$2 \times \sigma_{X}$	-5.23	-4.11	-1.97	-2.25	-2.18	-1.95	***-0.64***	-1.44
$2 \times \sigma_{A}$	-5.46	-4.15	-1.99	-2.33	-2.32	-1.93	-0.59	-1.45
κ_{t}, κ_{t-1}= 0.5	-5.38	-4.06	-1.96	-2.33	-2.32	-1.83	-0.43	-1.33
				Value Added				
$2 \times \sigma_{KL}$	***-6.30***	***-4.69***	***-2.24***	***-2.77***	***-2.92***	***-2.08***	***-0.62***	***-1.47***
$2 \times \sigma_{Y}$	-5.73	-4.33	-2.03	-2.43	-2.47	-1.94	-0.56	-1.31
$2 \times \sigma_{\square}$	-5.41	-4.23	-2.00	-2.33	-2.28	-1.97	***-0.63***	-1.32
$2 \times \sigma_{\square}$	-5.66	-4.31	-2.02	-2.42	-2.44	-1.94	-0.57	-1.31
$\kappa_{\square}, \kappa_{t-1}$= 0.5	-5.57	-4.22	-1.99	-2.42	-2.44	-1.85	-0.42	-1.19
				Welfare				
$2 \times \sigma_{KL}$	-3.86	-3.59	-2.14	-2.16	-1.59	-1.99	-0.20	-0.38
$2 \times \sigma_{Y}$	-3.87	-3.59	-2.16	-2.18	-1.60	-2.00	-0.22	-0.38
$2 \times \sigma_{X}$	-3.75	-3.56	-2.14	-2.15	-1.57	-2.00	***-0.24***	-0.38
$2 \times \sigma_{A}$	-3.84	-3.59	-2.15	-2.17	-1.60	-2.00	-0.22	-0.38
κ_{t}, κ_{t-1}= 0.5	-3.84	-3.58	-2.13	-2.15	-1.57	-1.99	-0.23	-0.38

* Bold italic entries indicate cases where impacts are larger than under base-case parameter values.

5. Discussion

Our numerical results compare with those of several other recent studies. Shibusawa (2020) applies an intertemporal CGE model to analyze the impact of earthquake-related capital stock losses in three Chinese provinces. Although the simulated recovery trajectories are qualitatively similar to ours, temporal adjustment is more sluggish—the most heavily damaged region experiences a 10% reduction in the capital stock, which triggers an immediate output decline of 3.5% that subsequently takes more than 25 years to recover to within 0.5% of the baseline. By contrast, in response to shocks that are twice as large, Bay Area counties achieve similar convergence to their baseline growth paths in less than a decade.

Our findings corroborate those of a study of the impacts of, and recovery from, the 2008 Wenchuan, China earthquake (Xie et al., 2018). That analysis employed a dynamic CGE model and analyzed some dynamic resilience tactics, such as increasing recovery investment and hastening its delivery. The authors highlight that, counter to some previous definitions of dynamic economic resilience emphasizing the importance of reducing the duration of the recovery, the analysis indicated that this is less important than kick-starting activity. The implication is that the entire trajectory of the recovery is the crucial aspect, and, specifically, shortening its duration only has a small effect overall, since periods further out in time typically contribute small amounts to the overall effect, while the impacts of activity in earlier periods carry over (Accumulate) throughout the recovery horizon (see also Zobel, 2014).

Focusing on supplier-customer networks, Inoue and Todo (2019) simulate an agent-based model of the supply chains of nearly one million firms to investigate how production losses propagate to, and persist in, regions directly and indirectly affected by the 2011 Great East Japan earthquake, as well as a prospective scenario of a major earthquake predicted to hit Japan in the near future. They find large losses in the latter case (10.6% of GDP), driven by indirect effects on production that are significantly larger than their direct impacts. Interestingly, their very different simulation methodology generates output dynamics that are qualitatively similar to Figure 2, exhibiting initial overshooting behavior followed by rapid recovery and finally slow convergence as the economy approaches its long-run pre-shock steady state. However, adjustment is rapid, with the economy recovering substantially by one year post-disaster.

The present study also shares points of commonality with, as well as departures from, the empirical disaster literature. Noy (2009) found that an economy's ability to moderate disaster-induced output losses depends on its capacity to mobilize resources for reconstruction, which increases with literacy, institutional quality, per-capita income, openness, and government spending. Although our simulations are unable to incorporate many of these factors, our findings corroborate the importance of resource mobilization for recovery, either through reducing barriers to increasing domestic output or via interregional trade. Notwithstanding evidence highlighting the puzzle that savings increase with the destructiveness of disasters at country scales (e.g., Skidmore, 2001). Filipski et al. (2019) find that at the regional scale populations' experience of death and destruction from a major earthquake has a substantially negative impact on savings rates. Moreover, Hanaoka et al (2018) document persistent gender-specific shifts in risk aversion (increase in male survivors' risk tolerance) after a major earthquake. Both findings raise questions about the microfoundations of our aggregate specification of agents' behavior. If indeed discount rates and propensities to save do change—not just between the baseline and counterfactual scenarios but also differentially across locales that experience different intensity of capital stock damage—that could alter the spatiotemporal patterns of recovery of activity and output, and present discounted welfare losses. Exploring such influences would require more sophisticated formulations of intertemporal utility (e.g., Douenne, 2020) and making differential regional adjustments to the intertemporal elasticity of substitution and the discount rate in the counterfactual scenario.

Our simulated economy allocates investment preferentially to the core earthquake regions with the most intense capital stock damage. Spatial patterns of recovery from other disasters have witnessed a somewhat different pattern. In particular, Hurricane Katrina (Xiao and Nilawar, 2013), the 2011 Christchurch earthquake (Brown et al., 2015) and the 1995 Kobe earthquake (duPont et al., 2015) all triggered long-term shifts in population, income, and employment away from the core disaster zone toward less damaged regions. In the appendix we illustrate how this outcome can arise from reduced incentives to invest in destroyed areas due to dissipation of gross investment spending (e.g., on structure demolition and debris removal) that attenuates actual new capital formation. While the possibility of such reconfiguration of the spatial economy was anticipated by previous HayWired analyses (Wein et al., 2020), assessing the implications is challenging in the absence of engineering estimates of dissipation costs.

Finally, regarding resilience, our analysis captures the vast majority of static resilience opportunities. Others that we have omitted, such as conservation and inventories, are quite limited. With increasing sophistication of production technologies, production lines have become more fragile, with less leeway to continue operating without critical inputs (Zolli and Healy, 2011). In a world of just-in-time production, firms maintain input inventories at low levels that are likely to run out in a matter of weeks—at best. Also, the model does not capture the effect of microscale dynamic resilience measures, such as minimizing paperwork to facilitate the payment of insurance claims or receipt of government assistance.

6. Conclusion

In a recent review, Botzen et al. (2019) call for improvements in the reliability of assessments of the economic impacts of natural disasters by increasing their spatial fidelity and building on advances in regional economics to elaborate the mechanisms by which disasters' effects ripple through the economy. Their starting point is quantifying localized disruptions to economic activity arising from the overlap between natural hazards' physical impacts and the local vulnerability of properties and assets at the appropriate spatial scales ("where and with what intensity the disaster hits"). The next step is understanding pathways of impact and their causal links to economic outcomes, by characterizing the manner in which positive or negative indirect effects, mediated through market and non-market channels, influence behavior in undamaged areas, and induce adjustments that amplify or attenuate the initial shock.

The present study answers this call to action. We build on detailed physical modeling of a hypothetical M 7.0 earthquake that generates a highly spatially resolved picture of the overlap between hazards (ground shaking, landslides and post-mainshock fires) and vulnerable assets in multiple economic sectors. In addition to the resulting capital losses (on the order of 2% statewide but nearly 30% in the most heavily damaged regions), we consider the impact pathways of short-term population displacement and longer-run out-migration from damaged areas for county-level labor supply trajectories (which reduce labor input by as much as 15%), as well as the transitory exacerbating effects of damage to transportation infrastructure capital limiting workers accessing workplaces, commodity market intermediation, and counties' ability to mobilize reconstruction investment (up to 7%). We find that these shocks caused all regions in the state undergo a near-complete recovery to their baseline growth trajectories within the span of a decade. Regional hounseholds' attempts to smooth consumption results in substantial interregional resource transfers to support large-scale reconstruction investment in the immediate aftermath of the disaster. In present discounted terms, output losses range between 0.5% and 6%, while welfare losses are 0.4% statewide but can be ten times as large in hardest-hit areas. Increased output via firms engaging in the key adaptive resilience tactic of production recapture can alleviate a substantial fraction of these losses—but only if barriers to upstream and downstream barriers to recovery can be lowered quickly.

Finally, there are several productive directions in which our analysis can be extended. The most straightforward is improving the model's suitability for policy and planning by adding detail: increasing its sectoral resolution, disaggregating additional counties within the Bay Area and surrounding regions, and including a broader range of resilience measures and potential constraints on their implementation. A more ambitious target for future inquiry is the potential for a disaster to shift the growth of economic activity away from the core disaster zone toward peripheral regions. The objective would be to elaborate how earthquakes' impacts on dynamic spatial economies are compounded by feedbacks that are dealt with parametrically here: structural and disaster-related barriers to investment, the implications of affected populations' near-term relocation and long-run migration decisions for regional labor supplies, and the extent to which reconstruction activity itself might attract labor in the short run, and over the longer run, in-migration. Given uncertainties in the mechanisms underlying these outcomes, and the potential for them to endogenously interact, this research would likely entail a substantial empirical component. The payoff is a more nuanced understanding of the implications of recovery processes for interregional growth patterns, and equity. Lastly, our findings highlight the criticality of disaster assistance—not in terms of the overall value of payments, but their timing and effectiveness in remedying cascading bottlenecks to kick-starting the recovery process. Improved characterization of the aforementioned mechanisms and interactions will likely generate opportunities to better identify critical barriers to recovery in core and peripheral locations, and establish understanding on how much of their obstructive effects can be abated through coordinated expenditures. Such knowledge can be of enormous practical benefit to planners and decision makers in shortening the long shadow of major disasters.

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Appendix A. Impacts of the HayWired Scenario with Alternative Disaster Assistance Payment Schedules

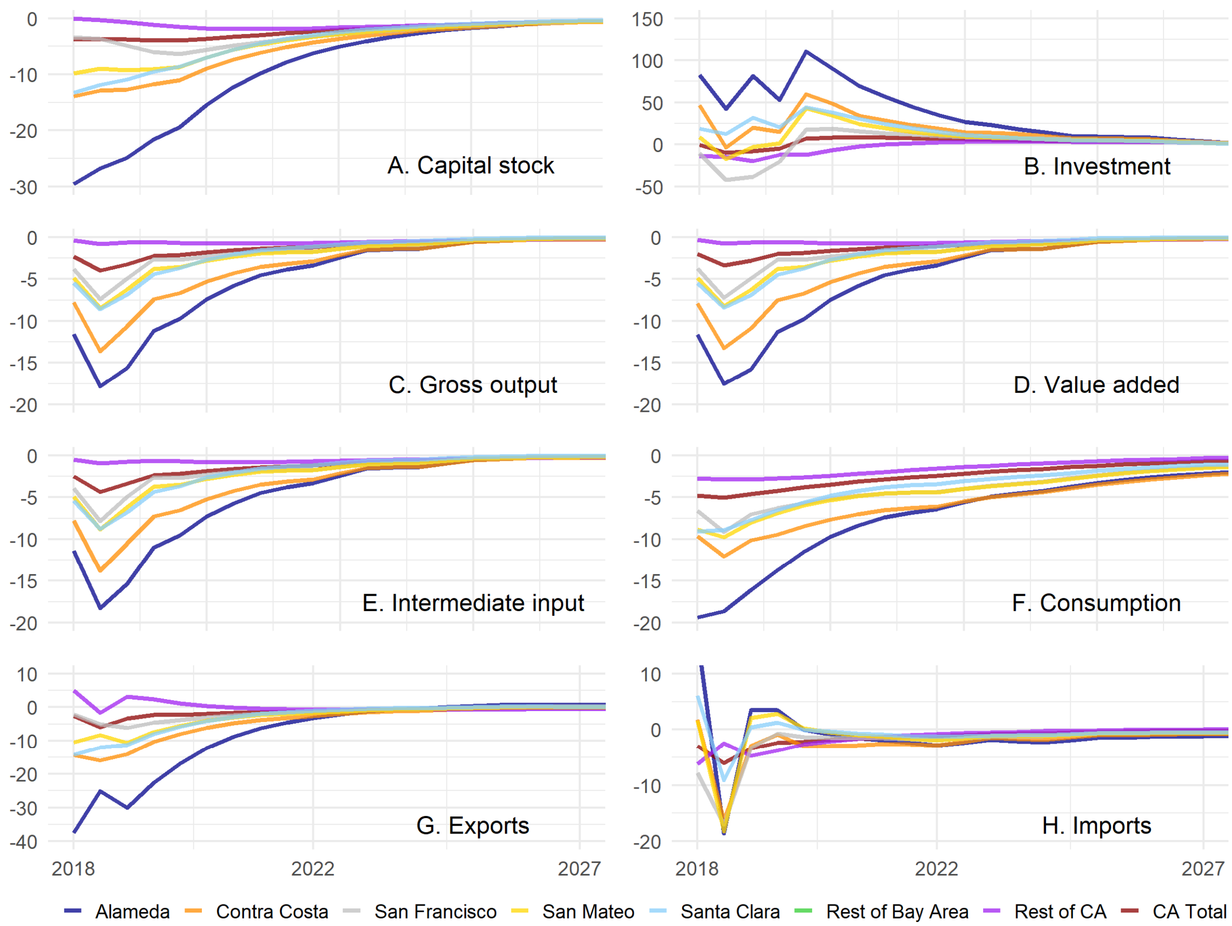

Figure A.1 Impacts of the HayWired Scenario With Production Recapture and 9-Year Disaster Assistance Payment Schedule, 2018-27: % Change Relative to Baseline Regional Trajectories

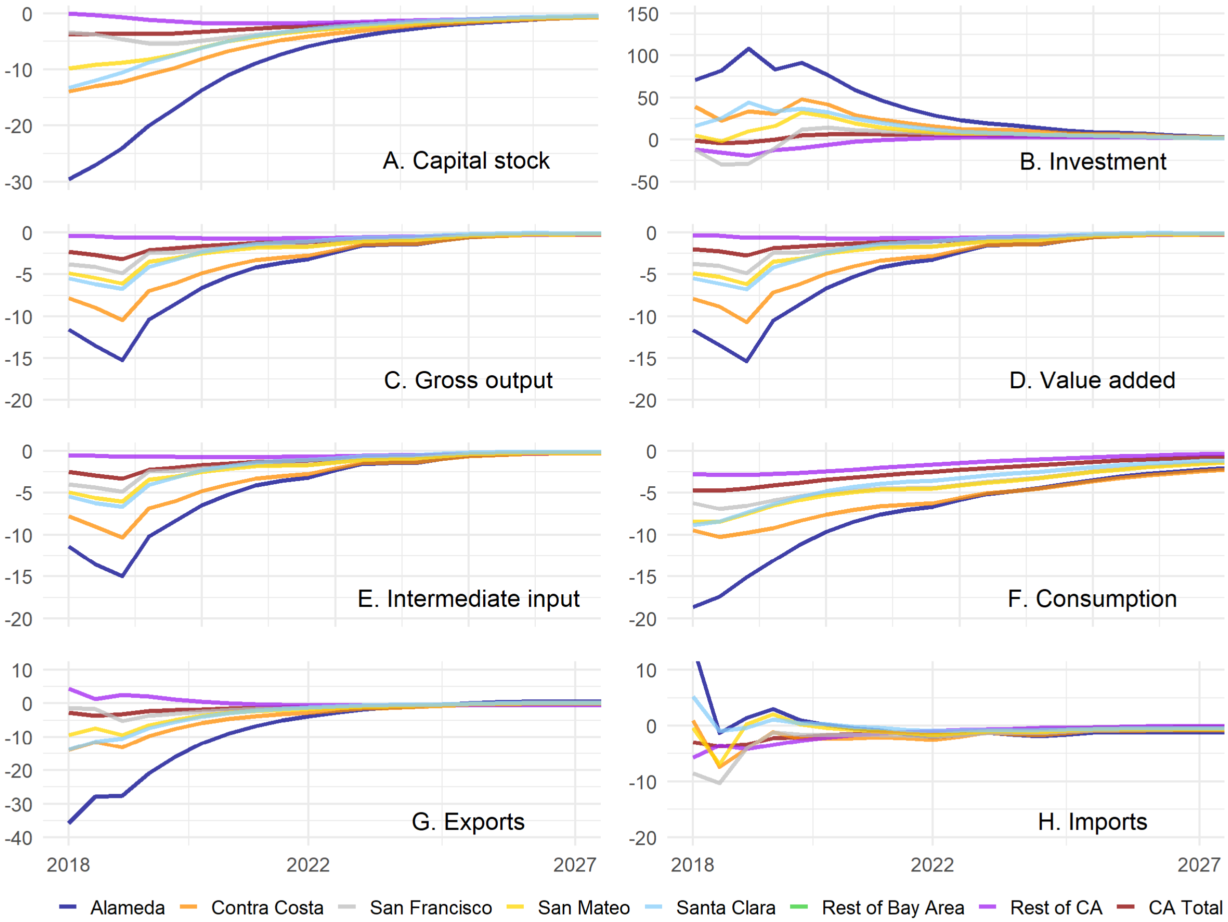

Figure A.2 Impacts of the HayWired Scenario With Production Recapture and 6-Month Restoration Investment, 2018-27: % Change Relative to Baseline Regional Trajectories

Appendix B. Optimal investment allocation for post-disaster reconstruction

The model elucidates the origins of the incentive to invest. New capital formation affects capital input, value-added and output (via eqs. (9), (4) and (3), respectively, as defined in the main text), and, in turn, domestic use and the Armington composite (via (5) and (7)), followed by consumption and contemporaneous utility (via (8) and (2)), and, finally, intertemporal welfare (via (1)). The marginal effect of investment on the social planner's objective can therefore be approximated as:

$$\frac{dW}{dI_r} \approx \frac{\partial W}{\partial U_r}\frac{\partial U_r}{\partial C_r}\left\{\frac{\partial C_r}{\partial I_r} + \frac{\partial C_r}{\partial A_r}\frac{\partial A_r}{\partial D_r}\frac{\partial D_r}{\partial Y_r}\frac{\partial Y_r}{\partial KL_r}\frac{\partial KL_r}{\partial K_r}\frac{\partial K_r}{\partial I_r}\right\} \tag{A.1}$$

The first term in curly braces is an additional dollar of investment's direct opportunity value in terms of forgone consumption, which by (8) simply evaluates to -1. The second term is an additional investment dollar's welfare benefit from increasing the resources available for consumption through the domestic component of Armington supply generated by increased capital and output. The social planner allocates investment to the region in which the expansion of production will yield the highest marginal net benefit in terms of intertemporal welfare. Accordingly, the model preferentially allocates investment to the regions for which the second right-hand side term in (A.1) is largest. This marginal benefit is influenced by the three impact pathways: $\partial D_r/\partial Y_r$ and $\partial C_r/\partial A_r$ affected by transportation disruption shocks in eqs. (5) and (8), respectively, and $\partial KL_r/\partial K_r$ affected by capital and labor losses in eq. (4). For transparency we simplify the rest of our exposition by setting $\Phi_r^T = \Phi_r^L = 1$ in order to focus on capital stock losses and recapture as drivers of investment allocation.

By eq. (1), early in the simulation horizon ($\eta \approx 1$), $\partial W/\partial U_r = \omega_r \eta N_r \approx \overline{C}_r$. By eq. (2), $\partial U_r/\partial C_r = 1/C_r = (\nu_r^C)^{-1}\left(\overline{C}_r\right)^{-1}$. By eq. (9), $\partial K_r/\partial I_{r,0} = \kappa_{r,0}$. Rearranging eqs. (5) and (8) and differentiating, we obtain $\partial D_r/\partial Y_r = \partial C_r/\partial A_r = 1$. In eqs. (3) and (7), input substitution facilitates divergence between the change in the dependent variable from its benchmark levels and changes in the explanatory variables from their respective benchmark levels. Expressing this effect as $KL_r/Y_r = \nu_r^Y\left(\overline{KL}_r/\overline{Y}_r\right)$ and $D_r/A_r = \nu_r^A\left(\overline{D}_r/\overline{A}_r\right)$, we can simplify the marginal products of value-added and domestic commodities composites to:

$$\frac{\partial Y_r}{\partial KL_r} = \alpha_{KL,r}\left(\frac{KL_r}{Y_r}\right)^{-1/\sigma_Y}\left(\frac{\overline{KL}_r}{\overline{Y}_r}\right)^{-(\sigma_Y-1)/\sigma_Y} = \alpha_{K,r}\left(\frac{\overline{KL}_r}{\overline{Y}_r}\right)^{-1}(\nu_r^Y)^{-1/\sigma_Y} \approx (\nu_r^Y)^{-1/\sigma_Y}$$

$$\frac{\partial A_r}{\partial D_r} = \beta_{D,r}\left(\frac{D_r}{A_r}\right)^{-1/\sigma_A}\left(\frac{\overline{D}_r}{\overline{A}_r}\right)^{-(\sigma_A-1)/\sigma_A} = \beta_{D,r}\left(\frac{\overline{D}_r}{\overline{A}_r}\right)^{-1}(\nu_r^A)^{-1/\sigma_A} \approx (\nu_r^A)^{-1/\sigma_A}$$

In eq. (4), with the labor supply fixed, the fall in the quantity of capital input from $\overline{K}_r$ to $(1-\Phi_r^K)\overline{K}_r$ hikes the marginal product of capital:

$$\frac{\partial KL_r}{\partial K_r} = \alpha_{K,r}\left(\frac{K_r}{KL_r}\right)^{-1/\sigma_{KL}}\left(\frac{\overline{K}_r}{\overline{\overline{KL}}_r}\right)^{-(\sigma_{KL}-1)/\sigma_{KL}} \approx \alpha_{K,r}\left(\frac{\overline{K}_r}{\overline{\overline{KL}}_r}\right)^{-1}(1-\Phi_r^K+\Phi_r^R\Phi_r^K)^{-1/\sigma_{KL}}$$
$$\approx (1-\Phi_r^K+\Phi_r^R\Phi_r^K)^{-1/\sigma_{KL}}$$

Investment's marginal welfare product is therefore

$$dW/dI_r \approx (\nu_r^C)^{-1}\{\kappa_{r,0}(\nu_r^A)^{-1/\sigma_A}(\nu_r^Y)^{-1/\sigma_Y}(1-\Phi_r^K+\Phi_r^R\Phi_r^K)^{-1/\sigma_{KL}}-1\} \qquad \text{(A.2)}$$

So long as the relative growth factors ν_r^A and ν_r^Y do not diverge "too" much from unity and the ameliorating effect of recapture is not "too" large", the incentive for reconstruction investment is positive and, if $\sigma_{KL} < 1$, nonlinearly increasing with the fractional loss of capital stock. Thus, the interregional distribution of marginal products—and incentives to invest—follows that of capital damage. Eq. (A.2) also shows that this fundamental pattern can be altered by barriers to reconstruction that lower the productivity of investment, through the impact of the maturation coefficient. In particular, if the magnitude of $\kappa_{r,0}$ is sharply declining with capital destruction, the incentive to invest in core regions that sustain heavy damage may be attenuated to the point that initial investment tends to be allocated to less-affected peripheral areas.