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Dynamic Economic Resilience and Economic Recovery from Disasters: A Quantitative Assessment

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This article analyzes the role of dynamic economic resilience in relation to recovery from disasters in general and illustrates its potential to reduce disaster losses in a case study of the Wenchuan earthquake of 2008. We first offer operational definitions of the concept linked to policies to promote increased levels and speed of investment in repair and reconstruction to implement this resilience. We then develop a dynamic computable general equilibrium (CGE) model that incorporates major features of investment and traces the time-path of the economy as it recovers with and without dynamic economic resilience. The results indicate that resilience strategies could have significantly reduced GDP losses from the Wenchuan earthquake by 47.4% during 2008–2011 by accelerating the pace of recovery and could have further reduced losses slightly by shortening the recovery by one year. The results can be generalized to conclude that shortening the recovery period is not nearly as effective as increasing reconstruction investment levels and steepening the time-path of recovery. This is an important distinction that should be made in the typically vague and singular reference to increasing the speed of recovery in many definitions of dynamic resilience.

KEY WORDS: Computable general equilibrium analysis; dynamic economic resilience; economic recovery; investment; Wenchuan earthquake

1. INTRODUCTION

The magnitude of disasters is increasingly measured by the economic losses they cause. However, recovery from disasters is usually measured in terms of the time it takes to return to a predisaster level, to a projected baseline level, or to what is now referred to as a "new normal"—a sustainable postdisaster level of economic activity. What has not been analyzed adequately to date is the connection between the variability of the time-path of disaster recovery and disaster losses in terms of such major considerations as economic output and employment.

On the one hand, economic recovery from disasters is about the repair and reconstruction of buildings and infrastructure along with social and political institutions, and the rehabilitation of the workforce. These major categories of economic inputs available for production (capital, labor, and institutions) are fixed quantities, or stocks. On the other hand, what is variable is the lost flow of economic activity between the point at which the disaster strikes and the point at which recovery is completed. This is determined primarily by the duration and time-path of the recovery.

Recovery from a disaster and its time-path are linked through the concept of *resilience*, of which

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Rose[1] has distinguished two types. *Static economic resilience* refers to the efficient use of remaining resources at a given point in time and is linked to compensating for deficiencies in the availability of production inputs by way of tactics such as conservation, substitution, accessing inventories, and relocation. *Dynamic economic resilience* refers to efficient investments in repair and reconstruction as a means of accelerating and shortening recovery. It is dynamic because it is obviously related to the time-path of the economy, but also because investment, which is required to repair/reconstruct capital and to rehabilitate labor, defers current consumption for the purpose of rebuilding capacity for greater future consumption. Ayyub[2] has also concluded that "enhancing community and system resilience could lead to massive savings through risk reduction and expeditious recovery." The variability of recovery is thus linked to resilience in the sense that both an accelerated (e.g., jump-starting rather than, say, linear or logistic) pace and shorter duration of recovery than normal can further reduce lost economic activity.

Much attention has been paid to mitigation to prevent the destruction of buildings and infrastructure, but lost economic output, a prominent indicator of "business interruption" (BI), can be even larger than property damage in major disasters, in part because of supply-chain reactions that radiate outward from the site of the disaster.[5] This is the case for the September 11, 2001, World Trade Center Attacks,[3] Hurricane Katrina,[4] and the Wenchuan earthquake.[5] Mitigation reduces potential BI as a joint product along with its protection of the capital stock, but the potential of dynamic resilience to reduce some of the remaining BI losses has not yet been adequately quantified.

The purpose of this article is to analyze the role of dynamic economic resilience in relation to recovery from disasters in general and to illustrate its potential in a case study of the Wenchuan earthquake. We first offer operational definitions of the concept linked to policies to promote increased levels and speed of investment in repair and reconstruction. We then refine a state-of-the-art modeling approach—dynamic computable general equilibrium (CGE) analysis—to incorporate major features of investment in repair and reconstruction and to trace the time-path of the economy as it recovers with and without dynamic economic resilience. We examine alternative forms, levels, and timings of investment to reduce BI through such dynamic resilience strategies as increased insurance compensation, rapid collection of investment funds, and adoption of new reconstruction technologies. We use the term "accelerating recovery" in our definition of dynamic resilience to capture aspects of steepening the time-path of recovery, as opposed to just reducing its duration. We find that shortening the recovery period is not nearly as effective as increasing and hastening the implementation of reconstruction investment levels (i.e., steepening the time-path) of recovery.

The next section of this article summarizes the concept of economic resilience and provides examples of actual recovery and accelerated recovery (dynamic economic resilience) in response to the Wenchuan earthquake. Section 3 presents a dynamic CGE model that has been refined to incorporate major aspects of dynamic resilience through the investment process and also summarizes the data used. Section 4 presents and interprets the results. Section 5 presents conclusions and policy implications.

2. DYNAMIC ECONOMIC RESILIENCE

2.1. Resilience Definitions

Modern interest in resilience stems from the work of scientists in the field of ecology 40 years ago,[6] and its use has spread widely since to the fields of engineering, organizational behavior, planning, psychology, sociology, and economics. Most applications have been to coping with short-term disasters, but, more recently, it has been extended to adaptation to long-term climate change. Although resilience has specific characteristics in each different field, it also has much in common across them.[7] The original Latin word resilience means "rebound." In ecology, it refers to "the ability of systems to absorb changes,"[6] or to "buffer capacity"[8] or to "the decrease relative to the potential decrease from the external shock."[9]

Following Rose,[1,10,11] static economic resilience refers to the ability or capacity of a system to maintain function (continue production) when shocked. This is consistent with the core theme of economics

[5]We refer to both first-order and higher-order impacts on economic activity. "First-order" refers to impacts of businesses directly affected by the disaster (and hence often referred to as "direct" effects), and "higher-order" refers to the various rounds of ripple effects on other businesses (which are often referred to as "indirect" or "general equilibrium" effects, depending on the type of model used to estimate them) (see, e.g., Rose[24] and Okuyama[25]).

of how best to allocate scarce resources, which become even more scarce in the aftermath of a disaster. Rose defines dynamic economic resilience as the ability and speed of a system to recover from a shock. It involves the efficient use of resources over time for investment in repair and reconstruction. However, we further delineate this definition to separate the term "speed" into two components: the shape (pace) and the duration of recovery (see more below).

Economic resilience refers to actions taken following a disaster, rather than before a disaster. Predisaster behavior is mainly focused on reducing vulnerability through mitigation. In addition, economic resilience focuses on the reduction of disruption of the *flow* of goods and services, often referred to as BI, stemming from the reduced capital *stock*. In contrast to property damage, which takes place at the point when the disaster strikes, BI begins at that point and continues until the economy has recovered or reached a new normal. At the same time, we acknowledge that resilience is a process, whereby resilience capacity can be enhanced prior to a disaster (e.g., increasing inventories, purchasing portable electricity generators, holding emergency management exercises, developing an orderly procedure for the processing of insurance claims, or providing government assistance), but is not implemented until after the disaster.

Both static and dynamic economic resilience have inherent and adaptive aspects.[(1)] *Inherent* ability prevails under normal circumstances (e.g., ability of individual firms to substitute other inputs for those curtailed by an external shock, or the ability of markets to reallocate resources in response to price signals). *Adaptive* ability is applied during crisis situations through ingenuity or extra effort (e.g., increasing input substitution possibilities in individual business operations, or strengthening the market by providing information to match suppliers without customers to customers without suppliers). Furthermore, economic resilience pertains to the economy at three levels: microeconomic (individual business or household); mesoeconomic (individual industry or market); and macroeconomic (combination of all economic entities, including their interactions).

This article focuses on dynamic resilience, including both inherent (e.g., increased imports to satisfy reconstruction investment goods demand) and adaptive resilience (e.g., use of new technology during reconstruction). Dynamic resilience is also applicable at three levels: micro- (e.g., dispensing disaster assistance funds for repair and reconstruction of businesses as soon as possible), meso- (e.g., new technology adoption), and macroresilience (e.g., planning the reconstruction process as early as possible).

The most comprehensive examination of dynamic resilience at the conceptual level thus far is that of Pant *et al.*[(12)] They define the concept as: "best understood in the context of the speed of system recovery," or rapidity, but then provide the additional insight that there is a tradeoff between system "operability" (functionality) and rapidity in reducing losses, citing sectoral interdependence as the main consideration. In our analysis below, we also identify a tradeoff, but explain it in terms of conditions affecting the shape of the recovery time-path and its duration.

2.2. Dynamic Economic Resilience Metric

Referring again to Rose,[(1,10)] dynamic economic resilience then has two aspects:

- the ability to recover
- the ability to recover rapidly.

The first of these is typically straightforward and can readily be observed and measured. It simply requires a "yes" or "no" answer.

The second aspect is much more complex than it might appear on the surface. Initially, it is important to distinguish resilience and recovery—they are not the same thing. Dynamic resilience represents the possibility of both an acceleration in recovery and reduction in its duration (the "recovered rapidly" aspect of the definition above). However, this requires a reference base, or baseline, by which to measure the accelerated, or more rapidly proceeding, recovery. We refer to this baseline as a "reference recovery scenario." The problem is how to define this reference case. Alternatives include:

(1) A historical average of recovery durations.
(2) A recovery duration in the aftermath of an actual event, such as the Wenchuan earthquake. The problem here is whether the recovery process was business as usual or if any measures were taken to accelerate it, and, if so, how to separate out the latter set.
(3) A conceptualized approach which could take either of the following two forms:
    (a) A stylized version based on the use of only a presumed level of investment funds and putting new capital in place at a standard pace. This would refer to existing

insurance coverage, a presumed level of relief funds held by the government of the effected region, and standard amounts of outside government and private aid. Still, it would require additional measurement and some simplifying assumptions to pin these down.

(b) A self-sufficiency version based on the use of only investment funds available within the region and excluding external amounts. This is an extreme case, but might be used where there is an emphasis on sustainability.[(13)]

In our analysis, we are dealing with an observable historical event. However, more information is needed, so we will utilize a combination of (2) and (3a) above for our reference case. Essentially, we begin by calibrating our model to historical data on recovery and then using the model to estimate the time-path. There is obviously an actual recovery time-path, but only a few select data points are known, and thus modeling is necessary. We use alternative (3a) in the sense that the historical recovery path does not include any accelerating features. We realize the limitations of our assumptions, but emphasize that our analysis is more about the *difference* between the dynamically resilient time-path and the reference case, or baseline, path, than the position of the latter itself.

We will then factor in the following three features to apply our model to the estimation of the dynamically resilient time-path:

- Additional insurance payments.
- Rapidly collected investment funds.
- Investment with new technology.

The difference between the two time-paths represents the contribution of dynamic economic resilience to accelerating the initial stages of recovery and also shortening its duration, both reducing BI losses. Note that dynamic economic resilience depends on effective investment, but that it is not measured by the level of investment but either by the duration and time-path of recovery, or, in economic terms, by the reduction in BI losses.[6]

2.3. Specific Examples of Actual Recovery and Dynamic Resilience in the Aftermath of the Wenchuan Earthquake

The Wenchuan earthquake occurred on May 12, 2008, with the epicenter located at Yingxiu Town, Wenchuan County, Sichuan Province of China (31.01° N, 103.40° E). The earthquake had a magnitude of M_s 8.0 and was the most destructive and widespread earthquake since the founding of the People's Republic of China (PRC), with 69,226 dead and 17,923 missing. The property damage from the earthquake reached 845.2 billion Chinese Yuan (CNY). In Sichuan Province, GDP grew by 14.5% both in 2007 (a year before the earthquake) and 2009 (a year after the earthquake). However, this growth rate was reduced to 11% in 2008, when the Wenchuan earthquake occurred. We analyze specific examples of the dynamic resilience strategies adopted in the aftermath of the Wenchuan earthquake and analyze how they helped reduce economic output losses (BI), and how some of the strategies could further do so if enhanced.

2.3.1. *Interregional Counterpart Aid*

This policy implemented after the earthquake emanated from the 19 nonaffected provinces providing support to the 24 disaster-affected counties (cities, districts) by providing manpower, material assistance, and technical assistance.[(14)] This strategy helped speed up recovery, and thus reduce BI. Specifically, the nonaffected areas provided in-kind workforce aid to the affected areas, of at least 1% of the previous year's local fiscal revenue of the nonaffected provinces.[(15)] This step ensured a basic minimum of the funding needed for recovery and reconstruction. Second, this strategy ensured that each affected jurisdiction received relief and avoided oversupply of relief to just one epicenter or a few of

[6]We note that there are several definitions and metrics of resilience in general and dynamic resilience in particular. For a recent example, the reader is referred to Hallegatte *et al.*,[(26)] who use the ratio of asset losses to welfare losses due to a disaster. The counterpart of our metric in relation to this formulation would be the ratio of BI (GDP loss) to GDP. While the Hallegatte *et al.* approach has an advantage when making cross-region or cross-country comparisons, we do not see advantages over our metric on net. This measure does not capture improved conditions from individual resilience strategies. If the measure is used in terms of changes associated with resilient actions, then the numerical value of the percentage change is likely to be similar to ours. We do note that using current economic welfare as a base would seem to be on more solid footing than projecting a baseline time-path, but the reference base time-path of most economies can reasonably be estimated, as we have done. Also, for recovery periods of more than a couple of years, even the metric by Hallegatte *et al.* would need a projection of welfare to be accurate, which then places their metric in the same position as ours in this regard.

the affected areas. Third, the worst hit areas were among China's poorest western regions, but the assistance was provided by eastern and central areas of China, which are more developed. In addition to promoting interregional equity, the measures ensured that advanced technologies were employed in the reconstruction process.

2.3.2. Interregional Reconstruction Funds Transfer

During the reconstruction process, besides the financial support from local government, the nation established an Earthquake Reconstruction Fund set up by the central government, acquired financial support from "counterpart assistance," and obtained private donations from the community. This embodied China's tradition of "when disaster strikes, help comes from all quarters." In total, about 93% of reconstruction funds came from outside the disaster area. If the reconstruction funds were sourced from within the disaster area, it would further squeeze its dwindling investment funds and exacerbate the economic impacts of disasters. The additional funds provided by nonaffected areas also helped restore the production capacity of the disaster area, thus further reducing BI.

2.3.3. Rapid Planning and Logistical Implementation

This refers to rapid completion of the reconstruction planning and approval processes, and early start of the reconstruction process. A relatively longer period after disaster is needed for organizing and implementing the reconstruction activity. However, if the government can plan and finish the approval process more rapidly, the reconstruction action can begin earlier, thus shortening the recovery period. Due to highly efficient and organized planning and logistical implementation by the local government after the Wenchuan earthquake, many reconstruction projects began in 2008 and 20% of all reconstruction tasks were completed that year. If it takes less time to remove the debris, to obtain new building permits, to plan and sequence the reconstruction, a larger portion of investment funds can be used in the early years after the disaster, and this leads to improving dynamic economic resilience.

2.3.4. Increased Insurance Compensation

The ratio of insurance compensation for property damage loss after the Wenchuan earthquake was merely 0.3%, which is far below the global average ratio of 40% for such similar disasters.[15] However, it still provided some funds for the earthquake reconstruction, especially important for some micro enterprises. China is further developing its catastrophe insurance regulations, which, when implemented, are expected not only to increase the amount of reconstruction funds, but also enable disaster-affected areas to obtain reconstruction funds more quickly and to start the reconstruction process as early as possible.

2.3.5. Rapidly Collecting Funds for Reconstruction

The official reconstruction period for the Wenchuan earthquake spanned 2008–2010, where 20% of funds were collected in 2008, 40% in 2009, and the rest in 2010 (2:4:4 proportion). The sudden nature of earthquakes often runs counter to government expenditure planning, making it difficult to accumulate large amounts of funds for reconstruction during the disaster year. However, during the year in which the Wenchuan earthquake occurred, the central government made great efforts to accumulate 20% of the total reconstruction funds, which helped speed up reconstruction, and thereby reduced the time direct BI took place due to damaged plant/equipment/infrastructure, and reduced the time indirect BI took place due to disrupted supply chains.

2.3.6. Adoption of New Technologies

The use of advanced construction methods and the purchase and installation of high-tech machinery and equipment during reconstruction undoubtedly sped up the reconstruction process and improved the quality of the effort. After the reconstruction, the new plant, equipment, and upgraded infrastructure further improved production efficiency and reduced BI.

Although the postearthquake reconstruction of Wenchuan is one of the largest and most well-planned reconstruction activities in China's history, it was not perfect. For example, the insurance coverage was very low, collection of reconstruction funds could have been much faster, and not all the latest technology was adopted for the reconstruction efforts. Moreover, we have stated the official figures released by China's government, and, while these figures suggest that the response was unprecedented in China's recent history, they are still far from optimal.

The major motivation for this research is to suggest further improvements in the response to the 2008 earthquake, as exemplified by the dynamic resilience scenarios of this study.

3. RESEARCH METHODS, SCENARIO DESIGN, AND DATA BASE

3.1. CGE Model

CGE modeling is the state-of-art tool for assessing total economic impacts of disaster and economic resilience.[16–18] It models the economy as a set of interactions among sectors (a type of sector-level supply-chain representation) responsive to changes in prices and to external shocks, so it is especially adept at capturing indirect, or general equilibrium, effects. The ability to capture these interdependencies is very important in modeling various dimensions of resilience.[12,19] In static resilience assessment, its advantage is the ability to model many production function responses, such as input substitution and conservation, as well as market reallocation. In dynamic resilience, its advantage is the ability to trace sources and recipients of reconstruction funds and capital goods and their effects on the duration and time-path of economic recovery.

The CGE model employed in this study is a Sichuan provincial CGE model. The data for the model, regional social accounting matrix (SAM), are benchmarked to the year 2007, as are the elasticity parameters, just one year before the earthquake. Our model employs the basic structure of DRC-CGE model (a CGE model developed by the Development Research Center of the State Council of China), which contains production, consumption, investment, trade, government, business, trade modules, and several macroclosure options and dynamic modules.[20] The enhanced version of the DRC-CGE model used here is of a recursive dynamic form, with the following adjustments to achieve a market equilibrium, as well as macroclosure rules to reflect the characteristics of dynamic resilience and economic recovery:

- Incorporate property damage due to disasters by reducing the amount of capital stock in each sector.
- Simulate postdisaster reconstruction investments according to the amount of available reconstruction funds.
- Vary reconstruction investment according to different assumptions about the pace of investment.
- Vary the source of interregional investment fund transfers to reflect the impact of interregional relationships on recovery process.
- Increase labor supply to stimulate economic recovery over time to reflect the return of local workers from other provinces and the temporary supply of nonlocal workers during the reconstruction period.
- Incorporate new technology that also stimulates rapid recovery during the reconstruction process and after the restoration of productive capacity.

3.1.1. Market Equilibrium

We improve market equilibrium of the DRC-CGE model in three respects.

Standard market clearing (supply–demand balance) is improved with Equation (1) below by dividing the total investment into infrastructure and business reconstruction investment, residential reconstruction investment, and normal investment (the investment in least damaged sectors, which is assumed to follow the predisaster annual investment growth rate to expand ordinary production capacity). Damage to houses is the main component of total property damage. Moreover, residential reconstruction investment accounts for a relatively large proportion of the total reconstruction investment (the sum of infrastructure and business reconstruction investment and residential reconstruction investment). Nevertheless, the capital stock formed from residential reconstruction investment hardly contributes to expanded production in the next period.[4] Thus, residential reconstruction investment mainly exerts a positive impact on the demand side of the economy and will have little impact on the supply side. However, infrastructure and business reconstruction investments are key to reestablishing production capacity:

$$XA_i = \overbrace{\sum_j XAp_{i,j} + QH_i + QLC_i + QGC_i + QINVn_i}^{\textbf{Local normal demand}} + \overbrace{QINVh_i + \sum_j QINVd_{i,j}}^{\textbf{Reconstruction demand}}, \quad (1)$$

where XA is the supply of commodity, XAp is the intermediate demand, QH is the household demand, QLC and QGC are local and central government demands, respectively, $QINVn$ is normal investment, $QINVh$ is residential reconstruction investment, and $QINVd$ is infrastructure and business reconstruction investment. "i" represents commodity i; "j" represents industrial sector j.

Standard CGE models balance the labor market under either the "neoclassical" assumption of full employment (perfectly inelastic supply) or the "Keynesian" assumption of variable employment (elastic supply at a fixed wage). Although disasters have significant effects on both labor supply and wage rates, the standard closure rules hold either labor supply or wages constant.[15] Therefore, we model labor flows among different sectors through the use of constant elasticity of transformation (CET) functions, in which labor is a variable factor whose endowment is price responsive. This is achieved by specifying a short-run labor supply curve with elasticity ω, which scales the labor supply from its benchmark level LS_0 (Equation (2)):

$$LS = LS_0 * W^{\omega}, \tag{2}$$

where LS is the labor supply, LS_0 is the labor supply in the base period, W is wages, and ω is the price elasticity of the labor supply.

Finally, all industries suffer huge capital stock losses from a disaster, so they all increase investments in the reconstruction period. We assume that capital is sector specific within the reconstruction period to eliminate the possibility of making up a sector's production capacity deficit by simply shifting capital between sectors. Given the specialized nature of most modern production processes, we deem this to be a reasonable assumption.

3.1.2. Macroclosure

The amount of investment is exogenous and is determined by total savings, which in turn is specified as endogenous, as well as from exogenous sources. For reconstruction investment, the funds can come from the total savings in the disaster-affected area (such as household savings, company profits, and local government subsidies) or from other regions (such as private donations, central governmental subsidies, and even foreign aid). Reconstruction funds can be used to produce the investment goods in the disaster area or to import these goods from other regions. First, when the model assumes that all of the reconstruction funding comes from nonaffected areas, the total savings of the disaster area are not affected due to extra reconstruction demand. This can further ensure normal consumption and investment for the disaster area. Second, when the model assumes some reconstruction funding is provided by the disaster areas themselves, their total savings are increased accordingly. Moreover, the normal consumption and investment in the disaster areas are displaced.

3.1.3. Dynamic Module

In addition to infrastructure and business and residential reconstruction investments, we model a baseline predisaster level of investment, which we term "normal investment." In this model, normal investments are distributed among various industries based on the industry investment structure in the base year, and then transformed into the capital stock (XCn) in the following period according to the investment coefficient matrix (B matrix) (Equation (3)).[21] The infrastructure and business reconstruction investments are also transformed into capital stock (XCd) according to the B matrix, and the distribution of transformed capital stocks among industries is determined by the proportion of property damage suffered by those industries (Equation (4)).

The model includes a separate housing sector. The damage to housing inventory will bring forth increased investments, but no contribution to the capital stock of industries. In each period, the damaged housing capital stock (XCh) is calculated by multiplying the total reconstruction investments in that period with the ratio of the housing sector's property damage to the total property damage. Then, according to the B matrix, the capital stock (XCh) required for housing reconstruction is derived from investment goods of various industries (Equation (5)):

$$XCn_i = B_{i,j}^{-1} QINVn_i, \tag{3}$$

$$XCd_i = B_{i,j}^{-1} \sum_j QINVd_{i,j}, \tag{4}$$

$$XCh = B_{h,j}^{-1} QINVh_i. \tag{5}$$

In actual practice, some damaged equipment, such as excavators used in the construction industry, was imported from other areas, instead of waiting for it to be produced locally in the disaster year (computationally, this is accomplished by increasing

Table I. Property Damage due to the Wenchuan Earthquake by Sectors in Sichuan Province (CNY 100 Million)

Sector	Damage	Sector	Damage
Agriculture	120.0	Transportation	895.5
Mining	205.8	Information services	365.4
Manufacturing	524.2	Commerce	800.3
Electricity utilities	634.4	Real estate	200.0
Gas distribution	40.8	Education services	1258.4
Water services	43.4	Housing services	2025.8
Construction	17.6	Total	7131.5

the appropriate import commodity in the model and directly transferring it to capital stock in the same year). In order to estimate this offsetting factor of reconstruction, in the CGE model, a portion of the capital stock is restored in the first year (*Transfer*), and, beginning in the second year, the remaining stock (*XCn* and *XCd*) is restored according to the "perpetual inventory process"(Equation (6)):

$$KStock_i = (1 - \delta_i)(KStock_{i,-1} - Damage_{i,-1} + Transfer_{i,-1}) + XCn_{i,-1} + XCd_{i,-1}, \quad (6)$$

where *KStock* is capital stock, δ is depreciation ratio, and *Damage* is property damage.

3.2. Scenario Design and Data Preparation

We establish the baseline scenario ("without-disaster" scenario), reference recovery scenario, and dynamic resilience scenario as follows:

- Baseline scenario: a nondisaster scenario in which capital stock was not reduced and the normal investment growth rate was maintained at the average of the past five years, i.e., 19%; GDP (an exogenous variable) of Sichuan Province grew 14% annually from 2008 to 2011, a growth rate of those provinces whose economic development level is similar to that of Sichuan Province.
- Reference recovery scenario: This focuses on reduced capital stock due to disaster and actual postdisaster reconstruction. For the damaged capital stock, because the disaster occurred in May 2008, the replaced capital stock is assumed to be half of the property damage loss in that year (property damage losses of specific industries are described in Table I). Beginning in 2009, the remaining reduced amount of capital stock has been calculated according to aggregate property damage loss. For the postdisaster reconstruction, we distinguish normal investment and reconstruction investment. The distribution of normal investment (in relation to the reference recovery scenario) among different sectors also maintains its 2007 ratios. Reconstruction funds from various sources are summarized in Table II, where "-" indicates that the data for that year are unavailable. We see that the funds from outside the disaster area—central government, counterpart assistance, donations, and insurance compensation—accounted for more than 90% of the total reconstruction funds. The proportion of annual funds collected during 2008–2010 was about 2:4:4 across the three years. Total factor productivity (TFP) improvement is set as an exogenous variable and is equal to 2% on an annual average basis (we note that besides TFP growth, economic growth was also driven

Table II. Reconstruction Investments Supported by Government over the Three Years after the Wenchuan Earthquake (CNY100 Million)

	Year	2008	2009	2010	Sum
Reconstruction funds source	Central government	498.93	1085.98	618.52	2203.43
	Local government[a]	–	177.46[b]	55.52	232.98
	Counterpart assistance	–	–	–	843.80
	Private donations[c]	–	–	–	760.22[d]
	Insurance compensation	–	–	–	16.60

[a]Only Sichuan Province.
[b]Accumulation of 2008 and 2009.
[c]Private philanthropies or charitable contributions within China and from outside such as from international NGOs.
[d]Includes the majority of special communist party dues of 9.73 billion Yuan, other donations of 55.582 billion Yuan, and donated material discount of 10.71 billion Yuan.

by the capital accumulation due to the 19% normal investment increase, and additional reconstruction investment).

- Dynamic resilience scenario: Despite all sectors having taken various recovery measures, China still has the potential to increase its dynamic resilience. According to the postdisaster reconstruction experience in other developed countries, China could implement further dynamic resilience through the following strategies without any increase in constrained aggregate public reconstruction investment funds as in the reference recovery scenario:

  - Additional insurance payments. The actual ratio of insurance compensation for property damage loss after the Wenchuan earthquake was only 0.3%. We refer to the international average level (40%) and assume that after implementation of China's catastrophe insurance regulation, earthquake insurance compensation in China could reach up to 20% of the property damage losses (half of the international average level). It is difficult to increase earthquake insurance penetration in any country. Ironically, due to the very low baseline penetration in China, it is possible to increase the penetration significantly percentagewise, which actually has been the case in China. Meanwhile, our modeling approach to post-disaster reconstruction only partially depends on insurance, as it is only one of several ways to surmount the challenges of collecting sizeable funds for reconstruction.
  - More rapidly collected reconstruction funds. The actual proportion for the Wenchuan earthquake for raising reconstruction funds during the three years following the disaster was 2:4:4. By accelerating the reconstruction schedule, there is a potential to further shorten the time for clearing up the rubble, reconstruction planning and approval processes, and the start of reconstruction activity. We assume that China can raise the disaster reconstruction funds at the same pace as that of the U.S. ArkStorm scenario reconstruction, where the ratio for disaster reconstruction funds raised during the postdisaster three-year period was 5:2.5:2.5 (i.e., 50% of the total in year 1, and 25% of the total in each of the following two years).[18,22] We acknowledge the difference between planned (potential) resilience and executed (actual) resilience. Some of the postdisaster assistance may never translate into actions on the ground, for multiple reasons (diversion, administrative costs, corruption, or procurement issues). Also, the constraints to reconstruction are not only financial but also technical (e.g., not enough skilled workers). In that case, increasing the financial investments will only lead to general inflation due to an increase in the wage and cost of scarce resources, not to an accelerated reconstruction.
  - Reconstruction with implementation of new technology. If the reconstruction planning encourages adoption of new technologies and the plant and equipment also use more advanced products, the productivity of firms will be further enhanced. For this, the TFP is set to increase by an additional 1% over the reference recovery scenario.

4. SIMULATION RESULTS

The Wenchuan earthquake struck in 2008 and the main reconstruction investment by the government occurred in the period 2008–2010. But investment made in 2010 only turned into new real infrastructure and plant/equipment in 2011, and did not affect economic production capacity until 2011. Therefore, in Fig. 1 we show the GDP trend from 2007 to 2011 under three scenarios:

- "Baseline scenario."
- "Reference recovery scenario" (this is our simulation approximation of the actual recovery).
- "Dynamic resilience scenario."

In both the dynamic resilience scenario and reference recovery scenario, during the earthquake year (2008), the efforts were partially focused on disaster emergency rescue, clearing debris and reconstruction planning, etc., so the actual reconstruction work was relatively slow. Even though part of the reconstruction funds were raised during the disaster year, time and execution are required for this investment to turn into new plant, equipment, and infrastructure, which usually happens during the next year. Therefore, the economic conditions in

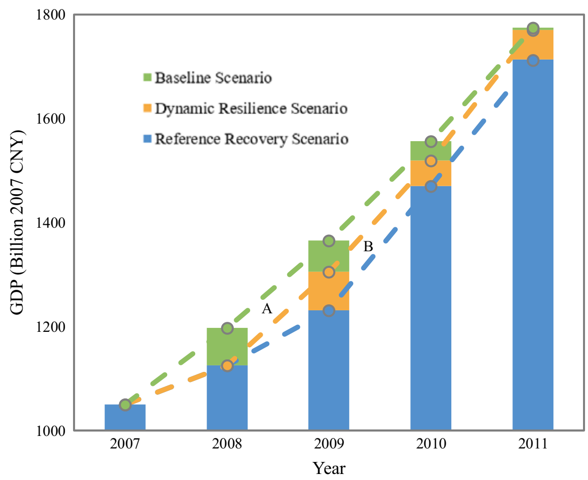

Fig. 1. Comparison of reference recovery and dynamic resilience scenarios during reconstruction to reduce BI.
Note: Area A = minimum loss; Areas A+B = maximum loss; the dashed lines only represent connecting lines of annual GDP loss after the disaster, rather than the evolution paths of daily or monthly GDP losses after the disaster.

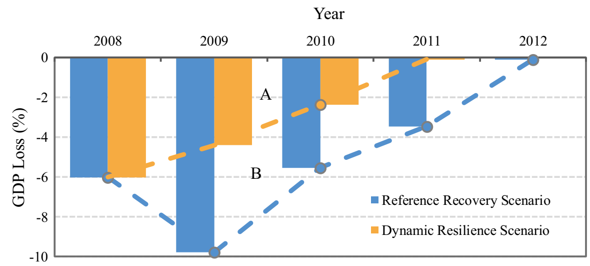

Fig. 2. Evaluation of dynamic resilience to shorten the recovery period and reduce BI.
Note: Area A = minimum loss; Areas A+B = maximum loss; the dashed lines only represent connecting lines of annual GDP loss after the disaster, rather than the evolution paths of daily or monthly GDP loss after the disaster.

2008 under both the dynamic resilience scenario and the reference recovery scenario are almost the same, and are both far worse than the economic situation under the baseline scenario.

After 2009, large-scale reconstruction work was started, so the economic conditions under the reference recovery scenario have apparently moved closer to the ones under the baseline scenario. Subsequently, due to more capital formation, economic conditions improved more rapidly during 2010 and 2011. Under the reference recovery scenario, the destruction of the capital stock is offset partially by the formation of fixed assets per year, and the gradual TFP increases each year due to technological progress; therefore, the economy continues to grow every year during the postdisaster period. When compared with the baseline scenario, since only part of the destroyed assets is rebuilt, the economic growth rate is far below the baseline scenario. Comparison of the dynamic resilience scenario and the reference recovery scenario shows that the former more closely tracks with the baseline scenario because more investment funds are accessed and at a faster pace.[7]

In Fig. 1, dynamic resilience reduced maximum economic loss from BI due to the Wenchuan earthquake (the combination of areas A and B) to a reduced level (area A). Compared with the baseline scenario, under the reference recovery scenario, maximum BI, measured using GDP loss in Sichuan Province, would be about 353.21 billion Yuan during the period 2008–2011; on average, this translates into the annual GDP growth rate falling by 1.0%. Under the dynamic resilience scenario, BI is 185.92 billion Yuan, with the average annual GDP growth rate falling by only 0.3%. Clearly, compared with the national economic growth target of an average 8% annually, the 1.0% drop in Sichuan Province's GDP due to the Wenchuan earthquake is significant, but under the dynamic resilience scenario, the GDP growth rate reduction is substantially reduced.

Reducing the length of the disaster recovery period is also one of the objectives of postdisaster reconstruction and can further reduce BI. In Fig. 2, we can observe the postdisaster GDP loss ratio relating to length of the recovery for the two recovery scenarios. Under the reference recovery scenario, the worst economic condition is in 2009, rather than the year the disaster occurred. This is because the Wenchuan earthquake occurred in May 2008, so the destruction of buildings, equipment, and infrastructure had only half a year to affect the economy that year, while it had the whole year to affect the economy in 2009. Moreover, new capital formation from reconstruction investment is relatively small in 2009—just

[7]We acknowledge our study does not reflect the reconstruction efforts of households, which lead to a reduction of other expenditures. However, household reconstruction efforts only affect the composition of household expenditure and do not necessarily change their total expenditure. Therefore, it is likely not to affect aggregate indicators of the economy, such as GDP. In all three scenarios of our study, we assume that total baseline investment after the disaster grew at the five-year predisaster average growth rate (see Subsection 3.2). This total investment also includes household investment.

Table III. Relationship between Dynamic Resilience and Economic Recovery

	2008–2011			2008–2012		
	GDP Loss[a] (level)	GDP Loss (%)	Dynamic Resilience (%)	GDP Loss[a] (level)	GDP Loss (%)	Dynamic Resilience (%)
Reference recovery scenario:[b]	**−353.2**	**−5.1**	–	**−355.7**	**−4.0**	–
Investment using funds from other provinces	−478.0	−6.9	–	−574.1	−6.4	–
Investment using funds from central gov't	−447.7	−6.4	–	−520.9	−5.8	–
Investment using funds from affected province	−513.0	−7.4	–	−635.6	−7.1	–
Investment using funds from private donations	−481.9	−6.9	–	−580.9	−6.5	–
Dynamic resilience scenario:[b]	**−185.9**	**−2.7**	**47.4**[c]			
Additional insurance payments	−284.0	−4.1	20.0			
Rapidly collected funds	−317.1	−4.6	10.2			
Investment with new technology	−305.7	−4.4	13.4			

[a]GDP loss is measured in billion 2007 CNY.
[b]The effects of the reference recovery scenario (Row 1) and dynamic resilience scenario (Row 6) are further divided into contributions from individual relief processes.
[c]Subtotals do not add up to column entries because of interaction among the effectiveness of individual resilience strategies.

20% of the total reconstruction investment—so the reference recovery measures could not effectively stop the GDP loss. While under the dynamic resilience scenario, as the postdisaster reconstruction investment allocation ratio is adjusted, the new capital formation from reconstruction investment in 2009 grows more rapidly to 50% of the total reconstruction capital accumulation. Furthermore, catastrophe insurance payments enlarged the sources of reconstruction funding and new technologies were also adopted. Thus, the economy would have begun to recover quickly beginning in 2009 with dynamic resilience.

Fig. 2 shows that under the dynamic resilience scenario, the GDP loss ratio in 2011 is almost zero because the economy had almost recovered to the baseline level. However, under the reference recovery scenario, the GDP loss ratio in 2011 is still large. The GDP loss ratio with reference recovery did not approach zero until 2012, reflecting that the postdisaster economy had basically recovered to the baseline level. Apparently, the recovery period is one year longer under the reference recovery scenario compared with the dynamic resilience scenario. The figure also depicts the difference between the maximum and minimum loss areas for our scenarios.

As a counterpart to Fig. 2, Table III further elaborates the relationship between dynamic resilience and recovery by presenting and decomposing the numerical results of the two scenarios. Under the dynamic resilience scenario, recovery is completed within three years, but it takes four years for recovery to be complete under the reference recovery scenario. Recovery strongly affects BI, which is represented as GDP loss. The strength of dynamic resilience determines the length of recovery period and size of BI. Here, we define the strength of dynamic resilience as the reduction of BI (economic activity as measured by GDP) under the dynamic resilience scenario as compared with BI under the reference recovery scenario. The recovery can be completed by 2011 by implementing dynamic resilience strategies on top of reference recovery. Dynamic resilience reduces BI by 47.4% during 2008–2011. Of that reduction, additional insurance payments, which provide additional reconstruction funds, contribute 20.0%, an amount proportional to the additional funds. However, the rapidly collected funds and investment with new technology do not require much additional reconstruction funds but contribute greatly to reducing GDP loss by 10.2% and 13.4%, respectively. The improved technologies (enhanced productivity) stemming from some of the reconstruction investment reaps benefits far beyond the reconstruction period. However, their measurement is made difficult by several factors, such as the lack of knowledge of the useful life of the plant and equipment. This aspect is beyond the scope of this article, but we acknowledge that the results here should be interpreted as a conservative (lower-bound) estimate of gains of dynamic resilience.

Table III shows that under the reference recovery scenario, recovery is completed within four years, with BI at 355.7 billion CNY. Under the dynamic resilience scenario, recovery is completed within three years, with BI amounting to 185.9 billion CNY. Wu *et al.*[23] also assessed the indirect economic impact of the same event. Our study and that of Wu *et al.* have very similar input data and results, which adds to the credibility of our study to some extent. For the input data, the two studies used similar total property damage: Wu *et al.*: CNY 749 billion; our study: CNY 713 billion. For economic impacts, the two studies have very similar results: the former concluded that the total value added (VA) loss is CNY 301 billion, while we have concluded that in the reference recovery scenario GDP loss is CNY 355.7 billion. The two studies also have similar recovery periods: the previous study found that VA almost recovered to the pre-earthquake levels 40 months after the shock (even though the study concluded that full recovery needed eight years, but after 40 months, the VA loss is close to 0), while our study found in the reference recovery scenario in 2012 (i.e., four years after the disaster) GDP almost recovered to the baseline scenario (no disaster scenario). At the same time, our study advances the literature in three key ways. First, Wu's paper assumes the economy operates at a maximum production capacity after the earthquake (120% of predisaster level) for disaster recovery, while our study directly incorporates the actual reconstruction investment from various sources, which embodies the dynamic resilience process. Second, the comparison shows that the relevant literature on postdisaster recovery is focused more on regional indirect economic impact evaluation, while we add to the literature by uncovering the relationship between post-disaster reconstruction, dynamic resilience, and recovery. Third, we also contribute to the literature by differentiating the effects of shortening the recovery period and accelerating the pace of recovery, of which the latter is likely to be far more beneficial, as we demonstrate.

Our results indicate that reducing the duration of recovery further reduces GDP losses, but only by the relatively small amount of 2.5 billion CNY (355.7–353.2). The main reason this improvement is so small is that recovery is nearly complete by 2011. Thus, increasing the level of investment and jump-starting its implementation reap far greater rewards than shortening the duration of recovery. This conclusion holds for recovery time-paths that are linear, logistic (S-shaped), or modestly exponential (i.e., most recovery paths) because relatively little of the recovery is then left to perform in the final year(s). In addition, the earlier start and greater steepness of the recovery path has a compounding, or cumulative, effect that increases with the rate of acceleration.

This general result prompts us to reiterate the importance of modifying standard definitions of dynamic economic resilience—the ability and speed of a system to recover from a shock. The reference to speed is too vague. It behooves analysts and decision-makers to distinguish between shortening the duration of recovery and the steepening of its time-path.

5. CONCLUSIONS

In order to advance resilience as a well-defined and practical concept, this article sets forth operational definitions and links them to specific policies to promote increased levels and speed of investment in repair and reconstruction. We analyzed dynamic economic resilience in the context of the Wenchuan earthquake, performing a quantitative assessment of the concept using a dynamic CGE model. The dynamic economic resilience strategies modeled included increased insurance compensation, rapidly collecting investment funds, and adoption of new reconstruction technologies. We also improved the standard dynamic CGE model to incorporate the characteristics of these dynamic economic economic resilience strategies. The results indicate that dynamic resilience could have reduced BI of the Wenchuan earthquake by 47.4% during 2008–2011 and could have shortened the recovery period by one year. We also make the case that the results can be generalized to conclude that shortening the recovery period is not nearly as effective as increasing reconstruction and repair investment levels and accelerating the pace of recovery in most cases.

The findings from this study have several policy implications. First, while property damage takes place at a single point in time, and cannot be decreased after a disaster strikes, BI is a temporal process spanning the period when the disaster strikes and when recovery is achieved. This characteristic of BI provides an opportunity to reduce it during post-disaster reconstruction. Potential BI loss thus needs to be assessed accurately to aid reconstruction planning. Second, this study has helped clarify the meaning of dynamic resilience and its relationship with recovery. We also illustrated the quantitative estimation of the concept. Our results indicate more precisely how dynamic economic resilience can be achieved and how much it can reduce disaster losses. Although we cannot stop natural disasters, BI can be most effectively reduced by increased investment levels and accelerated timing of repair and reconstruction.

Finally, the results can be generalized to conclude that shortening the recovery period is not nearly as effective as increasing reconstruction and repair investment levels and steepening the time-path of recovery. This is an important distinction that should be made in the typically vague reference to increasing the speed of recovery in many definitions of resilience.

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