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Recovery from Natural Disaster: A Numerical Investigation Based on the Convergence Approach

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Abstract

This article employs a simple growth model, using government-funded public infrastructure and external effects to examine how the 2011 Great East Japan Earthquake and Tsunami affected economic recovery in the post-disaster period. By examining the recovery period following the disaster, we concretely consider the recovery process from various angles. In the disaster area, many people have concerns about the length of the recovery. In considering the recovery progress, we also examine several economic and social policies that might help to shorten the recovery period.

JEL classification numbers: E61; H54; O41

Keywords: 2011 Great East Japan Earthquake and Tsunami; Natural disasters; Capital deepening externality; Public infrastructure; Speed of convergence

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These studies should in no way be read as an argument that minimizes the costs of war. And as long as war and the threat of war persist, the negative economic consequences appear to be large. However, the research suggests that economies (and people) are surprisingly *robust*. Once wars are completely ended, economies can at least sometimes recover from massive destruction over the course of a *single* generation. [emphasis added]

C. I. Jones, *Macroeconomics*, 3rd ed. (2014, p. 120)

1. Introduction

The analytical target of this paper is the 2011 Great East Japan Earthquake and Tsunami (hereinafter, GEJET), which occurred at 2:46 PM Japan Standard Time (JST) on 11 March, 2011. Using the well-known convergence analysis method, we examine the long-run process of recovery from a massive natural disaster, in particular the GEJET, by employing an endogenous growth model with public infrastructure (capital). More specifically, the effects of the disaster on the length of recovery period are investigated. It seems likely that the length of the transitional period will differ before and after the GEJET.

Massive disasters cause widespread human and physical damage and thereby result in significant economic and social impacts. These broad damages should have some sort of influence on the length of the recovery period. In our model, it is conceivable that the simulated value for the length of the post-disaster transition period corresponds to the length of the recovery process in actuality. In this respect, by comparing the results in this paper with the actual recovery status, we are able to evaluate the overall levels of recovery achieved at each stage.

In addition to being an important and interesting numerical analysis, we also seek to clarify what policies are effective for speeding up the recovery process through the use of a rigorous economic model. This is a meaningful exploration for improving critical issues in the disaster-affected area.

Before giving the details of our study, we provide an overview of the existing research. Although convergence analysis itself is a well-known method in growth theory (e.g., Barro and Sala-i-Martin, 1992; Barro et al., 1995; Ortigueira and Santos, 1997; Turnovsky, 2002), as far as we know, academic research on the recovery process from massive disaster that employs a convergence approach has been rarely conducted at the international level. [1] Given this state of research,

[1] Using the Solow model, the Japan Research Institute (2011) has developed a numerical simulation of the impact of the GEJET. That research takes a different approach than ours does; however, their study shares some traits with the present study. For the overall impact of disasters, see, for instance, Mimura et al. (2011) and Esteban et al. (2013). Tatano et al. (2004) and Ikefuji and Horii (2012) theoretically analyze the general relationships between massive natural disasters and economic growth. In Barro and Sala-i-Martin (2003, Ch. 5), the economic impacts of losses of physical and human capital are examined.

Shioji (2011) is a pioneering paper that took the GEJET into consideration. Based on a specific real business cycle model with the Stone–Geary preference, he showed that the impacts of public investment differ in the vicinity of massive disasters. However, Shioji (2011) did not discuss the length of the recovery period, which is our focus in this paper.

Some empirical studies on disaster research are of interest. It seems that the bulk of empirical studies covering the GEJET have not yet come, but Yamamura (2012) made a valuable contribution by investigating how the experience of the GEJET with the severe nuclear accident in Fukushima affects individual beliefs about the risks of nuclear accidents. However, the scarcity of research on disaster, not only the GEJET, means that little attention has been given to the empirical relationship between natural disasters and economic development generally. Skidmore and Toya (2002) make an early and valuable contribution in this area. Moreover, Toya and Skidmore (2007) and Loayza et al. (2012) are recent leading studies on the relationship between disasters and economic development.

Now we briefly explain the traits of the model developed in this paper. First, the stock of public infrastructure has a positive influence on activities relating to the production of goods. This is an extremely general observation in the recent literature on growth theory, including on endogenous growth models (e.g., Futagami et al., 1993; Agénor, 2010). Second, public infrastructure is mainly accumulated through government's public investment of funds received through proportional income taxes levied on private agents. Public infrastructure is affected by certain external effects. Such externalities, on which we expand later, can be interpreted as the effect where raising living standards further induces public capital accumulation; this seems to be empirically supported.[2] In any case, infrastructure is viewed as having a vital role in the present study, with the external effects of infrastructure provision being of particular importance in the model for creating a situation in which *investment drives further investment* in the disaster-affected area. The strength of these effects certainly exerts an influence on the speed of recovery. It seems that, in the accumulation of public infrastructure, public spending is borne entirely by the *public* sector, whereas the external effects are largely dependent on the vitality of the *private* sector. Regardless, the specification for generation of infrastructure constitutes a key part in this paper.

After presenting and developing a theoretical model, we conduct a numerical simulation for the model. In the numerical examination, first of all, certain indicators, including the convergence rate, are identified as pre-disaster benchmarks. Then, by using precise estimates of actual capital destruction by the GEJET, we recalculate the previous benchmark indicators. Thus, the rate of convergence to a steady state totally governs, in a theoretical sense, the transition dynamics during the post-disaster period. Moreover, for given levels of

[2] A simple empirical test conducted in Hosoya (2014), though its scope is limited, supports this type of externality.

capital destruction, the time between destruction and recovery to a specified level can be calculated. This yields *quantitative* implications for the recovery process. Finally, we confirm the model's behavior through changes in important parameters and identify some policies that could act to accelerate the process of recovery. In this last part, *qualitative* implications are indicated.

The rest of the paper is organized as follows. Section 2 presents a basic model and derives a theoretical speed of convergence. In addition, the properties of the dynamical system are clarified. Section 3 develops extensive numerical analyses on the recovery process from the GEJET and attempts to suggest beneficial recovery policies. In Section 4, we provide concluding remarks.

2. The model

2.1. Basic framework

In this section, we present a simple endogenous growth model with special attention given to the impacts of natural disasters. The present model basically follows the second model in Hosoya (2005), with both models being characterized by the inclusion of public factors. In Hosoya (2005), as an interesting feature, the evolution of public health stock (or public health infrastructure) is determined by the two *external* factors for agents: government health expenditure and external effects. We adopt this specification.

For models studying the relationship between natural disasters and economic growth, it is important to consider social infrastructure, including public capital. Natural disasters not only damage large amounts of private physical capital and cause loss of life (which affects the labor force) but also severely damage public infrastructure. Therefore, a suitable model for examining the present issue should include these factors. Moreover, we consider an externality that affects the provision of infrastructure. It appears that the pace of recovery from disasters reflects the degree of the externality. Accordingly, public infrastructure promoted by the externality is indispensable in the present investigation. In the later numerical analysis, when taking capital destruction into consideration, we focus attention on the ratio of private capital to public infrastructure. This ratio is a basic index for evaluating economic performance.

In the present setting, public infrastructure is simply introduced into the structure; specifically, it affects *only* individual labor productivity in the production of goods. Such a specification is highly general in an endogenous growth model, and is considered to be valid for practical use (see, for instance, Futagami et al., 2008). Let us begin a detailed investigation.[3] Formally, a representative agent maximizes (1) under the constraints (2)–(4):

$$\max_{C(t)} \int_0^{+\infty} \frac{C(t)^{1-\theta}-1}{1-\theta} e^{-\rho t} \mathrm{d}t, \quad \theta > 0,\ \theta \neq 1,\ \rho > 0, \tag{1}$$

[3]The description in this section follows that in Hosoya (2005, 2014).

subject to

$$\dot{K}(t) = Y(t) - C(t) - G(t), \quad K(0) = K_0 > 0, \tag{2}$$
$$Y(t) = K(t)^{\alpha}[H(t)L]^{1-\alpha}, \quad \alpha \in (0,1), \tag{3}$$
$$G(t) = \tau Y(t), \quad \tau \in (0,1), \tag{4}$$

where ρ is the subjective discount rate, and K, Y, C, H, and L represent physical capital, output, consumption, public infrastructure, and labor, respectively.[4] The labor supply is assumed to be constant, and so we have normalized labor to $L = 1$ throughout the paper; hence, all variables, except for H, are per capita. Parameters α and τ denote, respectively, the share of physical capital in goods production and the proportional income tax rate. Therefore, (4) implies that government expenditures, G, are financed by income tax revenue, τY, collected from private agents. The government balances its budget at each point in time. In a decentralized economy, public infrastructure is an exogenous stock variable for a private agent. Therefore, for a given level of public infrastructure, the agent's dynamic optimization yields the growth rate of per capita consumption as follows:

$$g_C \equiv \frac{\dot{C}}{C} = \frac{1}{\theta}\left(\alpha(1-\tau)\left(\frac{K}{H}\right)^{\alpha-1} - \rho\right), \tag{5}$$

where g_x denotes the equilibrium growth rate of placeholder x.

Next, we examine the evolution of public infrastructure. Public infrastructure is taken as *social overhead capital*, so it should be specified as an exogenous variable for each agent. Consequently, the government bears essentially all of the responsibility for infrastructure provision through public expenditures. In addition to this channel, it is assumed that the infrastructure level is enhanced by an external effect that results from living standards. That is,

$$\dot{H} = \delta G S, \quad \delta > 0, \tag{6}$$

where δ is a constant efficiency parameter and S is a variable for living standards. This sort of specification is often employed in the growth literature for models that include human capital and health infrastructure (e.g., Lucas, 1988; Capolupo, 2000; Gupta and Barman, 2010). Economies with higher living standards typically have ample public infrastructure, and vice versa. We explicitly include this sort of external effect into the model (as S).[5] Let us focus our attention on the amount of private capital per unit of public infrastructure, using this as a concrete index for living standards. It follows that economies with a higher score on this index also have higher living standards. We capture the effect as a sort of externality that arises from capital deepening, and so we call it a *capital deepening externality*. Therefore, we have $S = (K/H)^{\epsilon}$, where ϵ represents the degree of externality. Using this, the former accumulation equation

[4] In the following, we omit the time argument t.

[5] It is assumed that only the government is in a position to learn of the impact of S.

can be rewritten as

$$\dot{H} = \delta G \left(\frac{K}{H}\right)^{\epsilon}, \quad \epsilon \in (0,1). \tag{7}$$

Hosoya (2014) closely examines the empirical reasonableness of this specification. From the above, we arrive at

$$g_H \equiv \frac{\dot{H}}{H} = \delta\tau \left(\frac{K}{H}\right)^{\alpha+\epsilon}. \tag{8}$$

On the balanced growth path (BGP), the values of g_Y, g_C, g_K, and g_H are all equal to g ($g_Y = g_C = g_K = g_H \equiv g$) by definition. Applying $g = g_H$ to (8), we can derive $K/H = (g/\delta\tau)^{1/(\alpha+\epsilon)}$. Putting this into (5), we obtain the equilibrium growth rate along the BGP:

$$g = \frac{1}{\theta}\left(\alpha(1-\tau)\left(\frac{g}{\delta\tau}\right)^{\frac{\alpha-1}{\alpha+\epsilon}} - \rho\right). \tag{9}$$

From (9), we find that the equilibrium growth rate at the BGP depends on the six parameters $\{\alpha,\ \tau,\ \delta,\ \epsilon,\ \rho,\ \theta\}$. Concerning the properties of the BGP equilibrium, the following two propositions hold.

Proposition 1 (Existence and uniqueness) *There exists a unique equilibrium solution in which g is positive.* □

Proof : First, rewriting (9) leads to $\theta g + \rho = \alpha(1-\tau)(g/\delta\tau)^{(\alpha-1)/(\alpha+\epsilon)}$. Now we define the left and right sides of this equation by $\Psi(g)$ and $\Gamma(g)$, respectively. On the one hand, in the first quadrant in the (g, Ψ)-plane, Ψ is a linear function of g with a positive slope ($\theta > 0$). On the other, Γ is a strictly decreasing and strictly convex function of g (i.e., $\lim_{g\to 0}\Gamma(g) = +\infty$, $\lim_{g\to+\infty}\Gamma(g) = 0$, $\lim_{g\to 0}\Gamma'(g) = -\infty$, and $\lim_{g\to+\infty}\Gamma'(g) = 0$).[6] Therefore, the equilibrium solution for the BGP is uniquely determined. ■

Proposition 2 (Local stability) *The unique equilibrium under the corresponding dynamical system is locally saddle-path stable.* □

Proof : See Appendix A. ■

2.2. Speed of convergence

For the dynamical system developed above, we next derive the speed of convergence theoretically.[7] To investigate the convergence speed, we introduce new transformed variables: $X \equiv C/K$ and $Z \equiv K/H$. Differentiating these variables with respect to time, we obtain $\dot{X}/X = \dot{C}/C - \dot{K}/K$ and $\dot{Z}/Z =$

[6]Note that $\Gamma'(g) = \alpha(1-\tau)\left(\frac{\alpha-1}{\alpha+\epsilon}\right)(\delta\tau)^{(1-\alpha)/(\alpha+\epsilon)} g^{-(1+\epsilon)/(\alpha+\epsilon)}$.

[7]The following description also follows Hosoya (2005).

$\dot{K}/K - \dot{H}/H$. By using (2)–(5) and (8), two differential equations on X and Z are given by

$$\frac{\dot{X}}{X} = X + \left(\frac{\alpha - \theta}{\theta}\right)(1-\tau)Z^{\alpha-1} - \frac{\rho}{\theta}, \tag{10}$$

$$\frac{\dot{Z}}{Z} = -X + (1-\tau)Z^{\alpha-1} - \delta\tau Z^{\alpha+\epsilon}. \tag{11}$$

As a result, these equations characterize the dynamics of the model. Note that the initial value $X(0) \equiv C(0)/K(0)$ is not predetermined since $C(0)$ is the jump (control) variable. The Jacobian of the dynamical system characterized by (10) and (11) is represented as the following 2×2 matrix:

$$J \equiv \begin{bmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{bmatrix} = \begin{bmatrix} \frac{\partial \dot{X}}{\partial X} & \frac{\partial \dot{X}}{\partial Z} \\ \frac{\partial \dot{Z}}{\partial X} & \frac{\partial \dot{Z}}{\partial Z} \end{bmatrix},$$

where

$$a_{11} = \left.\frac{\partial \dot{X}}{\partial X}\right|_{\text{BGP}} = X^*,$$

$$a_{12} = \left.\frac{\partial \dot{X}}{\partial Z}\right|_{\text{BGP}} = \left(\frac{\alpha - \theta}{\theta}\right)(\alpha - 1)(1-\tau)X^*(Z^*)^{\alpha-2},$$

$$a_{21} = \left.\frac{\partial \dot{Z}}{\partial X}\right|_{\text{BGP}} = -Z^*,$$

$$a_{22} = \left.\frac{\partial \dot{Z}}{\partial Z}\right|_{\text{BGP}} = (\alpha - 1)(1-\tau)(Z^*)^{\alpha-1} - \delta\tau(\alpha+\epsilon)(Z^*)^{\alpha+\epsilon}.$$

The asterisk ($*$) denotes the BGP value.[8] Therefore, the characteristic polynomial for this two-dimensional system is

$$\text{Det } (J^* - \lambda I) = 0,$$

where J^* denotes the Jacobian evaluated at the BGP, λ is an eigenvalue of J^*, and I is the two-dimensional identity matrix. Consequently we have

$$\lambda^2 + (V_1 + V_2 - X^*)\lambda - \left(\frac{\alpha}{\theta}V_1 + V_2\right)X^* = 0, \tag{12}$$

[8]The BGP values of X and Z correspond to the solutions of the following nonlinear simultaneous equations (from (10) and (11)):

$$X^* + \left(\frac{\alpha - \theta}{\theta}\right)(1-\tau)(Z^*)^{\alpha-1} - \frac{\rho}{\theta} = 0,$$

$$X^* - (1-\tau)(Z^*)^{\alpha-1} + \delta\tau(Z^*)^{\alpha+\epsilon} = 0,$$

where $X^* > 0$ for a positive g. To satisfy this, we need $X^* = (1-\tau)(Z^*)^{\alpha-1} - g > 0$. In the following numerical analysis, the positivity condition on X^* is naturally satisfied.

where $V_1 \equiv (1-\alpha)(1-\tau)(Z^*)^{\alpha-1}$ and $V_2 \equiv \delta\tau(\alpha+\epsilon)(Z^*)^{\alpha+\epsilon}$. In (12), there are two roots, which are represented by λ_1 (negative root) and λ_2 (positive root). The negative root λ_1 is given by the following expression:

$$\lambda_1 = \frac{(X^* - V_1 - V_2) - \left[(V_1 + V_2 - X^*)^2 + 4\left(\frac{\alpha}{\theta}V_1 + V_2\right)X^*\right]^{1/2}}{2}. \tag{13}$$

Here, we define $\tilde{\lambda}$ as $\tilde{\lambda} = -\lambda_1$. As a result, the speed of convergence (i.e., convergence coefficient) for the present model is given by $\tilde{\lambda}$. Appendix B briefly shows the numerical algorithm for obtaining λ_1. The convergence rate, $\tilde{\lambda}$, characterizes the overall transition process of the economy. Therefore, we can obtain insights about economic recovery by observing variations in $\tilde{\lambda}$ after the occurrence of large-scale natural disasters. Note that, at the same time, the calculated $\tilde{\lambda}$ is valid as only an approximate value in the neighborhood of the BGP equilibrium because the present speed of convergence is derived by the linear approximation method. As will be discussed in a later section, the estimates for the rate of capital destruction are smaller than our previous estimates (by about 10–20% on average), even when limiting the target to the disaster-affected area. Also, the speed of convergence in the present model is relatively fast compared with typical neoclassical growth models; thus our focus on neighborhood of long-term equilibrium is reasonable. Consequently, the linear approximation method, which is advantageous for investigations in the vicinity of the steady state, seems to be a valid choice for our analytical environment.

3. Numerical analysis

In this section, we explore numerical computations based on (13). First, the basic numerical properties of the model are presented. Second, we focus on cases where broad and severe capital destruction occurs in association with a large-scale natural disaster, such as the GEJET in 2011, and numerically evaluate the economic impact of the disaster.

It is a fairly difficult how to determine benchmark parameters for numerical computations. For the present determination, the following two points are taken into consideration. First, according to the typical growth studies, including Barro et al. (1995), Ortigueira and Santos (1997), and others, it seems reasonable to assume a value of 2–3% as a per capita income growth rate at the BGP. Second, the average annual growth rate of U.S. per capita GDP over the last 140 years is about 2%.[9] From these facts, our benchmark case should replicate about 2% growth rate as a reasonable assumption.

[Insert Table 1 around here]

[9] See, for instance, Jones (2014, pp. 51–52). In general, it is considered that the U.S. economy is located on or in close vicinity to the steady state.

Table 1 provides a set of parameter values for the benchmark case. Under these parameter values, per capita income growth rate at the BGP is exactly 2%. Following the standard literature (e.g., Barro et al., 1995; Ladrón-de-Guevara et al., 1997; Ortigueira and Santos, 1997), the three parameters, ρ, θ, and α, are fixed in the present analysis for analytical simplicity. In growth studies, there is a certain consensus with respect to the value of these parameters. It is well known that a larger values of ρ, smaller values of θ, and larger values of α accelerate the speed of convergence when all else is held constant.[10] The varied parameters are τ, δ, and ϵ. An increase in τ contributes to economic growth and enhances the speed of convergence. This is the famous inverted-U relationship between income tax level and income growth rate, documented by Barro (1990), and its positive correlation corresponds to the left-hand region of the hump-shaped curve. As for δ and ϵ, the predicted results are obtained: the speed of convergence is accelerated by increases in those parameters.

The contribution of this study is to quantify the behavior of convergence after a large-scale natural disaster that causes massive capital destruction (e.g., a "megaquake"). In the present context, the convergence coefficient implies that *speed* governs the transition from old BGP to new BGP. Now, we make the following assumption for analytical purposes.

Assumption It is natural that the position of the balanced growth equilibrium, and therefore the rate of convergence, can be changed by a massive disaster. In the following, we regard the transition period derived by a computed convergence coefficient as the period for recovery from the disaster. Accordingly, the initial point of the recovery period corresponds to the time immediately after the disaster, while the terminal point is approximated theoretically as the point in time at which the overall recovery process is 99% complete.

Needless to say, due to the fact that the position of the long-run equilibrium itself varies, the terminal point generally differs from the steady state just prior to the disaster. Since large-scale natural disasters affect the capital composition between physical and public capital, they also influence the convergence speed. To intuitively grasp the impact of variations in the convergence speed on an economy, we compute the time required for an economy to reach a new BGP from an old BGP depending on the degree of economic recovery, and then perform a detailed investigation based on the numerical results.

[Insert Figure 1 around here]

As noted before, the target of our analysis is the GEJET. In setting the percentage of capital destruction caused by this calamitous event, the estimate by the Development Bank of Japan (DBJ) provides us with highly useful information. This estimate, released at a relatively early stage in the post-disaster

[10] Also, the coefficient $\tilde{\lambda}$ is sensitive to variation in θ.

period, estimated the percentage of capital destruction in detail on a regional basis. Figure 1 briefly shows the results of estimation by DBJ.[11] It is obvious that the recent GEJET was an unprecedented catastrophic disaster for the Japanese economy and society. As can be seen in Figure 1, however, the estimates for the capital destruction are fairly different from our impressions, even when considering them at the level of regional macroeconomy.[12]

By using the estimates above, the effect of capital destruction on the rate of convergence is examined in detail in the following section. It is reasonable to assume that the analytical unit of our model corresponds to a *regional* macro unit rather than a standard macro unit. In this case, the Pacific area of eastern Japan is a suitable unit; more concretely, in view of the damage, we focus on the coastal area in Iwate, Miyagi, Fukushima, and Ibaraki prefectures. The highlight of this study is that it clarifies, quantitatively, how the variations in the speed of convergence after the massive earthquake and tsunami affect the recovery process (i.e., transition dynamics among the BGPs) of the disaster area.

3.1. Comparing $\tilde{\lambda}$ between the pre- and post-disaster periods

Next we study the changes in the benchmark case (an economy experiencing 2% growth under the parameters displayed in Table 1) after a massive disaster. Using the parameter values shown in Table 1, the impact of the capital destruction on the speed of convergence is examined. From the estimated data introduced above, we set a value of 10% for the rate of physical capital destruction.[13] This value is close to the averages of Iwate and Miyagi prefectures, and the average in the coastal area of Fukushima prefecture (see Figure 1). That is, we assume that the recent earthquake and tsunami destroyed 10% of the physical capital in the corresponding area. The method of calculation given these damage estimates is shown in Appendix B. As a simulated situation, the damage estimates are reflected in the ratio of private physical capital to public infrastructure. For example, in a case where the rate of damage is assumed to be 10%, the value of ψ is set at 0.9. From the obtained X^* and Z^*, the income growth and convergence rates in the post-disaster period are recalculated.

First of all, the convergence rate decreases from about 5.7% to about 5.4% after the disaster, but the disparity is not large, contrary to our prediction. Although its absolute value is large compared with the typical estimates obtained in the earlier literature (e.g., Mankiw et al., 1992), our result is sup-

[11] Dark areas in the figure represent municipalities that include areas flooded by the tsunami.

[12] However, it is still fresh in our minds that the present massive earthquake caused a great deal of disruption throughout the economy, including supply-chain fragmentation. In addition, we had no choice but to exclude the severe accident at Fukushima Nuclear Power Plant No. 1 from the analysis given its leading negative and persistent impacts on the Japanese economy.

[13] Results for other rates of destruction (e.g., 20%) are available from the author upon request.

ported by recent contributions from research using the generalized method of moments (GMM) estimation method (e.g., Bayraktar-Sağlam and Yetkiner, 2014).[14] GMM estimation has often been employed in recent empirical growth studies. The resulting decrease in $\tilde{\lambda}$ leads to a lowering of the income growth rate from exactly 2% to about 1.75%.

A further interest of ours is to grasp the effect on the adjustment time.[15] After the disaster, the time needed for getting through 90% of the adjustment process lengthens to about 42.3 years. In comparison with the case of no capital destruction (i.e., pre-disaster), the gap is about 1.7 years.[16] One could view the relatively long process of the transition as absorbing most of the negative impacts from the disaster. Frankly, having experienced the catastrophic damage caused by the GEJET, we are reminded anew that the economy and people are surprisingly robust.

3.2. Potential length of recovery periods following the GEJET

In the assumptions of the previous section, the rate of capital destruction is set to 10%, and we attempt to evaluate the time required to achieve each recovery level.[17] Table 2 shows five estimation results for reaching recovery levels between 5% and 70%. From this, we find that it takes 12.7 years and 22.1 years to complete 50% and 70% of the total transition process, respectively. As examined in detail by Davis and Weinstein (2002), for instance, Hiroshima took about 30 years to recover its pre-war economic position. Based on this fact, our estimation can be considered as having a certain face validity.

[Insert Table 2 around here]

Although more than three years have passed since the 2011 GEJET at the time of this writing, it is often stated by the media that the progress of recov-

[14]Arnold et al. (2011) is also a recent contribution in the empirical growth literature dealing with conditional convergence. In that paper, a pooled mean group estimation is used. It is shown that an Uzawa–Lucas type endogenous growth model is consistent with the growth experiences in OECD countries, rather than a neoclassical growth model such as the augmented Solow model (e.g., Mankiw et al., 1992). Their obtained speeds of convergence were considerably higher than our results. In recent years, through the advancement of econometric tools, relatively high convergence rates have been frequently reported.

[15]As well known, the $100\times\beta\%$ of adjustment time from initial point to long-run steady state is given by $T(\beta) = \ln(1-\beta)/\lambda_1$.

[16]The case in which the rate of capital destruction is assumed to be 20% is also noteworthy. This rate is close to the rate of destruction in the coastal area of Miyagi prefecture (see Figure 1). By decreasing the convergence rate and income growth rate to 5.2% and 1.5%, respectively, the 90% recovery period is calculated as 44.1 years based on the benchmark parameters. The gap relative to the pre-disaster case is 3.5 years.

[17]Along with those in the previous section, other results are available from the author upon request.

ery has not been sufficient.[18] As discussed above, however, the present status of progress is acceptable under the convergence analysis method based on a rigorous model of economic growth. It is rather difficult to assess the overall recovery progress overall because much of the public infrastructure, including whole towns, has not been rebuilt to its pre-disaster state. Figures 2 and 3 show the current status in the disaster areas. The GEJET wrought great destruction in these areas, whose central cities were virtually eradicated. Hence, although this is undoubtedly going to be a difficult process of recovery, we can find that, as suspected, the progress of recovery is unsatisfactory at three years since the GEJET. Figure 2 shows Minamisanriku town in Miyagi prefecture as of August 2014. Few buildings and structures can be seen and its central area is full of weeds. Figure 3 shows Rikuzentakata city in Iwate prefecture as of September 2014. Enormous conveyor belts for moving sediment, extending toward the bank to be used in raising lands flooded by tsunami, tower over the place once known for *white sand and green pines*.[19]

[**Insert Figure 2 and Figure 3 around here**]

Except for some specific areas that have seen a steadily advancing recovery, the two photographs show a common situation in the towns of the devastated Pacific coast area. They precisely show the present predicament. No matter how you look at it, the progress toward recovery remains less than 30% complete. The results of Table 2 fit with the visual images above. The prediction for 10% recovery in about two years (1.9 years) is a reasonable view. It appears that in the current situation, three years out, that recovery of about 20%, from a broader perspective, is reasonable. Some important and intriguing results are summarized as follows.

Remark 1
The current status of recovery progress is acceptable under the convergence analysis method based on a growth model with public infrastructure. Currently, it appears that about 20% of the overall recovery process has been completed.

It should be noted that the above inference was obtained without accounting for exogenous shocks. Our results are likely to change depending on the presence or absence of technological shocks and shifts in economic policy. Therefore, how we respond to the computation results becomes crucial. By conforming to the objective function among the affected people as evenly as possible and moving forward decisively and maximizing cooperation between the public and

[18] Key background factors slowing the recovery are likely slow policy responses and the severe accidents at the nuclear power plant, among other factors.

[19] In Japanese, this has the evocative name ***hakusha-seishou***.

private sectors, we believe that the time until recovery and new opportunities in the disaster areas can be shortened. As noted before, our results can be considered as having a certain relevance and therefore can be used as the target and evaluation criteria for the recovery process.

3.3. Some experiments based on the benchmark case

As the last consideration of our numerical analysis, the effects of the change in δ and ϵ on the speed of convergence are examined in detail. These are characteristic parameters for the model, but no reliable values are suggested for them in the literature.[20] We present the following three cases.[21]

In the first case, $\delta = 0.2$ and $\epsilon = 0.2$ are applied. These parameters give rise to a steady-state growth rate of about 2.7%. Compared with the benchmark case where the rate of capital destruction was assumed to be 10%, a slight change in those parameters has a significant impact on the economy. Specifically, the speed of convergence changes considerably ($0.0544 \rightarrow 0.0759$), resulting in the 90% recovery period being condensed from about 42.3 years to about 30.3 years. To see the marginal effect of the increase in δ and ϵ, we test the following two cases: ($\delta = 0.25$, $\epsilon = 0.2$) and ($\delta = 0.2$, $\epsilon = 0.25$). The former combination yields $g = 0.0313$ and $\tilde{\lambda} = 0.0878$. The corresponding 90% recovery period in this case is about 27.07 years. In the latter combination, on the other hand, $g = 0.0292$ and $\tilde{\lambda} = 0.0854$ were obtained, corresponding to a 90% recovery period of about 27.72 years.

[Insert Table 3 around here]

In addition, Table 3 gives the periods necessary to achieve 5% to 70% recovery for each case. As in the case of the 90% recovery period, economic and social policies can substantially shorten the process of recovery from the disaster. An immediate goal for the stricken area will be to exceed half of the pre-disaster living standards. In line with our simulation, this goal can be replaced by considering the concrete question of how many years it will take to arrive at the 50% recovery level. According to differences in parameter values, we observe an uneven picture. The longest case, which corresponds to the benchmark case, takes about 13 years to reach 50% recovery. In contrast, the shortest case is about 8 years ($\delta = 0.25$, $\epsilon = 0.2$). Such a difference in recovery time is a devastating result to people who desperately want to recover. The characteristics of the structure of the economy, reflected in certain parameters, make a noticeable difference in living standards.

From the above observations, we particularly emphasize the role of efficient public infrastructure provision in promoting economic recovery. Amplifying the

[20] We update τ from 0.05 to 0.04 to improve empirical fitness. The other three parameters are identical with those in the previous case.

[21] The following computation assumes a 10% capital destruction rate.

theoretical implication, the following concrete proposal can be derived. To reconstruct destroyed social capital efficiently, it is important that each form of social capital resonates with the others, and thus *selection* and *concentration* are needed for infrastructure provision. First, local residents who lived far apart previously should be consolidated in the center of town.[22] Second, administrative agencies and private companies should be committed to generating and restoring suitable workplaces. Such plans would make certain the further acceleration of recovery. In any case, perfect provision of social infrastructure as a good *saucer* for local residents must take top priority.[23] This important knowledge is summarized as follows.

Remark 2
The efficient provision of public infrastructure serves as the driving force for moving the recovery forward from the disaster, and so it is necessary to select and concentrate on the provision of public infrastructure.

4. Concluding remarks

This paper theoretically and numerically investigated the recovery process from massive natural disaster, including the 2011 GEJET, by using an endogenous growth model characterized by public infrastructure and a capital deepening externality.

For the model, whose long-term equilibrium is uniquely determined and exhibits local saddle-path stability, we measure the transition time between any two long-term equilibria by numerical computation. As we have experienced, great disasters cause capital destruction over large areas, and therefore it is important to examine how the destruction affects the recovery period. Our assumed economy is one attaining 2% per-capita income growth. To satisfy this, we selected parameter values in line with the typical literature in the related field.

Our principal results are summarized as follows. First, assuming 10% capital destruction occurred in association with the GEJET and incorporating this into the computation, the convergence rate decreases from about 5.7% in the pre-disaster period to about 5.4% in the post-disaster period. Moreover, such a slowdown extends the 90% recovery period for another two years. Second, further numerical study of the post-disaster case leads to an estimate of slightly below 20% as the present recovery status. This estimate seems to be reasonable given the experiences of recovery during post-war reconstruction in Japan. Third, our model includes two important parameters on the efficiency of infrastructure provision and the capital deepening externality, and we found that

[22]In particular, in Iwate and Miyagi prefectures, a number of small-scale fishing villages dotted the rias (deeply inlets along the coastline) could be consolidated.

[23]This environment is obviously related to the capital deepening externality noted above. Accordingly, social capital with a strong externality further boosts the recovery process.

changes in these parameters have a significant influence on the speed of convergence. Slight changes in both parameters, for instance, shorten the 90% recovery period by more than ten years. This will be an astonishing result for all people involved in disaster recovery efforts. Success or failure in the policy approach could entirely change the nature of the recovery process.

In addition to the above quantitative implications, we can also derive some qualitative implications. To shorten the recovery period, we found that it is essential to improve the efficiency of infrastructure provision. Also, we confirmed that it is crucial for there to be external effects caused by an overall improvement in living standards (capital deepening externality). From these findings, the importance of general improvements in the recovery environment that promote positive external effects can be seen. To that end, selection and concentration of public infrastructure provision are critical factors for speeding the recovery.

Finally, for further investigation, we highlighted an essential extension of the research findings given in this paper. Likely, a meaningful future model would include levels of infrastructure into utility function, in addition to production functions. Using such a model, a similar analysis as conducted with the present model should be performed. Fortunately, because the basic properties of our future model are already clarified in Hosoya (2014), we will just have to combine that approach and convergence analysis.

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Appendix A. Proof of Proposition 2

From the corresponding Jacobian, we can determine the sign of the determinant as follows:

$$\text{Det } J^* = -\frac{\alpha}{\theta}(1-\alpha)(1-\tau)X^*(Z^*)^{\alpha-1} - \delta\tau(\alpha+\epsilon)X^*(Z^*)^{\alpha+\epsilon} < 0.$$

Since the reduced dynamical system includes one control-like variable, X, and one state variable, Z, the negative sign of the determinant implies that the equilibrium is locally saddle-path stable.

Appendix B. Numerical algorithm for obtaining λ_1

First, we specify the following nonlinear equation, $f(Z)$, to obtain the steady-state value of Z.

$$f(Z) = \frac{\alpha(1-\theta)}{\theta}(\psi Z)^{\alpha-1} - \delta\tau(\psi Z)^{\alpha+\epsilon} - \frac{\rho}{\theta}.$$

Here, ψ is a scale parameter on Z. As is obvious, ψ is equal to unity in the benchmark case. We then change the value depending on the analytical situation. Second, we search for Z^* satisfying $f(Z) = 0$ under the given parameters. Third, for the relevant Z^*, X^* is given by

$$X^* = \frac{\rho}{\theta} - \left(\frac{\alpha-\theta}{\theta}\right)(1-\tau)(Z^*)^{\alpha-1}.$$

As a consequence, these steps lead to obtaining λ_1.

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Table 1
Benchmark parameters

ρ	θ	α	τ	δ	ϵ
0.025	1.5	0.35	0.05	0.1	0.15

Table 2
Required number of years to reach each level of recovery (1)

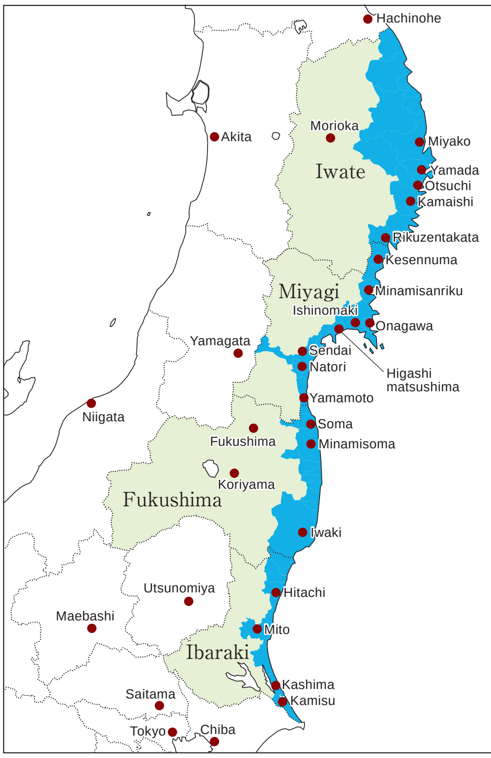
Recovery level	5%	10%	30%	50%	70%
Required years	0.94	1.94	6.55	12.73	22.12

Note: The rate of capital destruction is 10%. Each number is calculated under the benchmark parameters in Table 1.

Table 3
Required number of years to reach each level of recovery (2)

Recovery level		5%	10%	30%	50%	70%
	(δ, ϵ)					
	(0.2, 0.2)	0.68	1.39	4.70	9.13	15.85
Required years	(0.2, 0.25)	0.62	1.27	4.29	8.35	14.50
	(0.25, 0.2)	0.60	1.24	4.19	8.15	14.15

Note: The rate of capital destruction is 10%. Except for τ, δ, and ϵ, each number is calculated under the benchmark parameters in Table 1.



		Ratio of capital destruction
Iwate	Inland	2.9%
	Coast	47.3%
	Total	12.6%
Miyagi	Inland	5.1%
	Coast	21.1%
	Total	11.9%
Fukushima	Inland	3.7%
	Coast	11.7%
	Total	6.2%
Ibaraki	Inland	2.1%
	Coast	6.8%
	Total	3.6%
All four prefectures	Inland	3.3%
	Coast	17.2%
	Total	7.9%

Figure 1: Overview of the disaster areas from the 2011 GEJET

Figure 2: Current status of Minamisanriku town, Miyagi prefecture (Photo: K. Hosoya, August 2014)

Figure 3: Current status of Rikuzentakata city, Iwate prefecture (Photo: K. Hosoya, September 2014)