MEASUREMENT OF DYNAMIC DAMAGE COST OF THE GREAT EAST JAPAN EARTHQUAKE WITH RECONSTRUCTION PROCESS

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In order to examine the economic impact of the damage due to the Great East Japan Earthquake in 2011 and the reconstruction of the disaster-stricken areas and all prefectures, this study aims to develop a dynamic spatial computable general equilibrium model. This model describes the economic dynamics of the damage caused by the earthquake, the resulting reconstructions, and measures the dynamic benefits of reconstruction by using numerical simulations. The findings of this study are as follows: (1) The discounted present value of the dynamic damage cost along with reconstruction from the earthquake was estimated to decrease to about 17.9 trillion yen in total, which was 1.29 times greater than decreases in the direct damage cost of about 13.9 trillion yen in the Tohoku disaster-stricken areas. (2) The damage costs and benefits could be measured more accurately based on the economic theory by introducing the dynamic multiplier of damage costs and benefits into the conventional benefit measurement technique. (3) The forward-looking dynamic model, despite strict constraints and unrealistic assumptions, could show realistic results.

Key Words: the Great East Japan Earthquake, damage cost, reconstruction process, dynamic spatial CGE model, Ramsey model

1. INTRODUCTION

The Cabinet Office, Government of Japan1, 2) estimated approximately 16 trillion yen of capital stock damage due to the Great East Japan Earthquake in 2011, as shown in Table 1. Such capital stock damage is believed to have had serious impact on both aspects of supply and demand. On the supply side, supply constraints on intermediate input goods and final input goods caused great damage to some areas except the disaster-stricken areas (DSA). In particular, since the supply constraint on intermediate input goods reduces production outputs in areas except the DSA, it has significant spill-over effects on the regional level. Moreover, through decreases in employment opportunities and income in the DSA, various supply constraints affect demand. The decrease in income in the DSA brings about decrease in consumption demand, and it feeds through to the supply side.

On the other hand, in order to accelerate reconstruction in the DSA after the earthquake, the government decided to expand the financial framework for reconstruction to approximately 25 trillion yen in January 2013. There are various reconstruction measures undertaken by the government to recover capital stocks damaged by the earthquake; thus, a dynamic analysis is needed to determine the long-term effects of these reconstructions.

In order to examine the economic impact of the damage due to the Great East Japan Earthquake in 2011 and the reconstruction process on the disaster-stricken areas and all prefectures, this study aims to
Table 1: Summaries of earlier studies estimating the economic costs due to the Great East Japan Earthquake.

| Study                           | Approach                                      | Analysis                     | Estimation                                                                 |
|---------------------------------|-----------------------------------------------|------------------------------|----------------------------------------------------------------------------|
| Cabinet Office1, 2)             | • Production function approach                | ○ ○                         | • Approximately 16 to 25 trillion yen of capital stock damage in all disaster-stricken areas |
|                                 | • Capital stock damage: social overhead capital stock, private capital stock | ○ ○                         | • Decrease of approximately 1.25 to 2.25 trillion yen per year in GDP due to supply constraint by collapsed private capital stock |
|                                 | • Supply constraints by collapsed private capital stock, disconnected supply chain and electricity, Increase in output by capital stock recovery | ○ ○                         | • Decrease of approximately 0.25 trillion yen in the 1st half of the 2011 fiscal year due to disconnected supply chain |
|                                 | • Increase in output by capital stock recovery | ○ ○                         | • Estimation of supply constraints due to disconnected and unstable supply of electricity |
|                                 |                                               | ○ ○                         | • Increase of approximately 5 to 7 trillion yen in 2011 and approximately 6 to 9 trillion yen in 2012 in GDP by capital stock recovery |
| Yamazaki and Ochiai3)           | • Multi-regional CGE model: 8 regions and 17 sectors | ○ ○                         | • Decrease of 8.0% in real GDP in the Kanto region, including Tokyo, caused by damage due to the earthquake and 10% electricity shortage |
|                                 | • Supply constraints caused by disconnected supply chain and electricity | ○ ○                         | • Decrease of approximately 4.2 trillion yen per year in the Tohoku region, including DSA, and approximately 4.3 billion yen per year in welfare by damage as mentioned above |
| Osanai4)                        | • GDP gap by production function approach     | ○ ○                         | • Limited impact of capital stock breakdowns on GDP gap                    |
|                                 | • Assumption of capital stock breakdowns: 5% breakdown, 2.5% and 1% | ○ ○                         | • Large impact of the lower capacity utilization rate                      |
|                                 | • Assumption of decline in the capacity utilization rate: 20% down, 10% and 5% | ○ ○                         |                                                                       |
| Ishimaru5)                      | • Analysis of supply side                     | ○ ○                         | • Approximately 20 trillion yen of capital stock damage (approximately 8 trillion yen worth of private production equipment) in 11 disaster-stricken prefectures |
|                                 | • Production function approach                | ○ ○                         |                                                                       |
|                                 | • Capital stock damage                        | ○ ○                         |                                                                       |
|                                 | • Supply constraints by disconnected supply chain and electricity | ○ ○                         |                                                                       |
|                                 |                                               | ○ ○                         |                                                                       |
| Ishimaru and Taka-               | • Analysis of demand side                     | × ○                         | • Delayed recovery risk by heightened uncertainty over the future         |
| yama6)                          |                                               | ○ ○                         | • Recovery of investment by reconstruction demand                         |
|                                 |                                               | ○ ○                         | • Sluggish exports by decrease in productivity                            |
| Development Bank of Japan7, 8)  | • Estimation from existing disaster statistics and data of the Great Hanshin-Awaji Earthquake | ○ ○                         | • Approximately 16.4 trillion yen of capital stock damage in the Tohoku region including the DSA |
| Hayashiyama et al.9)            | • Multi-regional CGE model: 47 prefectures and 15 sectors | ○ ○                         | • Decrease of 1.51 to 2.83 trillion yen per year in total GDP             |
|                                 | • Supply constraints caused by collapsed private capital stock and disconnected supply chain | ○ ○                         | • Due to collapsed private production equipment, decrease of 1.12 trillion yen per year in real GDP, 67.1 billion yen total per year in welfare, and 1.63 trillion yen total per year in production output |
|                                 |                                               | ○ ○                         | • Due to disconnected supply chain, decrease of 0.39 to 1.71 trillion yen total per year in real GDP, 1.04 trillion yen total per year in welfare, and 3.49 trillion yen total per year in production output |
develop a dynamic multi-regional computable general equilibrium model, to describe the economic dynamics of damage and reconstructions after the disaster, and to measure the dynamic benefits of reconstruction by using numerical simulations.

2. LITERATURE REVIEW

Although a large number of studies have been made on the static measurement of the damage costs due to the Great East Japan Earthquake, little is known about the dynamic measurement of such costs (Table 1). On the other hand, a considerable number of studies have used dynamic models to assess the long-term impact of natural disasters. First, Tatano et al.\textsuperscript{12)} used an endogenous growth model with two regions and analyzed the impact of heterogeneity with respect to natural disaster damage on economic recovery after that disaster. Segi et al.\textsuperscript{13)} analyzed the effect of the disaster-preventing investment policy on disaster risk, by developing a dynamic stochastic macroeconomic model that demonstrates a disaster-preventing capital stock and clarifying the optimal dynamic path of capital stocks for production and disaster prevention. And, by using a dynamic model including an endogenous growth model, a series of studies on the maintenance cost and the optimal level of maintenance of social overhead capital stock were developed by Rioja\textsuperscript{14)}, Kalaitzidakis and Kalyvitis\textsuperscript{15)} and Dioikitopoulos and Kalyvitis\textsuperscript{16)}. Each study used a dynamic model and was able to examine the temporal spill-over effect of the disaster and public capital expenditure. Tatano et al.\textsuperscript{12)}, Kalaitzidakis and Kalyvitis\textsuperscript{15)}, and Dioikitopoulos and Kalyvitis\textsuperscript{16)} however, were theoretical studies, while Segi et al.\textsuperscript{13)} and Rioja\textsuperscript{14)} carried out theoretical and simulation analyses; thus, these studies were considered impractical. Second, Yamazaki et al.\textsuperscript{17)} developed a multi-regional, multi-sectoral, and quasi-dynamic computable general equilibrium (CGE) model that consisted of 8 regions and 23 sectors, and made simulation analyses on economic recovery from the natural disaster. Yamazaki et al.\textsuperscript{17)} showed that accumulation of capital stock in the disaster-stricken area (DSA) stimulated a rapid recovery from the disaster in the local economy, when the elasticity of substitution among domestic inter-regions and one between domestic supply goods and import were small. As the CGE model that Yamazaki et al.\textsuperscript{17)} used, however, was quasi-dynamic, an interest rate in this model was constant over time and it was different from a forward-looking dynamic model that we have developed in this study. Third, Morisugi and Morisugi\textsuperscript{18)} theoretically showed the differences between a static damage cost and a dynamic damage cost on flood due to climate change by using the Ramsey model. Also, Nakajima et al.\textsuperscript{19)} measured the dynamic damage cost of flood with climate change, by using multi-regional, multi-sectoral, and forward-looking dynamic CGE model that consisted of 8 sectors and 20 sectors and the theoretical framework based on Morisugi and Morisugi\textsuperscript{18)}.

For the existing studies mentioned above, in order to show the economic impact of the damage cost due to the Great East Japan Earthquake and the subsequent reconstruction processes on economic activities in the DSA and Japan, we developed a CGE...
model that had a forward-looking dynamic framework based on the Ramsey growth model. Then, as Tatano et al.\textsuperscript{12}) focused on the heterogeneity with respect to natural disaster damage that made the degree of damage cost different in each region, we developed a multi-regional model by dividing and classifying the region into eight regions.

3. MODEL AND SCENARIOS

(1) Structure of spatial CGE model

Our SCGE model uses the 2000 Inter-regional Input-Output Table (47 prefectures and 45 sectors) that was created by Miyagi et al.\textsuperscript{20}) and Ishikawa and Miyagi\textsuperscript{21}) as the reference data set. Table 2 and Table 3 show that we integrated 47 prefectures into 8 regions and 45 sectors into 20 sectors. Economic agents in our model consist of household, production sector, investment sector, export and import, and government. Based on the model developed by Ban\textsuperscript{22}), we modified our SCGE model.

a) Production sector

As shown in Fig. 1, all production functions in the domestic production sector are assumed to be the nested CES (constant elasticity of substitution) style. For the first step, labor $L_j^s$ and capital $K_j^s$ are aggregated into the composite production factor $VA_j^s$ using a Cobb-Douglas production function, and the composite inputs $N_j^s$ are made up of intermediate inputs $X_{ij}^s$ from all regions using a CES production function. For the second step, in order to produce the gross domestic output $Y_j^s$ for the $j$-th production sector in the $s$-th region, the composite production factor

| Table 2 Regional classification. |
|---------------------------------|
| **Region** | **Code** | **Prefecture** |
| 1 | Hokkaido | HKD | Hokkaido |
| 2 | Tohoku | THK | Aomori, Iwate, Miyagi, Akita, Yamagata, Fukushima |
| 3 | Kanto | KNT | Ibaraki, Tochigi, Gunma, Saitama, Chiba, Tokyo, Kanagawa, Niigata, Yamanashi, Nagano, Shizuoka |
| 4 | Chubu | CHB | Toyama, Ishikawa, Aichi, Gifu, Mie |
| 5 | Kinki | KIK | Fukui, Shiga, Kyoto, Osaka, Hyogo, Nara, Wakayama |
| 6 | Chugoku | CGK | Tottori, Shimane, Okayama, Hiroshima, Yamaguchi |
| 7 | Shikoku | SKK | Tokushima, Kagawa, Ehime, Kochi |
| 8 | Kyushu | KYS | Fukuoka, Saga, Nagasaki, Kumamoto, Oita, Miyazaki, Kagoshima, Okinawa |

| Table 3 Sectoral classification. |
|---------------------------------|
| **Sector** | **Code** | **47 Prefectural IO** |
| 1 | Agriculture | AGR | Agriculture |
| 2 | Forestry | FRS | Forestry |
| 3 | Fishery | FSH | Fishery |
| 4 | Mining | MIN | Mining |
| 5 | Foods | FOD | Foods |
| 6 | Other manufacturing products | OMF | Textile products; Timber and wooden products; Furniture and fixtures; Pulp, paper, paperboard, building paper; Publishing, printing; Leather, fur skins, and miscellaneous leather products; Ceramic, stone, and clay products; Miscellaneous manufacturing products |
| 7 | Chemical products | CPR | Chemical products, Plastic products, Rubber products |
| 8 | Petroleum and coal products | P.C | Petroleum and coal products |
| 9 | Iron and steel | I.S | Iron and steel |
| 10 | Metal products | MTL | Non-ferrous metals, Metal products |
| 11 | Industrial machinery | MCH | General industrial machinery, Machinery for office and service industry, Motor Vehicles, Other transportation equipment, |
| 12 | Electrical equipment | ELM | Household electronic and electric appliances, Electronic and communication equipment, Other electrical equipment, Precision instruments |
| 13 | Construction | CNS | Building construction and repair of construction, Public construction and Other civil engineering |
| 14 | Electricity | ELY | Electricity |
| 15 | Gas | GDT | Gas and heat supply |
| 16 | Water supply | WTR | Water supply and waste management services |
| 17 | Commerce | COM | Wholesale and retail trade, Finance and insurance, Real estate |
| 18 | Transport | TRS | Transport |
| 19 | Medical service | MED | Medical service, health and social security and nursing care |
| 20 | Services | ANC | Communication and broadcasting, Education and research, Public administration, Other public services, Business services, Personal services, Activities not elsewhere classified |
is combined with the composite inputs, using a Leontief production function.

b) Household consumption

Fig. 2 shows the structure of household consumption. We assume that there is one representative household in each region. In order to yield utility $U_i^H$ under a budget constraint, a household demands composite household consumption goods $N_i^H$ that are made up of intermediate household consumptions $X_i^H$ from all regions using a CES function.

c) Government sector

According to Ban22), the structure of government expenditure is assumed to be divided into government consumption and government investment. The government in each region earns revenue from income tax, production tax, and indirect tax, and under budget constraint, it determines the optimal consumption and investment. In addition, the government in each region is assumed to be myopic for investment, and it demands investment goods in its own region. For the structure of government behavior, see details in Ban22).

d) Private investment

The structure of the private investment sector is the same as that of the household consumption sector in Fig. 2. We assume that there is a virtual investment sector in each region. While the government sector invests in sectors in its own region, the private investment sector demands investment goods over the region.

e) Export and import

In accordance with Hosoe et al.23), Fig. 3 shows the structure of the substitution between imports and domestic goods and that of the transformation between exports and domestic goods. About imperfect substitution between imports and domestic goods, we assume the Armington’s assumption (Armington24)). The i-th Armington-composite-good-producing sector in the s-th region aggregates domestic goods $D_i^s$ and imports $IM_i^s$ into composite goods $Q_i^s$ using a CES function. On the other hand, gross domestic output $Y_i^s$ is transformed into domestic goods $D_i^s$ and exports $EX_i^s$ using a CET (constant elasticity of transformation) function. Both parameters of elasticity of transformation $\sigma_{DEX}$ and elasticity of substitution $\sigma_{DIM}$ are assumed to be 2.0 exogenously.

f) Domestic supply and demand goods

The relationship between the Armington composite goods $Q_i^s$ that are domestically supplied and goods that are demanded in each domestic final demand sector is shown as follows:

$$Q_i^s = \sum_j Y_i^s + \sum_j N_i^s + \sum_i X_i^s + \sum_j X_{iG}^s + \sum_j XI_{iG}^s$$

where $X_i^s$ is government consumptions, $XI_{iG}^s$ is private investments, and $XI_{iG}^s$ is government investments.

(2) Structure of dynamic model

This study extends the description of the dynamic model structure by Lau et al.25), Paltsev26), and Ban22). These studies adopted a Ramsey growth model to develop a dynamic structure.

First, we have three assumptions in describing a neoclassical growth model: 1) over all periods, an economy is on a steady-state equilibrium path, 2) in
the initial period, an economy is on a steady state, and 3) in the last period, under constraint that the growth rate of investment is equal to the growth rate of output, an economy is on a steady state.

A representative household maximizes the present value of lifetime utility subject to three constraints, i.e., that a production function in period \( t \) is assumed to be constant returns to scale in labor and capital, total output in period \( t \) is divided into consumption and investment, and the capital stock in period \( t + 1 \) is equal to the capital stock in period \( t \) depreciated at rate \( \delta \) plus investment in period \( t \).

\[
\max_{c(t)} \sum_{t=0}^\infty \frac{1}{1+\rho} U(c(t))
\]

subject to:

\[
Y(t) = F(K(t), L(t))
\]

where \( c(t) \) is consumption in period \( t \), \( Y(t) \) is output, \( I(t) \) is investment, \( K(t) \) is capital stock, \( L(t) \) is labor, \( U(\bullet) \) is utility function, and \( \rho \) is the time preference rate. In accordance to Barro and Sala-i-Martin^{27}, we assume a neoclassical production function \( F(\bullet) \) that satisfies the properties of homogeneity of degree one, positive, and diminishing marginal products, and the Inada conditions with respect to \( K \) and \( L \). Solving the utility maximization problem results in the first-order conditions, which can be rewritten as follows:

\[
P(t) = \left( \frac{1}{1+\rho} \right) \cdot \frac{\partial U(c(t))}{\partial c(t)}
\]

\[
PK(t) = (1-\delta) \cdot PK(t+1) + P(t) \cdot \frac{\partial F(\bullet)}{\partial K(t)}
\]

where \( P(t), PK(t), \) and \( PK(t+1) \) are the values of the corresponding Lagrange multiplier, and they can be interpreted such that \( P(t) \) is the output price in period \( t \), \( PK(t) \) is the capital price in period \( t \), and \( PK(t+1) \) is the capital price in period \( t+1 \). According to Paltsev^{26}, \( RK(t) \), \( W(t) \), and \( M \) represent rental rate of capital, wage rate, and consumer's income, respectively. Unit cost function \( C(\bullet) \) and demand function \( D(\bullet) \) are represented as \( C\left( RK(t), W(t) \right) \) and \( D\left( P(t), M \right) \). Then, we can formulate the equilibrium conditions in terms of three classes of equations: i) zero profit conditions, ii) market clearance conditions, and iii) income balance conditions, as the mixed complementarity problem.

i) zero profit conditions:

\[
P(t) \geq PK(t+1),
I(t) \geq 0,
I(t)\left( P(t) - PK(t+1) \right) = 0
\]

\[
PK(t) \geq RK(t) + (1-\delta) \cdot PK(t+1),
K(t) \geq 0,
K(t) \left( PK(t) - RK(t) + (1-\delta) \cdot PK(\bullet) \right) = 0
\]

\[
C(RK(t), W(t)) \geq P(t),
Y(t) \geq 0,
Y(t) \left( C(RK(t), W(t)) - P(t) \right) = 0
\]

ii) market clearance conditions:

\[
Y(t) \geq D(P(t), M) + I(t),
P(t) \geq 0,
P(t)\left( Y(t) - D(P(t), M) - I(t) \right) = 0
\]

\[
L(t) \geq Y(t) \left( \frac{\partial C(RK(t), W(t))}{\partial W(t)} \right),
W(t) \geq 0,
W(t)\left( L(t) - Y(t) \frac{\partial C(RK(t), W(t))}{\partial W(t)} \right) = 0
\]

\[
K(t) \geq Y(t) \left( \frac{\partial C(RK(t), W(t))}{\partial RK(t)} \right),
RK(t) \geq 0,
RK(t)\left( K(t) - Y(t) \frac{\partial C(RK(t), W(t))}{\partial RK(t)} \right) = 0
\]

iii) income balance conditions:

\[
M = PK(0) \cdot K(0) + \sum_{t=0}^\infty W(t) \cdot L(t), M > 0
\]

In this study, equilibrium conditions in the statics can be shown as equations (9), (11), (12), (13), and (14), while those in the dynamics can be shown as two equations (10) and (15) in addition to these static conditions. In addition, we assume that the depreciation rate of capital stock is 4% per year, interest rate is 5% per year, and population growth rate is 0.1% per year. In the time series data of total population in Japan by MIC^{28}, as the annual average growth rate from 2000 to 2010 is 0.089%, we assume the population growth rate of 0.1%.

Second, though our dynamic model needed to converge to a steady-state path, we employed Paltsev^{26} and Ban^{22} who assumed that their models were on a steady-state path in the initial period. If the solution is on a steady state, the following equations hold for any periods:

\[
P(t+1) = P(t)
\]

\[
P(t-1) = (1+r)P(t) = (1+\delta)P(t) + RK(t)
\]

\[
(n+\delta) \cdot K(t) = I(t)
\]

\[
RK(t) \cdot K(t) = VK(t)
\]
in accordance with Ban\textsuperscript{22}).

\begin{equation}
I(0) = \frac{(n + \delta)}{(r + \delta)} \cdot VK(0) \tag{17}
\end{equation}

Third, we had to solve the infinite horizontal problem numerically. Lau \textit{et al}.\textsuperscript{25} had shown that the terminal condition introduced in (18) could approximate the infinite horizon equilibria with endogenous capital accumulation. In accordance with Lau \textit{et al}.\textsuperscript{25}, Paltsev\textsuperscript{26}, and Ban\textsuperscript{22}, we introduced the level of the post-terminal capital stock as an endogenous variable and added a constraint wherein the growth rate of investment was equal to the growth rate of output in the terminal period. (assumption 3)). We assumed one calculation period as one year and calculated each scenario for 50 periods.

\begin{equation}
\frac{I(T)}{I(T-1)} = \frac{Y(T)}{Y(T-1)} \tag{18}
\end{equation}

Finally, in order to describe the existence of competitive equilibria by multiple agents in a numerical model, we employed the method by Lau \textit{et al}.\textsuperscript{25} in which the existence of equilibria by multiple agents could be ensured by explicitly illustrating a distribution problem of financial assets in the terminal period. Ban\textsuperscript{22} also employed the same method. For these formulations, see Lau \textit{et al}.\textsuperscript{25} and Ban\textsuperscript{22} in detail.

\textbf{(3) Setting of the Great East Japan Earthquake}

In this study, the Tohoku region (THK), which includes Iwate, Miyagi, and Fukushima, was assumed as a DSA as a result of the Great East Japan Earthquake. Then, direct impact of the earthquake on the DSA was assumed to spill over our economic activities in areas that included 20 production sectors in 8 regions. In addition, because assuming that both capital stock and labor in the DSA were damaged simultaneously made the model and interpreting the results more complex, we focused only on the capital stock damage in the DSA.

After the Great East Japan Earthquake in 2011, the Cabinet Office, Government of Japan\textsuperscript{1,2}, and Development Bank of Japan\textsuperscript{7,8} estimated the direct damage on capital stock. As for the seven prefectures, namely, Hokkaido, Aomori, Iwate, Miyagi, Fukushima, Ibaraki, and Chiba, the Cabinet Office, Government of Japan\textsuperscript{1,2} estimated these damages from about 16 trillion yen to about 25 trillion yen. Similarly, Development Bank of Japan\textsuperscript{7,8} estimated damage of about 16 trillion yen. From these estimations, it was likely that the sum of capital stock damage in four prefectures, namely, Iwate, Miyagi, Fukushima, and Ibaraki, was about 16 trillion yen and that in the Tohoku region was about 14 trillion yen. In addition, notice that various kinds of damage caused by the Fukushima Daiichi nuclear disaster were not included in these estimations.

Next, capital stock damage applied in our SCGE model was assumed. The capital stock damage discussed above is the stock concept. On the other hand, since capital stock data used in a SCGE model was the flow concept, capital stock damage due to the earthquake was transformed into that of the flow concept. According to Hayashiyama \textit{et al}.\textsuperscript{9} and Nakajima and Sakamoto\textsuperscript{11}, we calculated the damage rate of capital stock $\hat{s}^s$ in the s-region by dividing the total amount of estimated capital stock damage by the total amount of capital stock estimated. Then, by using estimated damage rates of capital stock $\hat{s}^s$ and an initial private capital endowment before the earthquake $K^s_{t=0}$, an initial private capital endowment in the s-th region after the earthquake $K^s_{t=1}$ is

\begin{table}[h]
\centering
\caption{Estimation of capital stock damage by the Development Bank of Japan\textsuperscript{7}).}
\begin{tabular}{|c|c|c|c|c|c|c|c|}
\hline
\textbf{DSA} & \textbf{Estimated Capital Stock (1 bn. Yen)} & \textbf{Estimated Capital Stock Damage (1 billion Yen)} & \textbf{Damage Rate (\%)} \\
\hline
Iwate & & & & & & & \\
\hline
Inland & 26,369 & 457 & 22 & 64 & 211 & 754 & 2.9 \\
Coast & 7,449 & 1,943 & 607 & 191 & 781 & 3,522 & 47.3 \\
Total & 33,818 & 2,400 & 629 & 255 & 992 & 4,276 & 12.6 \\
\hline
Miyagi & & & & & & & \\
\hline
Inland & 31,443 & 856 & 40 & 148 & 551 & 1,595 & 5.1 \\
Coast & 23,182 & 2,031 & 1,446 & 290 & 1,130 & 4,897 & 21.1 \\
Total & 54,625 & 2,887 & 1,486 & 438 & 1,681 & 6,492 & 11.9 \\
\hline
Fuku- & & & & & & & \\
shima Inland & 34,314 & 630 & 7 & 263 & 370 & 1,270 & 3.7 \\
Coast & 15,941 & 1,244 & 145 & 151 & 319 & 1,859 & 11.7 \\
Total & 50,254 & 1,874 & 152 & 414 & 689 & 3,129 & 6.2 \\
\hline
Ibaraki Inland & 47,827 & 460 & 40 & 175 & 318 & 993 & 2.1 \\
Coast & 21,727 & 766 & 87 & 355 & 275 & 1,483 & 6.8 \\
Total & 69,553 & 1,226 & 126 & 530 & 593 & 2,476 & 3.6 \\
\hline
Total Inland & 139,952 & 2,403 & 109 & 650 & 1,451 & 4,612 & 3.3 \\
Coast & 68,299 & 5,985 & 2,285 & 987 & 2,504 & 11,781 & 17.2 \\
Total & 208,251 & 8,387 & 2394 & 1,637 & 3,955 & 16,373 & 7.9 \\
\hline
\end{tabular}
\end{table}
defined in (19). In addition, calculating the capital stock damage discussed above means that we applied the results estimated by the Development Bank of Japan\textsuperscript{7,8}, and we employed direct capital stock damage of 13.9 trillion yen due to the Great East Japan Earthquake in Table 4.

\[
K^t_{l=1} = (1 - \delta^s) \cdot K^t_{l=0}
\]  

(19)

(4) Definition of damage cost

Damage cost equivalent to negative benefit is the utility differences, converted to monetary term, between scenarios with and without the Great East Japan Earthquake. As shown in (20), our damage cost is an instantaneous equivalent variation (EV) and this equivalent variation based on price in the reference equilibrium is defined as the difference between household consumption with and without the disaster.

\[
EV(t) = C^w(t) - C^{\text{stat}}(t)
\]

(20)

On the other hand, dynamic multiplier of damage cost is defined in (21), where \(EV_{\text{static}}\) is a static damage cost or a direct damage cost due to the Great East Japan Earthquake, and is equivalent to \(\delta^s \cdot K^t_{l=0}\) in (19). This index means that the ratio of a dynamic damage cost to a static damage cost represents direct damage due to the Great East Japan Earthquake. While a static damage cost is constant over time without consideration of an economic growth, a dynamic damage cost diminishes over time with consideration of an economic reconstruction from the Great East Japan Earthquake. That is because each household increases investment and decreases consumption to maximize its lifetime utility over an entire period, and an accumulation of capital stock in the DSA simulates recovery of production ability in the economy. This study applies 4% as a social discount rate used in Japan.

\[
\varphi = \sum_t \left( \frac{EV(t)}{(1 + r)^t} \right) / EV_{\text{static}}
\]

(21)

Also, using GDP, an economic reconstruction process from the disaster is shown in Fig. 4. Although the disaster causes a sharp fall in the economic growth path in the DSA like in 2011, as the economy recovers from it over time, it can be seen that an economic reconstruction path approaches a path that could be achieved without the disaster, that is, a reference path. In addition, GRP in the s-th region is defined, which consists of final demands in its own region (household consumption, government consumption, private investment and government investment in the s-th region), inter-regional export and import, and international trades (export and import).

4. SIMULATION RESULTS

(1) Dynamic damage cost

Fig. 5 shows the changes in dynamic damage costs in each region and Japan due to the Great East Japan Earthquake. First, in the initial period when the earthquake was assumed to occur, we estimated the damage cost in Japan at about 1,487 billion yen per year, in Hokkaido (HKD) at about 12 billion yen per year, in Tohoku (THK) at about 1,203 billion yen per year,
in Kanto (KNT) at about 176 billion yen per year, in Chubu (CHB) at about 26 billion yen per year, in Kinki (KIK) at about 31 billion yen per year, in Chugoku (CGK) at about 7 billion yen per year, in Shikoku (SKK) at about 7 billion yen per year and in Kyushu (KYS) at about 24 billion yen per year. After the period, the damage cost decreases over time in all regions. Then, in Fig. 6, while the present values of dynamic damage cost in Tohoku and Kanto, which was estimated to be 11,855 billion yen and 5,044 billion yen, were large, the present value of “benefit” in Chugoku was estimated to be 86 billion yen.

Second, from time series of dynamic damage costs in each region in Fig. 5, it can be seen that, while damage costs in Hokkaido, Tohoku, and Kanto are negative in an entire calculation period, the other regions except for three regions become positive from the 12th period (CGK) to the 26th period (KYS). The dynamic damage cost in Japan, however, is negative over an entire period. As Hokkaido and Kanto are located next to Tohoku, which was damaged due to the earthquake and because these regions trade with each other, a supply constraint due to the earthquake in Tohoku has negative effects on economic activities in Hokkaido and Kanto.

Third, as the static damage cost (direct damage cost) due to the earthquake was 13,897 billion yen and the present value of dynamic damage cost was calculated to be 17,932 billion yen, the dynamic multiplier was estimated to be 1.29. That makes it possible to interpret that damage cost with consideration of economic reconstruction is 1.29 times greater than the direct damage cost without it.

(2) Economic reconstruction

Fig. 7 shows the rates of change of GDP and GRP with respect to a no-earthquake situation. The rates of change in GDP and GRP in Tohoku approach zero over time. Also, though the rates of change in GRP in any region except for Tohoku are positive in the initial period, after becoming negative, these rates approach zero over time.

On the other hand, Fig. 8 shows the trends in GDP in Japan and Fig. 9 shows the trends in GRP in Tohoku, comparing scenarios with or without the earthquake, respectively. In these two figures, an economic growth path with consideration of economic reconstruction in red line approaches an economic growth path that could be achieved without the earthquake in blue line. Especially, though the earthquake causes GRP to sharply fall in Tohoku, it can be seen that the economic reconstruction makes the economic activity in Tohoku to rapidly recover. Also, the results of trends in GDP and GRP in Tohoku are explained in Fig. 4 as previously mentioned, and show that the economy with the earthquake would be able to return to the economy without it in the future.

In addition, Table 5 shows the regional and sectoral changes in production rates at the last period. From a sectoral point of view, in Chubu (CHB), Kinki (KIK), Chugoku (CGK), Shikoku (SKK), and Kyushu (KYS), while the change in production rate in the secondary industry is negative, the one in the tertiary industry is positive. On the other hand, In Tohoku (THK), while the secondary industry has positive production rate, the tertiary industry has a negative one. Also, Hokkaido (HKD) and Kanto
(KNT), which are located near the Tohoku region, have the same results. Moreover, compared with change in production without the disaster at the last period, though the change in production rate in Japan is negative, there are regions and sectors that increase in production with the disaster. Therefore, it can be seen that production substitution among regions occurs in the process of economic recovery from the disaster.

(3) Sensitive analysis

In order to consider the temporal-spatial impact of the elasticity of substitution among domestic inter-regions and one between domestic supply goods and imports on regional economy, we conducted four sensitive analyses by using four elasticities of substitution: 0.5, 1.0, 2.0 (default), and 4.0. Also, comparing with the results of Yamazaki et al.\(^{17}\) that used sensitive analysis of these parameters on the elasticity of substitution by using a recursive dynamic CGE model, we also checked the validity of our forward-looking dynamic model and discussed the relationship between the inter-regional and domestic-import elasticity of substitution and the pattern of economic reconstruction in Tohoku.

At first, Fig. 10 and Fig. 11 show dynamic damage costs and the rates of change in GRP in Tohoku with respect to four different elasticities of substitution. These two figures show that the smaller the elasticity of substitution among domestic inter-regions and one between domestic goods and import, the faster the speed of economic reconstruction.

Second, Fig. 12 and Fig. 13 show the degrees of contribution of GRP in Tohoku under the elasticity of substitution 0.5 and 4.0, respectively. In the case of small elasticity of substitution shown in Fig. 12, while decreases in household consumption account for the downturn of GRP and decreases in export and inter-regional export and increases in inter-regional import are the factors for the downturn of GRP, increases in private investment lead to improvement of GRP over time. On the other hand, in the case of large elasticity of substitution in Fig. 13, though decreases in export and inter-regional export and increases in inter-regional import account for the downturn of GRP in the earlier period, increases in export and inter-regional export and decreases in inter-regional import become the factors for improvement of GRP from the middle periods.

Third, Table 6 and Table 7 show the regional and sectoral changes in production rates at the last period. In the case of small elasticity shown in Table 6, production abilities in almost all sectors in Tohoku recover up to or above the level of that without the disaster. Also, while decrease in production in Tohoku is large (-0.210%) in 2.0 of elasticity of substitution, one is small (-0.003%) in 0.5 of elasticity. Therefore, it can be seen that the smaller elasticity of substitution could allow rapid recovery of production ability.

Finally, Yamazaki et al.\(^{17}\) concluded that smaller elasticity of substitution could achieve a rapid recovery in the economy. That is because increase in investment (savings) and increase in income level in the DSA stimulate accumulation of capital stock in the DSA. We also checked this result. At first, as small elasticity of substitution means the specialty of

Table 5 Regional and sectoral production change (%).

| Region | AGR | FRS | FSH | MIN | FOD | OMF | CPR | P_C | I_S | MTL | MCH | ELM | CNS | FLY | QFT | WTR | COM | MED | ANC | TOTAL |
|--------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-------|
| HKD   | -0.02 | -0.03 | -0.03 | -0.02 | -0.02 | -0.02 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 | -0.01 |
| THK   | 0.04  | -0.07 | -0.02 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 |
| KNT   | 0.04  | -0.07 | -0.02 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 | -0.07 | -0.05 |
| CHB   | -0.05 | 0.37  | -0.01 | -0.03 | -0.13 | -0.18 | -0.24 | -0.17 | -0.12 | -0.12 | -0.11 | -0.11 | -0.11 | -0.11 | -0.11 | -0.11 | -0.11 | -0.11 | -0.11 | -0.11 |
| KIK   | 0.00  | 0.33  | -0.03 | -0.04 | -0.05 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 |
| CGK   | 0.00  | 0.33  | -0.03 | -0.04 | -0.05 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 |
| SKK   | 0.00  | 0.33  | -0.03 | -0.04 | -0.05 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 |
| KYS   | 0.00  | 0.33  | -0.03 | -0.04 | -0.05 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 | -0.04 |
| TOTAL | -0.051 | -0.185 | -0.022 | -0.012 | -0.015 | -0.020 | -0.027 | -0.036 | -0.021 | -0.033 | -0.032 | -0.031 | -0.030 | -0.029 | -0.028 | -0.027 | -0.026 | -0.025 | -0.024 |
The degree of contribution of GRP in Tohoku (elasticity: 0.5).

The degree of contribution of GRP in Tohoku (elasticity: 4.0).

outputs produced in Tohoku is so high, the earthquake causes production price in Tohoku to rise, as shown in Fig. 14. Next, rise in production prices and reinforcing the value of capital stock in the DSA increase production factor prices, as shown in Fig. 15. As a result, by increasing the household income in Tohoku as shown in Fig. 16, private investment in Tohoku and investment demand in Tohoku increase as shown in Fig. 17. Therefore, in the case of small elasticity of substitution among domestic inter-regions and a small one between inter-regional goods and import, stimulating the recovery of production ability in the economy through increasing investment in the DSA makes rapid economic reconstruction feasible. We have shown that our study has the same conclusions as those of Yamazaki et al. (17).

What is the significance of the same results between this study with the forward-looking dynamic model and that of Yamazaki et al. (17) with the backward-looking (recursive) dynamic model?

First, from a long-term perspective, the forward-looking dynamic model is consistent with the economic theory. As shown by Ban (22), since the forward-looking model determines a sequence of savings and investment based on the discounted present value of the rate of return to capital over the future, the advantage of the forward-looking model is that it makes it possible to obtain the impact of change in economic and environmental situations in the future on the determination of savings and investment before this change. On the other hand, for the existence of steady-state equilibria, the forward-looking model needs the same growth rate of population in all regions. The disadvantage of the model would be this assumption that is extremely strict and unrealistic.

| Table 6 Regional and sectoral production change (%) (Elasticity: 0.5). |
|-----------------|---------------|---------------|---------------|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
|                | HAD | THK | EKT | CHB | EWB | CGS | SKS | KNT | HKD | TOTAL |
| GRP            | -0.12 | 0.05 | -0.12 | -0.21 | 0.04 | 0.06 | -0.17 | 0.04 | 0.02 | -0.07 |
| Consumer       | -0.38 | -0.38 | -0.48 | -0.80 | 0.04 | 0.06 | -0.17 | 0.04 | 0.02 | -0.07 |
| Savings        | 0.01  | 0.56  | -0.05  | -0.16  | -0.15  | -0.17  | -0.26  | -0.29  | 0.095  | -0.028 |
| Investment     | 0.04  | 1.49  | 0.02  | -0.11  | -0.15  | -0.14  | -0.56  | -0.24  | 0.095  | -0.028 |
| Goods          | 0.02  | 0.44  | 0.04  | 0.00  | 0.01  | 0.00  | 0.01  | 0.02  | 0.02  | 0.025 |
| Services       | 0.01  | 0.51  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |
| Private        | 0.02  | 0.38  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |
| Inter-regional | 0.02  | 0.38  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |
| Export         | 0.02  | 0.38  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |
| Import         | 0.02  | 0.38  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |
| Table 7 Regional and sectoral production change (%) (Elasticity: 4.0). |
|-----------------|---------------|---------------|---------------|---------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------------|---------------|---------------|---------------|---------------|---------------|---------------|
|                | HAD | THK | EKT | CHB | EWB | CGS | SKS | KNT | HKD | TOTAL |
| GRP            | -0.10 | -0.06 | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  | 0.00  |
| Consumer       | -0.38 | -0.38 | -0.48 | -0.80 | 0.04 | 0.06 | -0.17 | 0.04 | 0.02 | -0.07 |
| Savings        | 0.01  | 0.56  | -0.05  | -0.16  | -0.15  | -0.17  | -0.26  | -0.29  | 0.095  | -0.028 |
| Investment     | 0.04  | 1.49  | 0.02  | -0.11  | -0.15  | -0.14  | -0.56  | -0.24  | 0.095  | -0.028 |
| Goods          | 0.02  | 0.44  | 0.04  | 0.00  | 0.01  | 0.00  | 0.01  | 0.02  | 0.02  | 0.025 |
| Services       | 0.01  | 0.51  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |
| Private        | 0.02  | 0.38  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |
| Inter-regional | 0.02  | 0.38  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |
| Export         | 0.02  | 0.38  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |
| Import         | 0.02  | 0.38  | 0.01  | 0.02  | 0.01  | 0.03  | 0.02  | 0.02  | 0.02  | 0.025 |

Fig. 14 Production prices in Tohoku (Elasticity: 0.5).
Second, from the point of view of numerical calculation, since the backward-looking dynamic model is preferable to the forward-looking model, the backward-looking dynamic model has been employed in a large number of dynamic CGE models. The backward-looking model has a static framework, but it has a dynamic structure in which capital stock in the next period is accumulated based on investment determined by an exogenous saving rate. The advantage of the backward-looking model is that it makes it possible to perform a long-term simulation within a short calculation time and to perform detailed setting in various conditions, and different growth rates of population in each region. On the other hand, the disadvantage of the model would be inconsistent with the economic theory by a dynamic model.

The significance of the similarity of the results of this study with those of Yamazaki et al. is that the forward-looking model, under strict constraints and unrealistic assumptions, can show realistic results. Also, in dynamic analysis with long-term perspectives, since it is important to obtain various impacts of the economic and environmental changes in the future—not only on the economy after the change, but also on the economy before the change—the forward-looking dynamic model can show the economic impacts that the backward-looking dynamic model cannot analyze. Therefore, the results of this study can be considered appropriate and significant.

5. CONCLUDING REMARKS

In order to examine the economic impacts of the damage due to the Great East Japan Earthquake in 2011 and the reconstruction process on the disaster-stricken areas and all prefectures, we developed a dynamic spatial computable general equilibrium model that consisted of 8 regions and 20 industrial sectors. We also described the economic dynamics of damages and reconstructions after the earthquake, and measured the dynamic benefits of the reconstruction processes. The findings of our study are as follows:

1. The discounted present value of the dynamic damage cost with reconstruction from the earthquake was estimated to decrease to about 17.9 trillion yen in total, which was 1.29 times greater than decreases in the direct damage cost of about 13.9 trillion yen in Tohoku disaster-stricken areas.

2. Our result has two significant aspects. One is that the only measurement of the direct damage cost is underestimated regardless of benefit or damage cost (negative benefit). The other is that, by introducing the dynamic multiplier of damage cost and benefit into the conventional benefit measurement technique, we can measure damage cost and benefit more accurately based on the economic theory.

3. Compared with the results of an earlier study with the backward-looking dynamic model in our sensitive analysis, we found that the forward-looking dynamic model, under strict constraints and unrealistic assumptions, could show realistic results.

Further discussion is needed in the future. The measurement of benefits dealing specifically with the temporal dimension can be divided into intertemporal (lifetime) measure and instantaneous measure. Though the former is defined as a theoretically exact benefit measure, measuring it requires an extremely large and complex computation. On the other hand, Johansson showed that the relatively lower calculation cost had been used in a large number of empirical studies. The instantaneous EV we employed can be calculated immediately from calculation results of our simulation analysis. As the use of the instantaneous EV, however, sacrifices some theoretical consistency, we need to develop a model introducing the intertemporal benefit measure.

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