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New concept of societal resilience against natural hazards

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Abstract

It can be found in the past numerous literatures that there are many natural disasters where societal resilience is a key issue for describing the recovery process from damage state such as earthquake disaster, heavy rainfall, volcanic eruption, etc. Many relevant researches on "resilience" against natural hazards have been conducted with variety of definitions of “resilience”. “Resilience” has often been treated in a time axis as a resilience rate, degree of recovery per unit time from the damage state. In most of them, “resilience” is described as degree of capability of recovery from the damage of systems in a specified time.

If a target system has no interaction with and no dependency from its external supplying systems during the recovery process, it would be valid to evaluate the resilience of the system alone. Considering the recovery mechanism within the system, the system must possess capability of self-recovery which can rarely be realized in most of systems such as societal systems, physical systems, engineering systems, even biological systems. Most of modern recovery mechanism depend heavily on physical supply, human support from the external systems or external environment, all of which must still have extra capability of supporting the system in damage. How high the resilience of a societal system is depends upon not only how high the self-recovery capability is, but also upon how much support can be obtained from its surroundings.

In light of the above thoughts, the present paper proposes new concept of the societal resilience of societal system or a target region, which can take account of its self-recovering capability and dependence of support from external systems. The new concept will be applied to several typical natural disasters such as earthquakes, tornados, etc. Degradation of societal resilience in case of earthquakes is significant since most of earthquakes can affect wider regions and damage them simultaneously. In case of local disasters such as tornados, landslides, however, societal resilience of the target region could be kept because of support of external regions. These different damage characteristics of natural disasters can be taken into consideration when the societal resilience is estimated.

In this paper, theoretical formulation of societal resilience as stated in the above will be shown and is applied to some recent actual disasters in Japan to examine its effectiveness of the concept of the societal resilience which is proposed herein.

Keywords: Resilience, Disaster resilience, Disaster recovery, Societal resilience

1. Introduction

Concept of resilience that describes restorative capacity or robustness of a system has attracted great attention in the engineering field in recent years [1]. Also in building or urban engineering resilience gains high recognition, and especially regional resilience, restorative capability from disaster damage, attracts attention. However, the definition or treatment of the resilience varies among studies, and in addition most of them do not go much beyond concept demonstration, do not go far enough to evaluate quantitatively [2] [3].

In most of relevant researches, general definition of resilience [4] is used extensively is shown in Fig.1, where its vertical axis is for the recovery ratio of an intended system, and horizontal for elapsed time after initiation of damage. At first time the system has 100% function, at next time suffers damage from disasters, and then restores its function with time. The all of integration of recovery curve drawn by the recovery process is defined as resilience. In other words, most of resilience used is the concept describing temporal recovery process from damaged to normal states.

Several works study the regional resilience against natural hazard in accordance with this definition. Some works studied about resilience of utilities or medical function [5] [6], and the others about resilience of population recovery from earthquakes [7] [8]. But, considering that recovery process in region of distress proceeds not only by self-support, but also with restoration supports from surrounding regions, spatial dependency and interaction among regions must be taken in to consideration as shown in Fig.2, its conceptual scheme.

Nevertheless none of work has evaluated the regional resilience directly introducing these recovery supports so far. And another thing, most of previous studies deal with only specific single hazard as earthquake, and then they cannot be generally applied to a multiple of hazards.

In this context, this paper proposes new definition and evaluation methodology for more general regional resilience, which is with consideration for recovery supports effects, and can be applied to general resilience process due to variety of hazards.

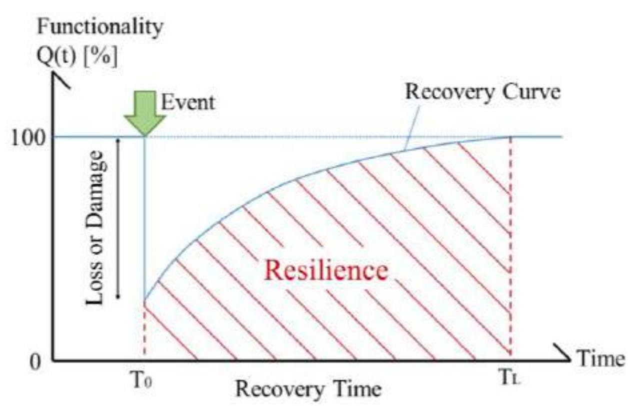


Fig. 1 – General definition of resilience

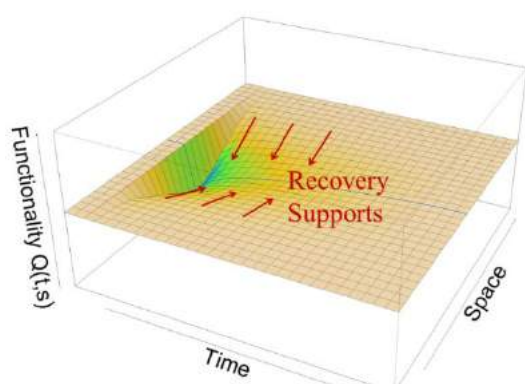


Fig. 2 – Regional resilience with consideration for recovery supports

2. Theoretical fomulation

In this paper a diffusion analysis model is adopted in order to describe spatial effect of restoration supports in a regions. The diffusion analysis describes temporal and spatial transition state of diffusion material density such as smoke flow or heat conduction. Then this diffusion phenomenon is related to spatial spread of restoration support which are expected during and after disasters.

2.1 Diffusion analysis model

Diffusion analysis solves a diffusion equation about transition of a diffusion material density in discretely-distributed two-dimensional space mesh as shown in Fig.3. A two-dimensional linear non-stationary diffusion equation is given in the following.

$$\frac{\partial \phi}{\partial t} = D\left(\frac{\partial^2 \phi}{\partial x^2} + \frac{\partial^2 \phi}{\partial y^2}\right) + Q \tag{1}$$

Where ϕ is a density of diffusion material; t is time; x and y are space coordinates; D is a diffusion rate as a function of space but not time-dependent; Q is time constant increment of a density.

The discrete expression of Eq. (1) in discrete temporal-spatial axes in an ith- and j-th mesh is given by

$$\frac{\phi_{i,j}^{n+1} - \phi_{i,j}^{n}}{\Delta t} = D\left(\frac{\phi_{i-1,j}^{n} - 2\phi_{i,j}^{n} + \phi_{i+1,j}^{n}}{\Delta x^2} + \frac{\phi_{i,j-1}^{n} - 2\phi_{i,j}^{n} + \phi_{i,j+1}^{n}}{\Delta y^2}\right) + Q \tag{2}$$

Where n is the time step. A density at n+1 step is obtained recurrently from a density at n step in Eq. (2) .

2.2 Practical recovery activity

Meguro proposed that three fundamental but essential types of recovery activities, “Self-aid”, “Mutual-aid”, “Public-aid”, are important for recovery of region of distress [9]. “Self-aid” is activity within a single distressed region; “Mutual-aid” and “Public-aid” are interactive activities with surrounding regions.

2.3 Relationship between actual phenomenon and model

Figure 4 shows correspondence between these actual recovery activities and parameters to be used in the diffusion analysis model. The actual distribution of recovery state in regions is explained by the distribution of density ϕ in the analysis model. Considering the recovery of region, ϕ will be termed as Recovery Index (RI). Then, progress of recovery of region corresponds transit of Recovery Index ϕ. “Self-aid” is explained by the internal increment in mesh, which is obtained by the increment rate of density Q. Q is termed as Self Recovery Rate (SRR). “Mutual-help” or “Public-help” is explained by the transition by diffusion of density from surrounding meshes, which is obtained by the diffusion rate D. D is termed as External Supply Rate (ESR), which represents rate of transmission of external supply per unit time.

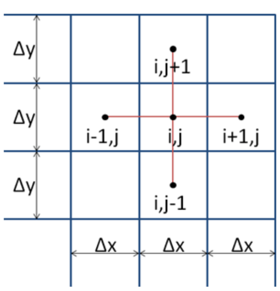


Fig. 3 – Two-dimensional space mesh in diffusion analysis

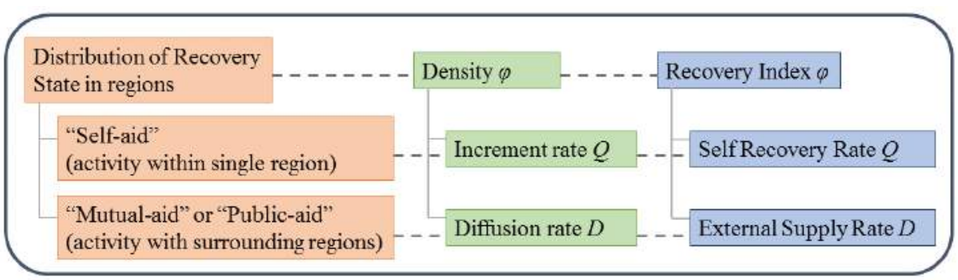


Fig. 4 – Relationship between factual phenomenon and diffusion analysis model

3. Model validity

3.1 Analysis object

The targets of simulation were regions in three prefectures (Iwate, Miyagi, and Fukushima Prefecture), six months after The Great East Japan Earthquake (from March to August, 2011) as shown in Fig.5. It is the earthquake of magnitude 9.0 centered in Pacific Ocean off Sanriku at 14:46 PM on May 11th, 2011. This disaster extensively harmed regions of Tohoku mainly by the following great tsunami.

The result of simulation is compared with the observed data. The observed data is Recovery Index in “The Great East Japan Earthquake – Recovery, reconstruction index” [10] published by NIRA (National Institute for Research Advancement). RI in this literature is described as the ratio of the functionality of region to that before the disaster. Total Recovery Index (TRI) is now defined as an averaged index, Individual Recovery Indexes (IRIs), including occupancy rate of provisional housing, utilities (electric power, gas or water), transport facilities (railroad or road) and so on as shown in Table.1. In this paper not only TRI, but also IRIs were targeted. Since it is described in each administrative district or in each local municipality, it needs to be transformed to regional mesh unit form to use for analysis.

Table. 1 – Example of observed RI

100 = full recovery

Date	Ratio of refugees to population	Occupancy rate of provisional housing	Electric power	Gas	Railroad	Road	Debris removal ratio	Debris desposal ratio	Charity supply rate	Medical facility (Hospital)	Medical facility (Clinic)	Total Recovery Index
Sendai-shi												
201103	86	--	99.8	21.3	19.8	100	0	--	0	100	98.5	47.5
201106	98.3	53.3	100	100	100	100	18	--	4.5	100	98.7	69.2
201109	100	93.5	100	100	100	100	70	1.9	45.8	100	98.7	82.7
201112	100	98.9	100	100	100	100	97	7.8	78	100	98.7	89.1
201201	100	98.9	100	100	100	100	97	9.7	81.7	100	98.7	89.6
201202	100	98.9	100	100	100	100	97	10	83.5	100	98.7	89.8
201203	100	98.9	100	100	100	100	97	12.9	88.5	100	98.7	90.5
201204	100	98.9	100	100	100	100	97	18.4	91.2	100	98.7	91.3
201205	100	98.9	100	100	100	100	98	21.4	92	100	98.7	91.7
201206	100	98.9	100	100	100	100	98	24.2	92.4	100	98.7	92
201207	100	98.9	100	100	100	100	99	24.2	92.6	100	98.7	92.1
201208	100	98.9	100	100	100	100	99	32.5	92.8	100	98.7	92.9
201209	100	98.9	100	100	100	100	99	37.6	92.9	100	98.7	93.4
201210	100	98.9	100	100	100	100	99	43	99.2	100	98.7	94.4
201211	100	98.9	100	100	100	100	99	48.4	99.2	100	98.7	94.9
201212	100	98.9	100	100	100	100	99	50.8	99.2	100	98.7	95.1
201301	100	98.9	100	100	100	100	99	53.1	99.2	100	98.7	95.4
201302	100	98.9	100	100	100	100	99	63.6	99.2	100	98.7	96.3
201303	100	98.9	100	100	100	100	99	71.7	99.2	100	98.7	97

3.2 Analysis condition

Since the Japanese tertiary regional mesh has 1 km grid in both of latitude and longitude, the two-dimensional space mesh for discretization is set as 1 km grid. The unit time in analysis (1 step time) was 6 hours, and then 120 steps were comparable to 1 month. The initial RI ϕ in the analysis is plugged with RI in observed data immediately after the disaster.

SRR Q (related to internal recovery activities) is considered to be depend on RI, and then decided based on initial RI.

ESR D (related to external recovery activities) is also considered to be depend on RI, but its effect to transition of RI was more than SRR. Therefore, ESR D with the best reproducible precision was estimated by the following optimization method.

3.3 Optimization method for estimating External Supply Rate D

In this paper, the steepest descent method, one of the gradient methods, is adopted to identify the parameters because this method is so simple to calculate a lot of parameters. The algorithm of the steepest descent method is shown below.

Some function $f(\boldsymbol{\Theta}_0)$, a function to be minimized, has the parameters set $\boldsymbol{\Theta}_0$ given by

$$\Theta_0 = [a_0 \quad b_0 \quad \cdots \quad z_0]^T \tag{3}$$

Where a_0, b_0, …, z_0 are parameters of $f(\boldsymbol{\Theta}_0)$. With Θ_0 as initial value for searching, the gradient of $f(\boldsymbol{\Theta}_0)$ for $\boldsymbol{\Theta}_0$ is obtained as below

$$\nabla f(\Theta_0) = \frac{\partial f(\Theta_0)}{\partial a_0} + \frac{\partial f(\Theta_0)}{\partial b_0} + \cdots + \frac{\partial f(\Theta_0)}{\partial z_0} \tag{4}$$

By using $\nabla f(\Theta_0)$ best suited parameters were sequentially searched as below

$$\Theta_{n+1} = \Theta_n - \beta \nabla f(\Theta_0) \tag{5}$$

By Eq. (5), parameters move to smaller gradient direction, and finally the parameters for minimum of the function $f(\boldsymbol{\Theta}_0)$. In Eq. (5) the adequate range of weight coefficient β depends on sorts of problem of dealing with, and is set not to diverge of analysis result.

In this paper, the parameters set to be estimated was ESR D in each mesh in two-dimensional space. The minimization function is an RMS (root-mean-square) error function between observed and simulated RI as below

$$RMS[error] = \sqrt{\frac{1}{n_i n_j n_k} \sum_{i=1}^{n_i} \sum_{j=1}^{n_j} \sum_{k=1}^{n_k} (\phi_{observed}(k) - \phi_{simulated}(k, D_{ij}))^2} \tag{6}$$

Where $RMS[error]$ is a minimization function, $\phi_{observed}$ is RI in observed data, and $\phi_{simulated}(D_{ijk})$ is RI in simulated result, depending on ESR D. i and j are coordinate in mesh and n_i and n_j is a number of meshes for error calculation. k is step number and n_k is a number of steps for error calculation.

The distribution of ESR obtained by the steepest descent method is shown in Fig.6.

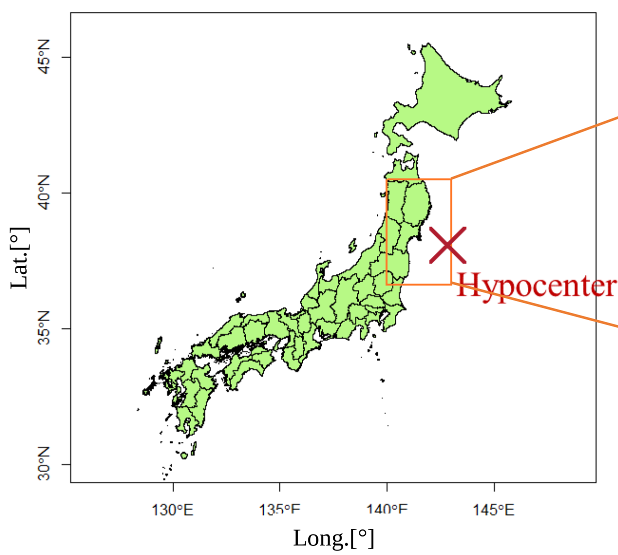


Fig. 5– Object regions in Japan

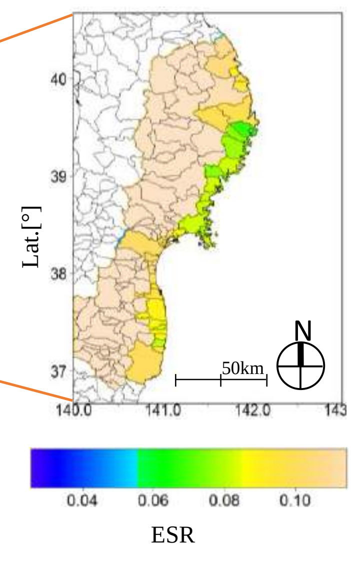


Fig. 6– Distribution of ESR estimated

4. Result of TRI

The result of simulation about TRI is shown in this chapter.

4.1 Overall reproducibility of phenomena

The comparison maps between TRI of diffusion simulated result and observed TRI is shown in Fig.7.

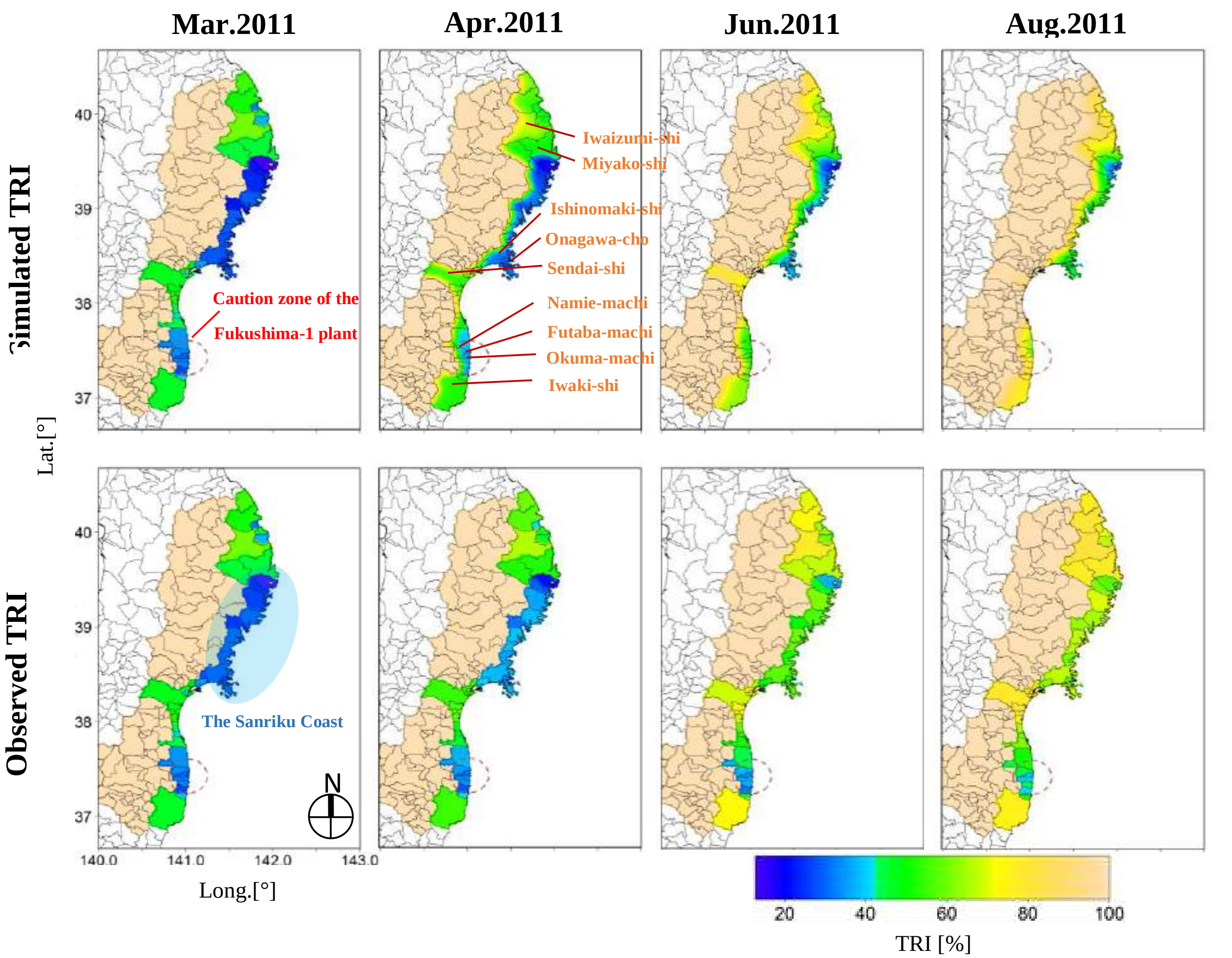


Fig. 7 – Comparison map of simulated and observed TRI

In Fig.7, monthly TRI from March to August are plotted as heat maps. In each figure the upper map shows simulated result and the lower shows observed data. Additionally, the red dashed circle shows the caution zone associated with the Fukushima-1 plant (Fukushima Daiichi Nuclear Power Station).

At the first step, in March, in the inshore areas including the Sanriku Coast (the area of light blue ellipse in the left lower map) TRI weakened by tsunami damage. Since then, the broad appearance of gradually increment of TRI in observed data is reappeared by simulated TRI distribution at each step. Focusing on the local, however, the appearances differed in the areas around Fukushima-1 plant; in observed data the recovery gets delayed, on the other hand in simulated recovery progresses slightly faster than observed.

4.2 Numerical accuracy

For reviewing numerical accuracy of TRI, the comparison between observed data and simulated result is shown in Fig.8.

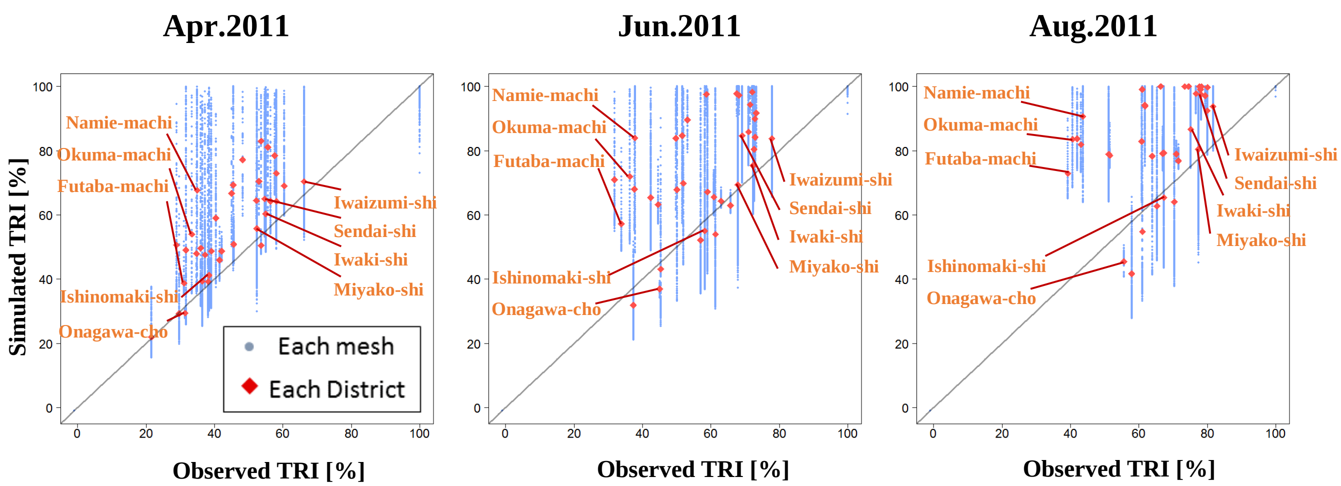


Fig. 8 – Comparison of simulated and observed TRI

The left graph shows April, the median June, and the right August. The vertical line shows the simulated TRI and the horizontal the observed TRI. The blue points are values at each analysis mesh and the red points are mean values in each district.

The distribution of ratio of TRI of simulated to TRI of fact is shown in Fig.9.

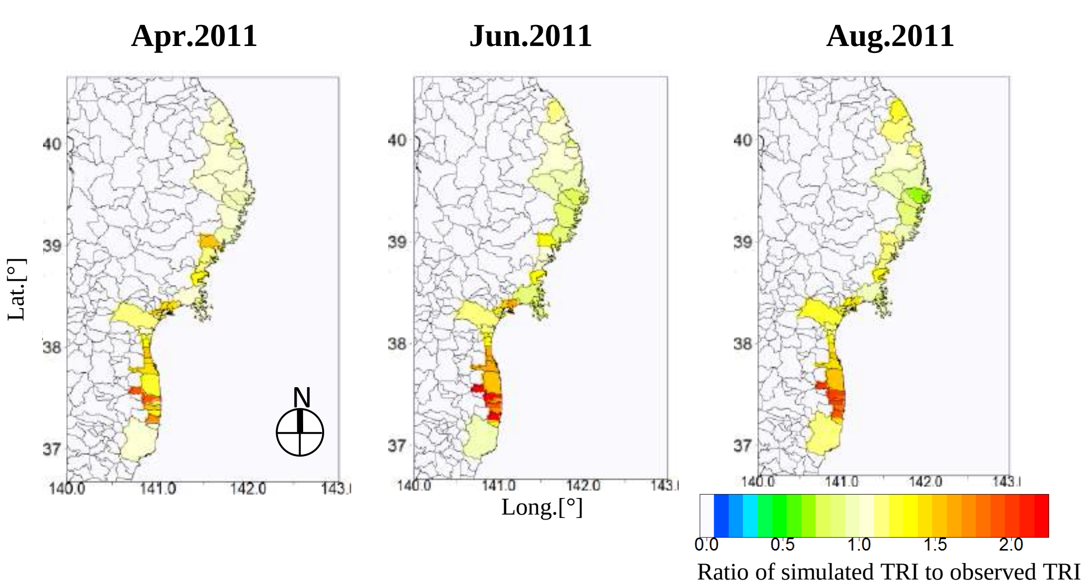


Fig. 9 – Ratio of simulated TRI to observed TRI

The richer color districts are less accurate; rich red denotes overestimate and rich light blue denotes underestimate.

From Fig.8 and 9, repeatable precisions in the districts around Fukushima-1 plant (Namie-machi, Futaba-machi, Ookuma-machi, and so on) had bad correspondence. However, some districts (Sendai-shi, Iwaki-shi, miyako-shi, Ishinomaki-shi, Onagawa-cho, and so on) had good agreeement.

4.3 Recovery curve

The temporal alteration of TRI in each district is shown in Fig.10.

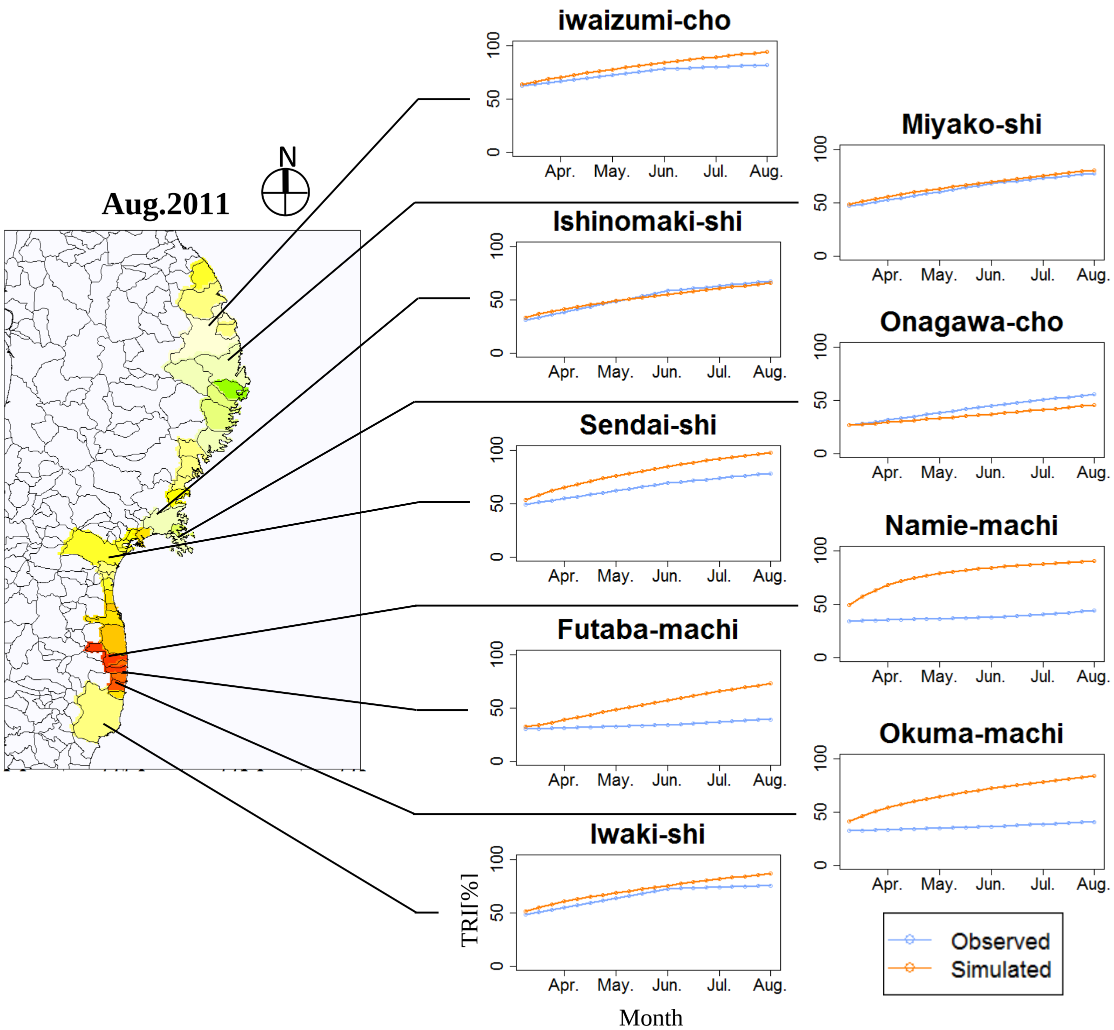


Fig. 10 – Recovery curve of TRI

In the districts around Fukushima-1 plant the recovery curves of TRI differed between observed and simulated; the simulated recovery process was earlier (in other words, the simulated was overestimate). On the other hand, in some districts including Sendai-shi and Ishinomaki-shi, the simulated recovery curves finely corresponded to the observed.

5. Result of IRIs

The result of simulation about IRIs is shown in this chapter.

Because of their size of effect to recovery process, three IRIs, the function recovery ratio of medical facilities, the debris removal ratio, and the railroad and road recovery ratio, was considered.

5.1 Function recovery ratio of medical facilities

These are the result of simulation about the first IRI, the function recovery ratio of medical facilities.

Fig.11 shows the comparison map, Fig.12 the ratio of simulated to observed IRI, and Fig.13 the recovery curves of IRI.

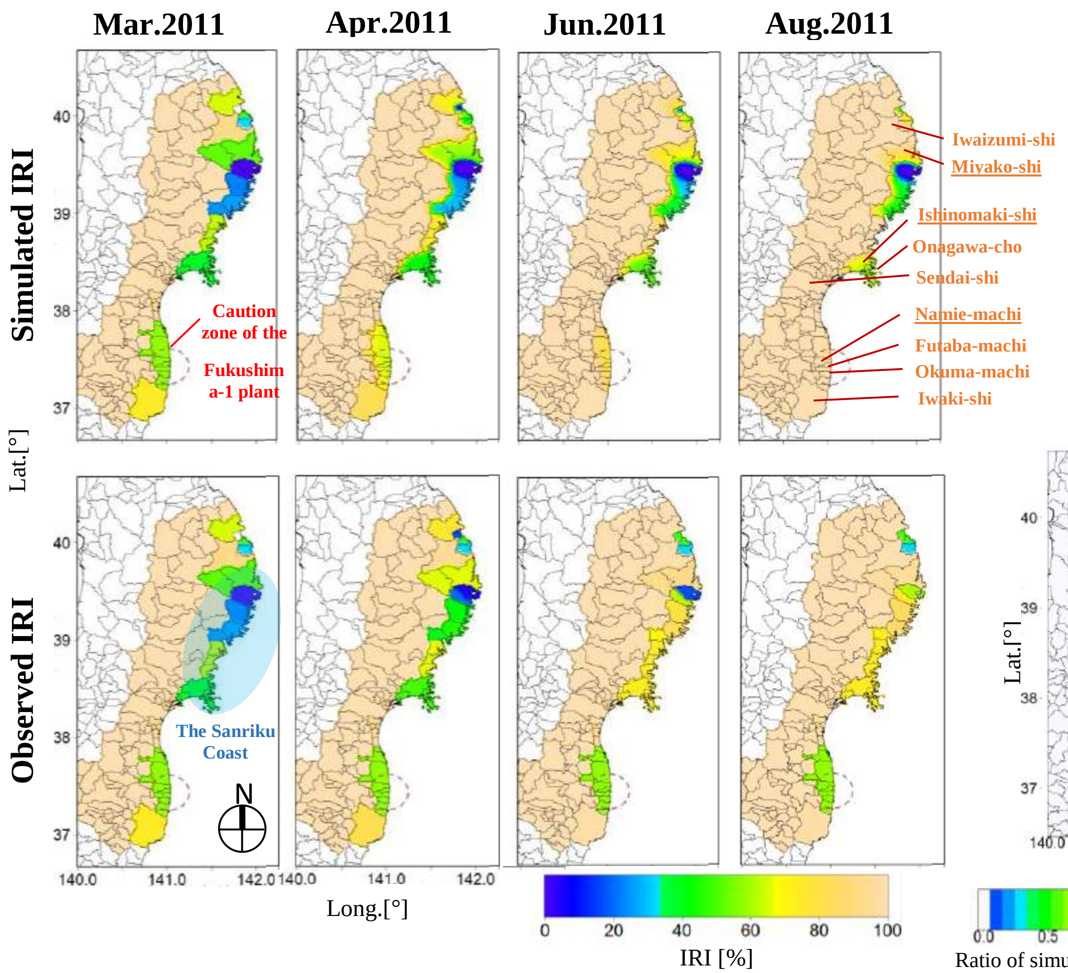


Fig. 11 – Comparison map (medical facilities)

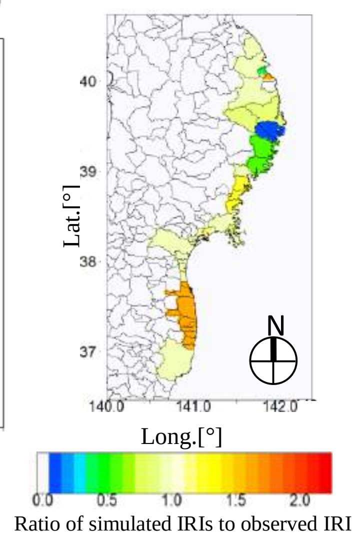


Fig. 12 – Ratio of simulated to observed IRI (medical facilities)

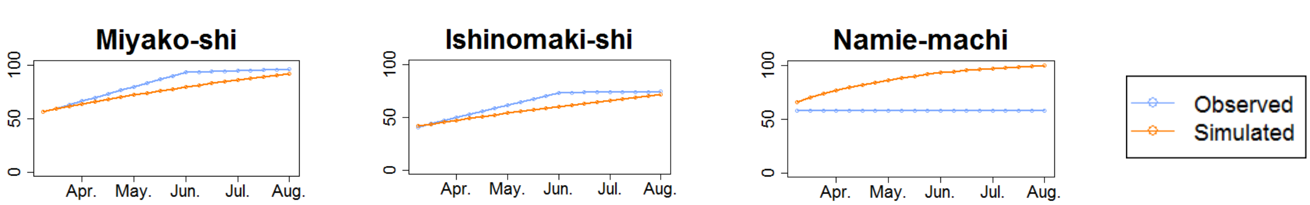


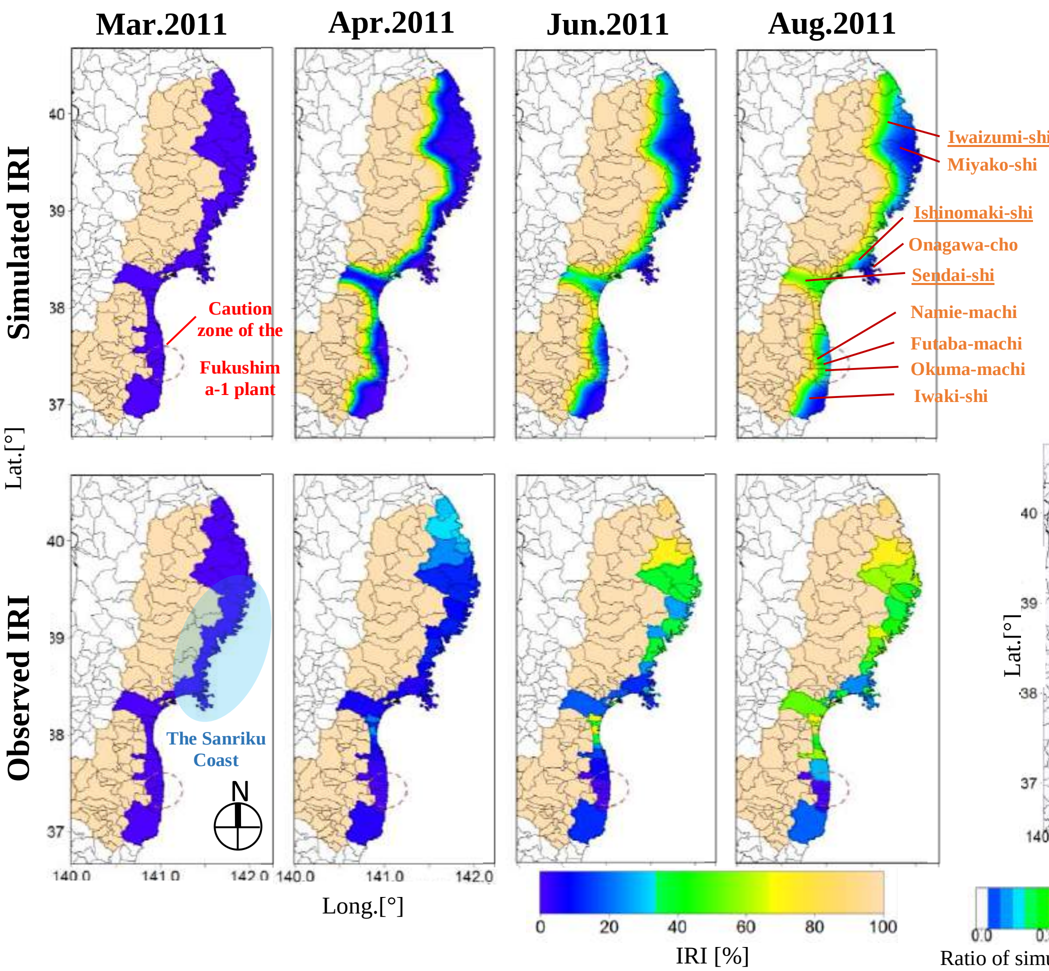
Fig. 13 – Recovery curves of IRI (medical facilities)

In the districts around Fukushima-1 plant or on the Sanriku Coast, the reproducibility of analysis was not good. However, in the other districts, the simulated IRI corresponded to the observed.

5.2 Debris removal ratio

These are the result of simulation about the second IRI, the debris removal ratio.

Fig.14 shows the comparison map, Fig.15 the ratio of simulated to observed IRI, and Fig.16 the recovery curves of IRI.



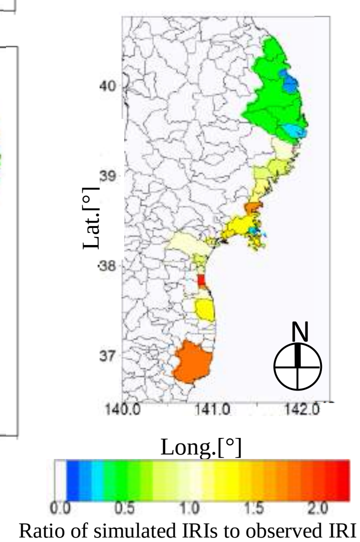


Fig. 14 – Comparison map (debris removal)

Fig. 15 – Ratio of simulated to observed IRI (debris removal)

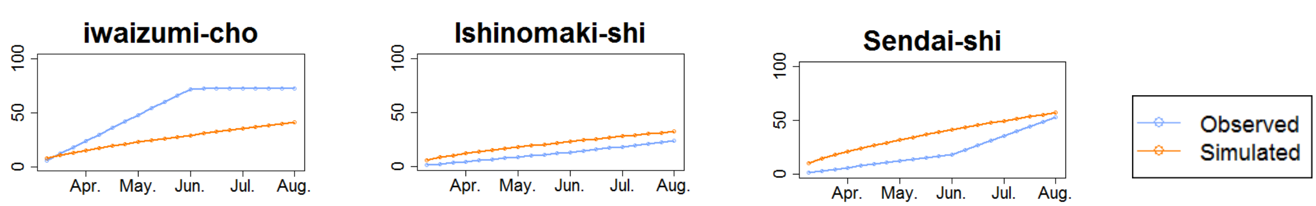


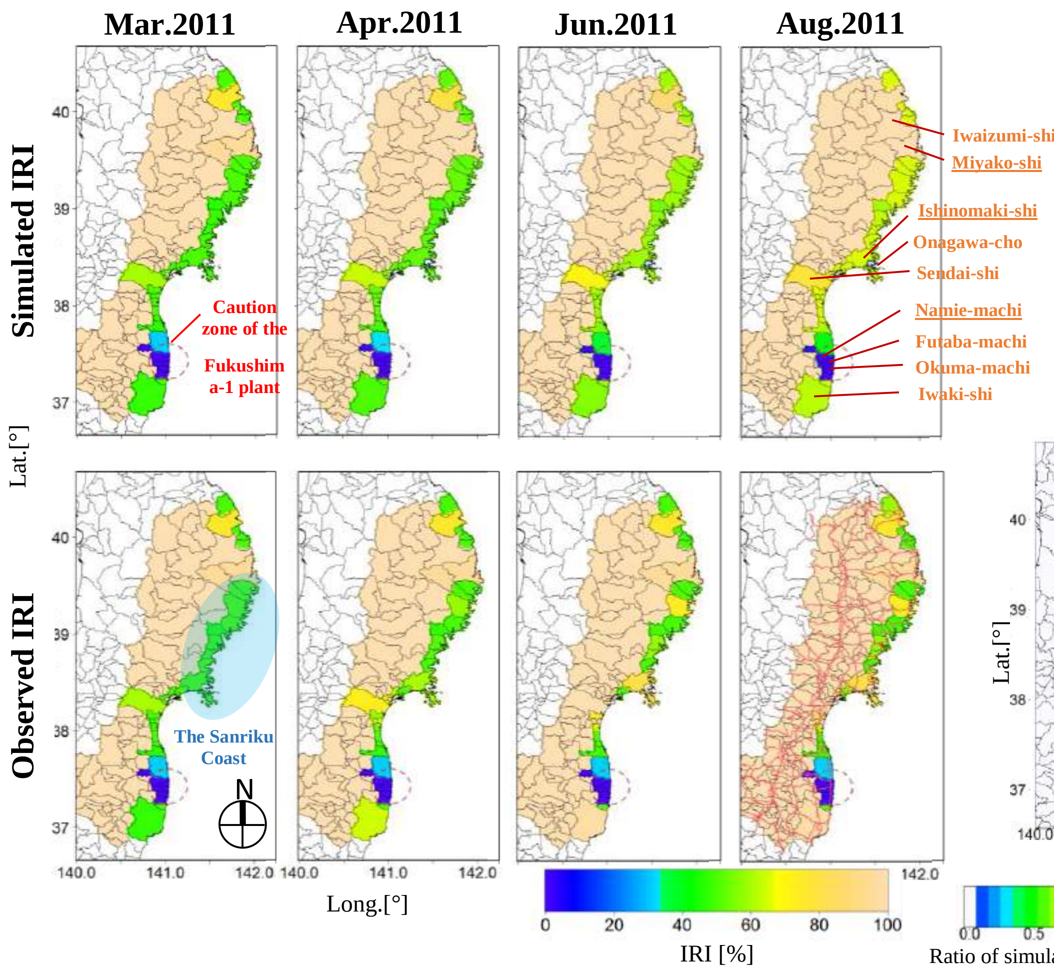
Fig. 16 – Recovery curves of IRI (debris removal)

In the result of the debris removal ratio, although some districts had good correspondence, the reproducibility was so bad in many districts. That is because the observed debris removal ratio has a sharp transition as can be seen from Fig. 16, and thus it is hard to describe these phenomenon as diffusion model.

5.3 Railroad and road recovery ratio

These are the result of simulation about the third IRI, the railroad and road recovery ratio.

Fig.17 shows the comparison map, Fig.18 the ratio of simulated to observed IRI, and Fig.19 the recovery curves of IRI. In addition, the road network is shown in the observed map on August in Fig.17.



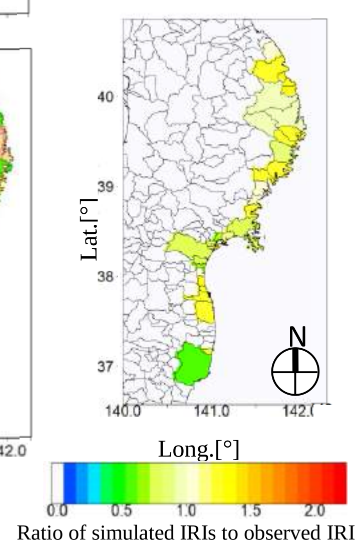


Fig. 17 – Comparison map (railroad and road)

Fig. 18 – Ratio of simulated to observed IRI (railroad and road)

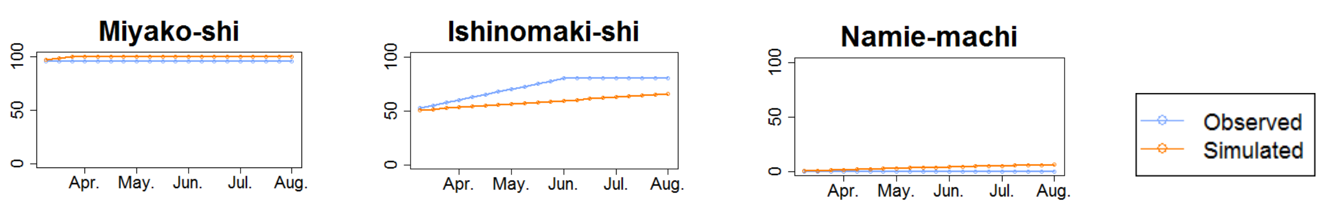


Fig. 19 – Recovery curves of IRI (railroad and road)

About the IRI of railroad and road the reproducibility of analysis was quite good in many districts. That is because of the recovery process of railroad and road. Comparing the road network with the observed IRI, it is seen that the districts with tight road net (i.e. Sendai-shi) has fast recovery than with sparse road net (i.e. districts on the Sanriku Coast). And another thing, the districts near to Sendai-shi, the capital city, (i.e. Ishinomaki-shi) has fast recovery than faraway from Sendai-shi (i.e. districts on the Sanriku Coast). In this way, the railroad and road has spatially diffusive recovery process, and thus the diffusion model is better suited for this phenomenon.

5.4 Discussion

Comparing the result of TRI in section 4 with IRIs in section 5, the reproducibility or numerical accuracy differed.

And another thing, they were difference among IRIs. The IRI of debris removal ratio didn't have a good reproducibility because of its sharp transition, on the other hand the IRI of medical facilities or the railroad and road had a certain level reproducibility.

When IRIs are dealt it is important to consider whether the describable or indescribable the each targeted IRI is by diffusion phenomenon, since the characteristic of recovery processes vary in each IRI.

6. Conclusion

This paper, emphasizing that the temporal-spatial effect is important for evaluation of the regional resilience from disaster, proposed a diffusional analysis model as a completely new evaluation method.

This model was applied to Recovery Index of The Great East Japan Earthquake, and the simulated result was compared with observed data. As a result, though RI in some districts differed, RI in overall region had a relatively reasonable level reproducibility. That is to say that validity of this model is proved at the certain degree.

If the parameter of this model is chosen adequately, the future forecast of recovery process from disaster damage would be possible. Thus, its forecast would come in handy as basis for decision making of recovery plan.

After this, the upgrading of parameter estimation method and the general application to a multiple of hazards including earthquake, tsunami, or tornado are expected.

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