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Could the magnitude of the 3/11 disaster have been reduced by ecological planning? A retrospective multi-hazard risk assessment through map overlay

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HIGHLIGHTS

- Japan's 3/11 disaster could have been reduced through ecological planning.
- A 1980 environmental inventory largely predicted areas impacted by 3/11 disaster.
- Japan's most recent risk mapping fails to indicate the 3/11 disaster impacted areas.
- Map overlay can be instrumental for multi-hazard risk assessment.
- Its effectiveness requires open, integrated and comprehensive risk information.

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ABSTRACT

On March 11, 2011, the Great East Japan Earthquake triggered a series of catastrophes in Japan. The sheer magnitude of this compound disaster—known as the 3/11 disaster—raises a question whether it was simply unavoidable. However, this study demonstrates that the 3/11 disaster could have been significantly reduced by strategic ecological planning, if not avoided altogether. Using an environmental inventory developed by the Japan National Land Agency (JNLA) in 1980, we conducted a retrospective multi-hazard risk assessment for Tohoku through map overlay. We found that 89 % of the damaged highways, 88.2 % of the damaged buildings, and 81 % of the wrecked Fukushima nuclear power plants and associated facilities in the 3/11 disaster are subject to high risks of one or more hazards identified in the 1980 environmental inventory. This implies that the historic data has "predicted" the major damages in the 3/11 disaster occurred 31 years later. A similar assessment using the 2019 risk data by Japan's Ministry of Land, Infrastructure, Transport and Tourism (MLIT) shows that this current risk mapping, nevertheless, largely fails to indicate the aforementioned damages. Our study suggests that even simple "map overlay" can be instrumental to multi-hazard risk assessment; however, for map overlay to be effective, a high-quality environmental inventory map with integrated and comprehensive risk information is necessary, and thus risk mapping quality matters. To reduce compound disasters, the political will is most important to ensure that the results of multi-hazard risk assessment is taken into account in spatial planning.

1. Introduction

On March 11, 2011, a magnitude 9.0 earthquake occurred off the northeast coast of Japan and triggered a tsunami, leading to an unprecedented catastrophe in the Tohoku region. The Great East Japan Earthquake—also known as the 3/11 disaster—is considered to be a

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compound disaster (Hazarika et al., 2012). A compound disaster is defined as "an emergency situation with adverse consequences resulting from different, but related, disaster-agents" (ICLA, 1996), and it is characterized by extensive spatial and physical extent of damages and prolonged recovery (Kawata, 2011). As a compound disaster, the 3/11 disaster involved a natural disaster (earthquake) triggering another (tsunami), then causing a technical disaster—the nuclear accident at the Fukushima Daiichi Nuclear Power Plant. Buildings collapsed and were swiped away; blackouts and traffic standstill occurred throughout Tohoku. A total of 121,991 buildings were completely destroyed and 282,902 half-destroyed (The National Police Agency, 2020). The 3/11 disaster involved the death of 15,899, injuries of 6,157, and displacement of more than 470,000 people (Fire and Disaster Management Agency, 2011). The death toll related to stress and fatigue arising from living as evacuees is estimated to be ~1,700 (Smith, 2015). As of May 2022—11 years after the catastrophe, a total of 2,523 people is still missing (Nihon Keizai Shimbun, 2022) and 38,139 still not allowed to return to the Fukushima Prefecture, mainly due to radioactive contamination (Nippon.com, 2022). The 3/11 disaster demonstrated to the world once again the colossal power of nature.

Composed of a diversity of environments, Japan is subject to a variety of natural hazards. While tremendous efforts have been invested in disaster risk reduction, Japan continues to see catastrophic events. However, Japan is certainly not alone. Many countries around the world share the similar challenge. In particular, compound disasters are on the rise in recent years. More recent examples include storm surges and mudslides in Montecito, California in 2018; floods and mudslides in Western Europe (especially catastrophic in Germany) in 2021; and Hunga Tonga–Hunga Ha'apai eruption and tsunami in 2022. The aggregation of impacts from a series of interacting hazards collocated in time and space can overwhelm the response capacity of any community or nation (Liu & Huang, 2014). However, since compound disasters are a relatively new notion, their research is still in its infancy (Cui et al., 2021). Governments around the world are still grappling with compound disasters (see Ministry of the Environment of Japan, 2021; UNDRR, 2021). To better respond to them, efforts have been made to enhance risk communication and emergency responses, such as in Japan, Taiwan, and USA. However, to our knowledge, there has not been a comprehensive risk management plan designed specifically for compound disasters.

Effective policies and actions to reduce compound disasters requires multi-hazard risk assessment in the first place. Currently, individual hazards are well researched and better understood (Cui et al., 2021). However, single-hazard risk assessments do not reflect the reality where there can be multiple hazards of different risk levels across a heterogeneous area (Bernal et al., 2017; De Ruiter et al., 2020; Kon & Higaki, 2017; Moftakhari et al., 2019). The spatial extent is often localized, rarely at a regional scale at which compound disasters often occur (De Ruiter et al., 2020; Gruber & Mergili, 2013; Kirschbaum et al., 2009; Peduzzi & Herold, 2005). Moreover, existing risk assessments largely ignore scenarios of extreme and compound events (Sadegh et al., 2018). Data necessary for multi-hazard risk assessment across a large geographic area is often inadequate or unavailable (Gong & Forrest, 2014; Li, 2011). Compared to single-hazard risk assessment, multi-hazard risk assessment is a lot more challenging because it is not a simple sum of single-hazard risks but should be a joint investigation into the interactions between multiple hazards (Wang et al., 2020). This is because such interactions could have unexpected effects not captured in the independent risk assessments of single hazards (Cutter, 2018; Kappes et al., 2012; Ming et al., 2022; Sadegh et al., 2018). To tackle the inherent complexities in such interactions, modelling has been an important approach to multi-hazard risk assessment; however, it requires extensive data with different hazard characteristics (Bernal et al., 2017; Cutter, 2018). Despite the advances in modelling that have improved probability analysis and risk simulation, tremendous uncertainties remain (Sadegh et al., 2018). Multi-hazard risk assessment still faces at least three challenges: "(1) proper consideration of hazard interdependency, (2) physically based modelling of hazard interactions, and (3) fully quantitative risk assessment to show the probability of loss." (Ming et al., 2022).

Despite the challenges in multi-hazard risk assessment, it is indisputable that compound disasters can be reduced by preventing exposure to known single-hazard risks in the first place. While we recognize the importance of multi-hazard interactions, we argue that overlapping single-hazard risk maps can still be instrumental for compound disaster risk management. When an ideal multi-hazard risk assessment that takes multi-hazard interactions into account is unavailable or unaffordable, such a simple assessment can be a surrogate, and land development should consider the result in the spatial planning process.

Spatial planning that takes into account risk mapping results is not new. It is a fundamental approach to ecological planning, pioneered by Ian McHarg with his seminal publication of "*Design by Nature*" in 1969. Ecological planning requires a thorough understanding of the site, and hence, a comprehensive environmental inventory is important (McHarg, 1969). The massive scale of the 3/11 disaster raises the question whether a calamity like this could have been prevented through better spatial planning by avoiding land development in areas exposed to multi-hazard risks in the first place. This current study is an attempt to answer this question by examining a historical set of environmental inventory that involves risk mapping. Using map overlay, we performed a "retrospective", simple multi-hazard risk assessment in Tohoku to explore whether the 3/11 disaster could have been minimized, if not prevented altogether.

Credited to Ian McHarg, map overlay is a method developed for landuse suitability analysis—a critical part of ecological planning. Landuse suitability analysis involves determining the suitability of a land parcel for a specific landuse based on a set of environmental and cultural criteria. While map overlay was developed as a planning tool, McHarg believed that "it should be possible to identify certain areas where there are disasters to life and health, for example from volcanism, earthquake, mudslide, or flooding…, [and] it will become increasingly important that all planning of the sort we describe should be oriented toward the capability of the use of government to enforce plans…" (McHarg et al., 2007, p. 56–57). Map overlay has been widely applied in environmental planning and landscape architecture with the advance of Geographic Information System (GIS). However, it is much less known in disaster risk management. There have been a few studies applying map overlay to hazard risk assessment (e.g., Yang & Li, 2011; Berry & BenDor, 2015; Wagner, Merson, & Wentz, 2016; Uehara, 2019); however, these studies focus mainly on single, as opposed to multiple, hazard risks.

To bridge this research gap, this current study explores map overlay as a proxy for multi-hazard risk assessment, using the 3/11 disaster in Tohoku as an example. Besides using a historic environmental inventory dated back to 1980, we also performed a similar exercise using a more current risk data as a reference.

2. Research method

In this section, we first provide a background of the 3/11 disaster in Tohoku and then introduce the two data sets used in this study. Subsequently, we explain the process of our retrospective risk assessment, where composite risk maps were generated from these two data sets for comparisons against the actual damage locations in the 3/11 disaster.

2.1. Tohoku and the 3/11 disaster

The ground zero of the 3/11 disaster, Tohoku consists of six prefectures and covers an area of 67,952 km^2 (Fig. 1). The 3/11 disaster mainly affected the eastern part of Tohoku, including the Fukushima, Miyagi, and Iwate Prefectures. The coastal area was hit the hardest. The area affected by the earthquake was approximately 100,000 km^2, while

Fig. 1. Tohoku is a northeastern region in Japan and includes six prefectures: Aomori, Akita, Iwate, Yamagata, Miyagi, and Fukushima. Sendai is the largest city in Tohoku. The 3/11 disaster mainly affected the coastal prefectures including Fukushima, Miyagi, and Iwate.

the area flooded by the tsunami was 561 km^2.

2.2. Data sets

The focal data set of this study is the environmental inventory issued in 1980 by the Japan National Land Agency (hereafter referred to as the JNLA environmental inventory). Serving as a reference, the other data set is the current risk mapping by the Ministry of Land, Infrastructure, Transport and Tourism of Japan (MLIT), which is officially known as the MLIT Hazard Map Portal Site (hereinafter referred to as the MLIT Hazard Map) (MLIT (Ministry of Land, Infrastructure, Transport and Tourism), 2019).

2.2.1. The 1980 JNLA environmental inventory

In 1980, JNLA issued an inventory on the environmental characteristics of Tohoku for the third National Land Development Plan (NLDP) (JNLA (Japan National Land Agency) and Regional Planning Team, 1980). The first and second NLDPs were formulated in 1962 and 1969 respectively, which provided long-term directions for the development of cities, housing, transportation, and other social infrastructures in Japan. Formulated in 1977, the third NLDP was inspired by McHarg's ecological planning, and hence its inclusion of a comprehensive environmental inventory. It was the first NLDP that attempted to balance nature conservation with land development—with an aim to create a living environment in harmony with nature—by applying McHarg's ecological planning approach to Tohoku. Back then, most of Tohoku was still undeveloped, which provided an opportunity for more environmentally-sensitive spatial planning that takes into account natural constraints, such as hazard risks. Nevertheless, this third NLDP was not implemented.

The 1980 JNLA environmental inventory consists of four meticulously hand-drawn maps of Tohoku: (1) landuse and vegetation, (2) geology, (3) slopes, and (4) terrain (Fig. 2). The landuse and vegetation map is associated with liquefaction risk, geology map with earthquake and landslide risks, slope map with slope failure risk, and terrain map with flood risk. Each map includes a matrix that shows different environmental characteristics and their associated hazard risk levels (see Appendix 1). There are four risk levels: high, relatively-high, relatively-low, and low. In short, five sets of relative risk levels are embedded in the 1980 JNLA environmental inventory: (a) liquefaction risk based on the landuse and vegetation map, (b) earthquake risk based on the geology map, (c) landslide risk based on the geology map, (d) slope failure risk based on the slope map, and (e) flood risk based on the terrain map.

The 1980 JNLA environmental inventory covers the entire area of Tohoku, which is approximately 744 times of the area covered by a typical map of city planning and risk assessment done by a municipality in Japan (Fig. 2). Despite covering an extensive area, each map of the inventory has a high resolution. Most importantly, the JNLA environmental inventory includes information of different hazard risks associated with different environmental aspects (i.e., landuse and vegetation, geology, slope, and terrain). Such comprehensive, regional-scale, yet detailed risk mapping simply cannot be achieved by combining individual mapping efforts from different municipalities, which often carry out risk mapping at different resolutions.

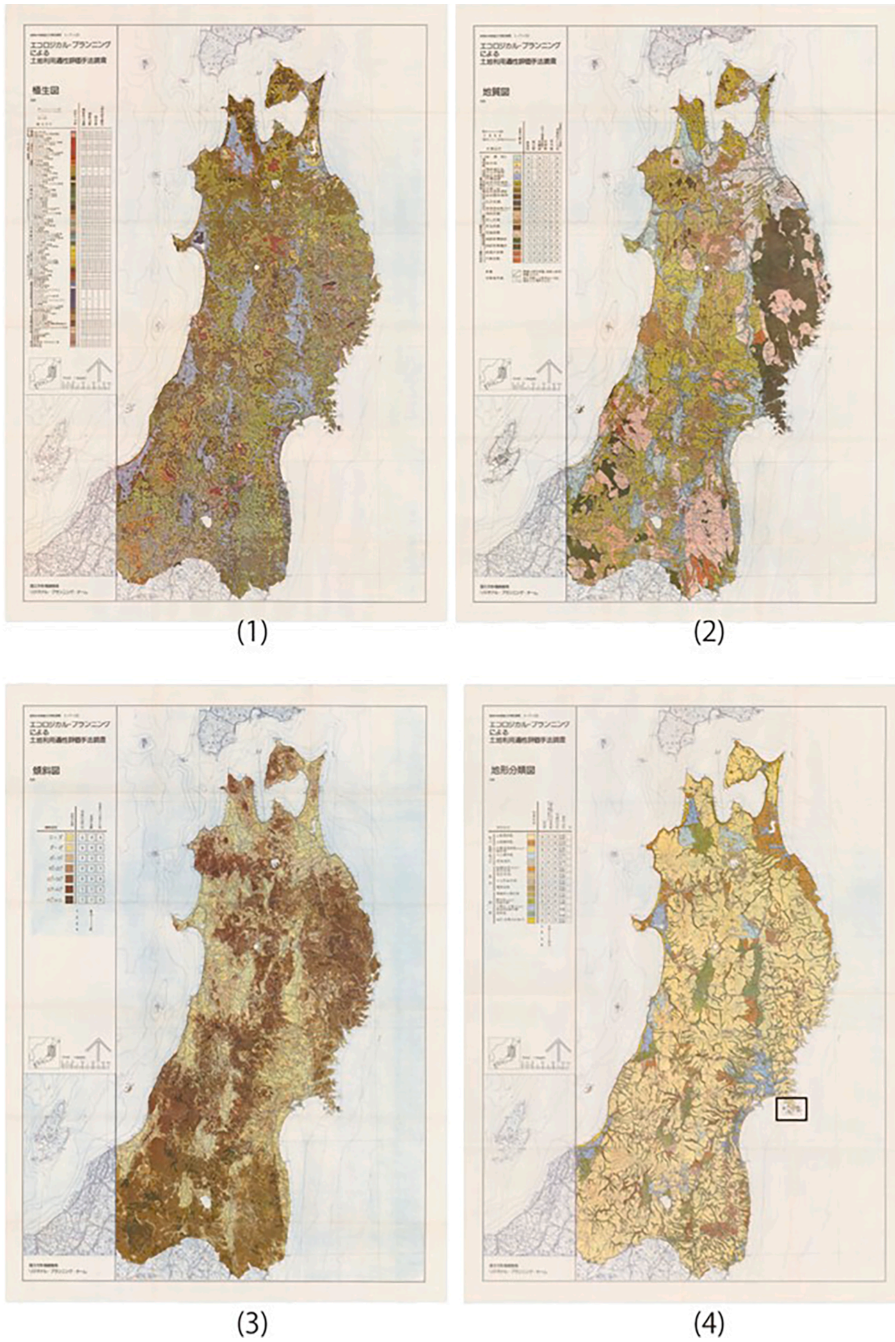

Fig. 2. The four maps of the 1980 JNLA environmental inventory: (1) landuse and vegetation, (2) geology, (3) slope, and (4) terrain. See Appendix 1 for the matrix of each map. The square in (4) indicates the spatial extent, which a municipality of Japan would typically cover in city planning and risk assessment.

2.2.2. *The 2019 MLIT hazard map*

Since 2007, MLIT has been responsible for Japan's hazard database—the MLIT Hazard Map. This database is open access and presents the latest hazard risk assessment results in Japan. Two major types of hazards are mapped: flood and slope-related hazards. Flood risk pertains only to major rivers, but not their tributaries. Slope-related hazards include landslide, debris flow, slope failure, and avalanche. Compared to the 1980 JNLA environmental inventory, the MLIT Hazard Map includes two new hazards (debris flow and avalanche) but does not include liquefaction and earthquake. It is important to note that in the MLIT Hazard Map different hazards are not associated with different environmental aspects, and risk assessment does not cover every piece of land, unlike what was done in the JNLA environmental inventory. This study used the MLIT Hazard Map updated in 2019.

2.3. *Retrospective multi-hazard risk assessment*

The objective of this study is to examine the degree to which the 1980 JNLA environmental inventory can indicate the actual damages in the 3/11 disaster. While the disaster involves a variety of damage forms, we focus on the damage of highways and buildings, as well as the wrecked Fukushima nuclear power plants and associated facilities. We compare these damage areas against the composite risk maps from the 1980 JNLA environmental inventory and from the 2019 MLIT Hazard Map. Human causalities are not included in this study because unlike a damaged structure whose location corresponds to where the hazard occurred, because of the tsunami many bodies were moved far from the locations associated with the causes of death.

2.3.1. The damages of highways and buildings

Transportation plays an important role in emergency response and disaster recovery. Since highways are lifelines during a disaster, it is important to avoid siting them in areas highly prone to hazards. Throughout the total of 870 km of highways connecting different prefectures in Tohoku, there was a total of 60 sites damaged by earthquake, landslide, and/or liquefaction; and there were two forms of damages: 43 cracks and 17 collapse (Fig. 3; NEXCO East, 2011). The tsunami didn't damage the highways.

Buildings were damaged by both the earthquake and tsunami. Buildings were considered damaged if they were totally destroyed (being completely washed away by the tsunami or flooded the entire first floor), largely destroyed, or partially destroyed (mildly flooded). There was a total of 251,972 damaged buildings (City Bureau, Ministry of Land, Infrastructure, Transport and Tourism (MLIT), 2012), which were located in four out of the six prefectures of Tohoku and concentrated along the coastlines of Iwate, Miyagi, and Fukushima (Fig. 3).

To allow for comparison of damaged highways and buildings locations against the risk mapping of the JNLA environmental inventory, the four original A0-sized, hand-drawn environmental maps were scanned and geo-referenced with risk information extracted to create risk maps operable in ArcGIS. The overlay of these risk maps led to a composite risk map. Another composite risk map was generated from the 2019 MLIT Hazard Map, by acquiring polygon data of risk assessment and overlaying the four slope-related risk maps and the flood risk map

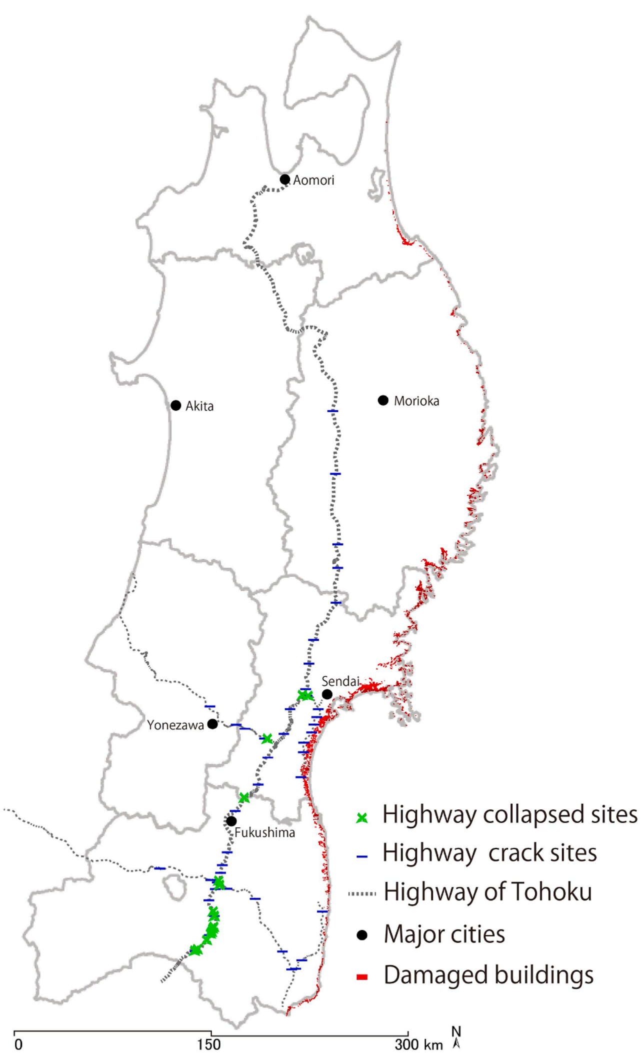

Fig. 3. Damaged highways and buildings in Tohoku during the 3/11 disaster.

(Fig. 4). The two composite risk maps from the two data sets are quite different in their risk information (Fig. 4). We note that although risk assessment in the 1980 JNLA environmental inventory involves identifying four different risk levels (high, relatively-high, relatively-low, and low) of each hazard, our JNLA composite risk map only shows "high" hazard risks. This is to avoid unnecessary complications. The MLIT Hazard Map does not include four different risk levels, only indicating whether a risk exists or not. This is why in Figs. 8-9 and Tables 1-3 the JNLA composite risk map indicates "high hazard risks", while that of MLIT indicates only "hazard risks".

2.3.2. The wrecked Fukushima nuclear power plants and associated facilities

A major emergency in the 3/11 disaster was a nuclear accident, classified as level 7—the worst in history under the International Nuclear Event Scale. There were two nuclear power plants: Fukushima Daiichi (hereinafter referred to as F1) and Fukushima Dai-ni (hereinafter referred to as F2), and their associated facilities included the Shin-Fukushima Substation and the Fukushima Prefectural Nuclear Emergency Off-site Center (Fig. 5). The earthquake caused F1 and F2 to automatically cease nuclear power generation. The following tsunami made it impossible for F1 to generate the power necessary for cooling the reactors, coupled with the failure to receive external power supply from the Shin-Fukushima Substation, eventually leading to a meltdown. F2, on the other hand, managed to avoid the worst scenario, as its emergency power generation was still operable, and it received external power from the Shin-Fukushima Substation. The Emergency Off-site Center was supposed to serve as a base for the national and prefectural governments to respond to the nuclear accident in Fukushima. However, this facility failed to function due to the power failure caused by the earthquake and due to radioactive contamination. An area of 800 km^2 was contaminated by radiation as a result of the Fukushima nuclear accident.

To allow for comparison of the wrecked Fukushima nuclear power plants and associated facilities against the JNLA environmental inventory, we zoomed in to Fukushima's coastal municipalities and manually traced the aforementioned four raster maps to create vector maps (Fig. 6). This allowed the creation of a composite risk map of this coastal region. We assume that areas prone to flooding are also vulnerable to tsunamis; therefore, JNLA's mapping of flood risk can be considered a proxy for tsunami risk. Since the publication of the JNLA environmental inventory, several land reclamation projects along Tohoku's coastline have added a total of 965 km^2 of land to the region. Despite this additional land accounts for only 0.01 % of Fukushima Prefecture's coastal municipalities, it was added when making the aforementioned vector maps. We assigned this additional land a "high" risk level for earthquake, because reclaimed land is artificially constructed by soils or sands, and according to the JNLA environmental inventory (geology map), it is of the lowest seismic resistance. The reclaimed land is also assigned a "high" risk level for flood and tsunami due to its coastal location and relatively low elevation.

3. Results

3.1. The damages of highways and buildings

The damaged highway and building locations are overlaid on the 1980 JNLA composite risk map and on the 2019 MLIT composite risk map (Figs. 7 & 8). Overall, 89 % of the 60 damaged highway sites (81 % of cracks and 94 % of collapse) occurred at locations subject to one or more high hazard risks in the JNLA composite risk map; however, none of them overlaps with the risky areas in the MLIT composite risk map (Table 1). Out of the total 3256.8 ha footprint area of all damaged buildings, 88.2 % is within areas subject to one or more high hazard risks in the JNLA environmental inventory; while only 8.4 % is within the areas subject to one or two hazard risks in the MLIT composite risk map

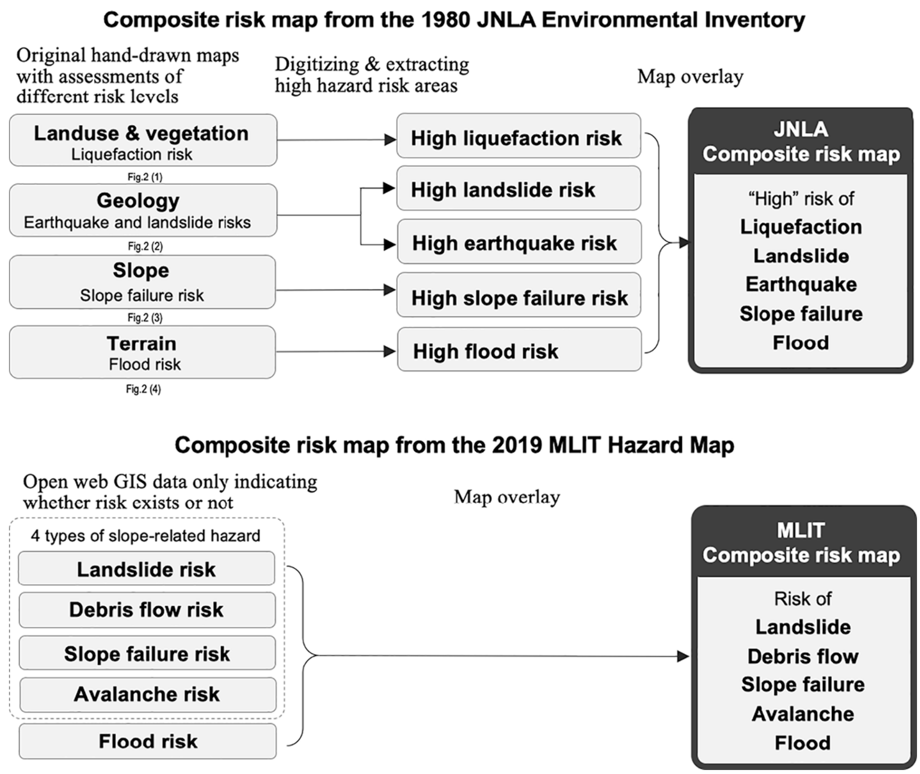

Fig. 4. Diagrams showing different processes and contents of the composite risk maps derived from the two data sets.

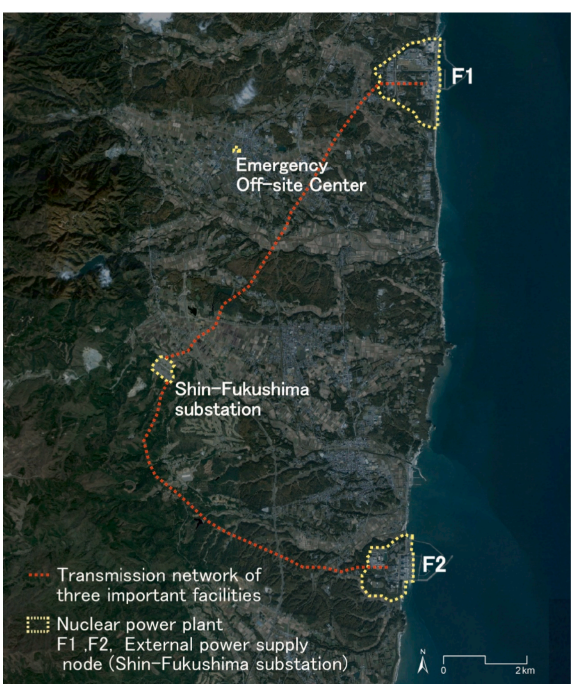

Fig. 5. Locations of the Fukushima nuclear power plants (F1 and F2) and associated facilities (the Shin-Fukushima Substation and the Fukushima Prefectural Nuclear Emergency Off-site Center).

(Table 2). The results imply that damages of highways and buildings in 3/11 disaster in 2011 were—to a large degree—foreseeable in 1980. On the contrary, according to the 2019 MLIT composite risk map, almost all of these damage locations appear to be without risks because these locations are not subject to any hazard risk assessment.

3.2. The wrecked Fukushima nuclear power plants and associated facilities

With a combined area of 519 ha, the Fukushima nuclear power plants and associated facilities are overlaid on the 1980 JNLA composite risk map and on the 2019 MLIT composite risk map (Fig. 9). Overall, 81 % of the total 510 ha (87 % of F1, 64 % of F2, 100 % of Fukushima Prefectural Nuclear Emergency Off-site Center area, and 100 % of Shin-Fukushima Substation) are subject to one or more high hazard risks in the JNLA composite risk map; however, none overlaps with the risky areas in the MLIT composite risk map (Table 3). The result indicates that it was already pointed out in the 1980 JNLA environmental inventory that the nuclear power plants and associated facilities were exposed to multiple hazards. However, even after the nuclear accident has occurred, on the 2019 MLIT composite risk map the locations of the nuclear power plants and associated facilities still appear to be risk-free.

4. Discussion

The Great East Japan Earthquake is considered unpredictable by Japanese earthquake experts (Nikkei Science, 2011). However, our retrospective risk assessment shows that the 1980 JNLA environmental inventory identified most of the multi-hazard risks for the locations damaged by the 3/11 disaster in 2011, at least in terms of the damaged highways and buildings, as well as the nuclear power plant. It implies that the 1980 JNLA environmental inventory can "predict" the 3/11 disaster in 2011. In this section, we discuss key lessons learned through our map overlay study.

4.1. Map overlay can be instrumental to multi-hazard risk assessment

Considered highly challenging, multi-hazard risk assessment is still an evolving research area (Wang, He, & Weng, 2020), and advances in modelling is considered necessary (Eisner, 2015). However, as mentioned earlier, multi-hazard risk modelling continues to be

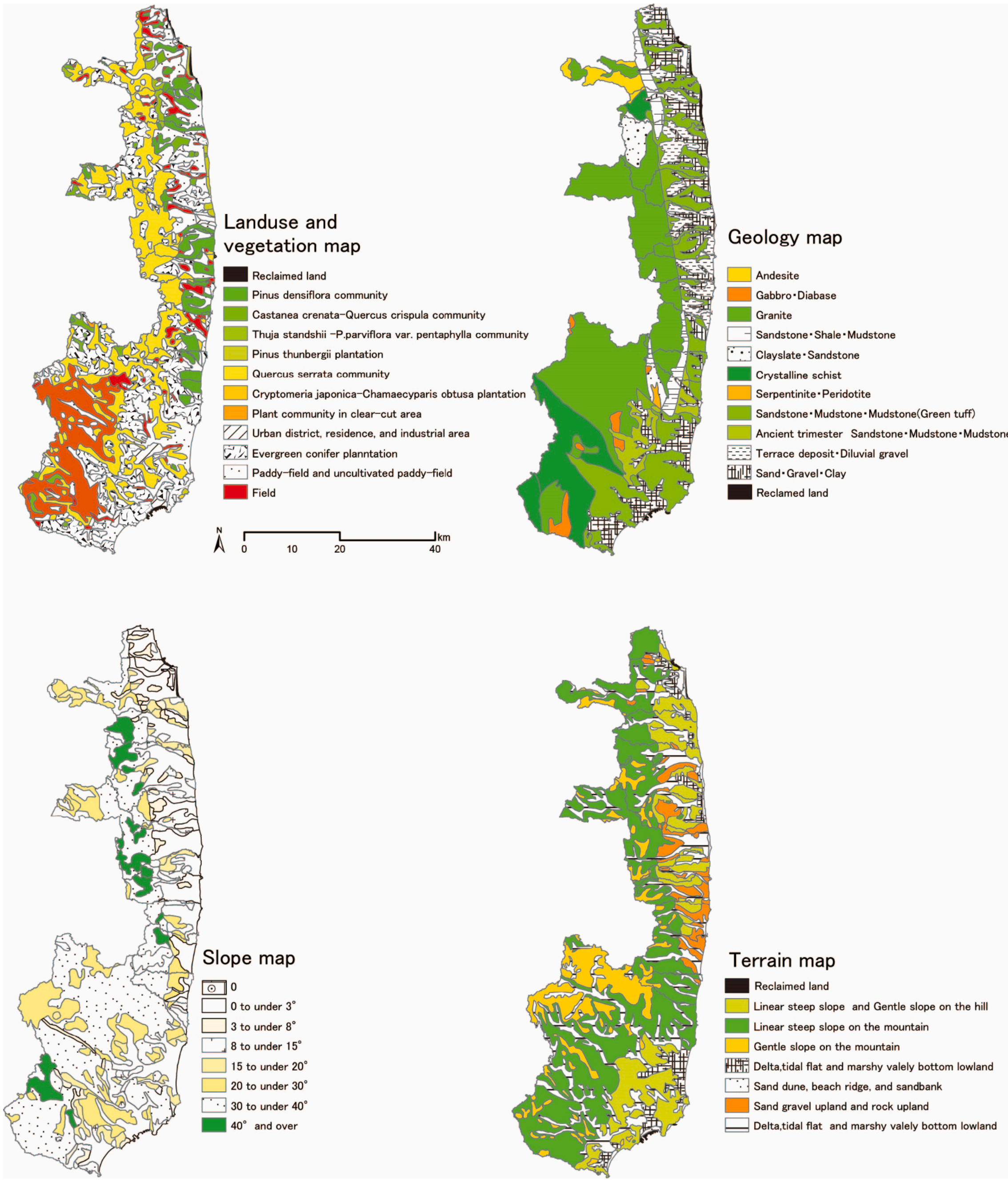

Fig. 6. The four vectorized maps of Fukushima Prefecture's coastal municipalities.

challenged by data inadequacy and inherent complexity in multi-hazard interactions (Sadegh et al., 2018; Wang, He, & Weng, 2020). Accurate prediction in multi-hazard risk assessment is considered paramount, and it is argued that the difficulties in accurately describing the formations and evolutions of compound disasters limit the identification and control of multi-hazard risks (Cui et al., 2021). Nevertheless, when a risk assessment without using any computer modelling—done 31 years before the 2011 compound disaster—can largely pinpoint the damages, it raises a question whether the technological challenge in accurate prediction is a real hurdle to compound disaster risk reduction.

Advances in risk modelling have greatly enhanced probability-based risk assessment, allowing ever precise prediction of the occurrence probability of a certain event. More precise probabilistic identification of multi-hazards can better inform landuse suitability analysis in ecological planning to site new developments more wisely. However, it could be problematic if multi-hazard risk assessment hinges heavily on accurate prediction. On the one hand, the lack of accurate prediction could serve as a convenient excuse for not taking action to reduce compound disasters in existing developed areas. On the other hand, trust in probabilistic risk assessment, which derives from the most advanced knowledge and technology and thus provides a sense of accuracy, could lead to ill-preparation (see Esselborn & Zachmann, 2020). Based on the probabilistic risk assessments of earthquake and tsunami, the Japan government, as well as the Tokyo Electric Power Company that built and operated the Fukushima nuclear power plants, believed that the safeguards put in place were sufficient (TEPCO, 2012). This over-reliance on probabilistic assessment has been considered to be among the reasons behind the Fukushima nuclear accident (Eisner, 2015).

Despite increasing research into multi-hazard risk assessment, its methods and theories are still far from mature (Wang, He, & Weng,

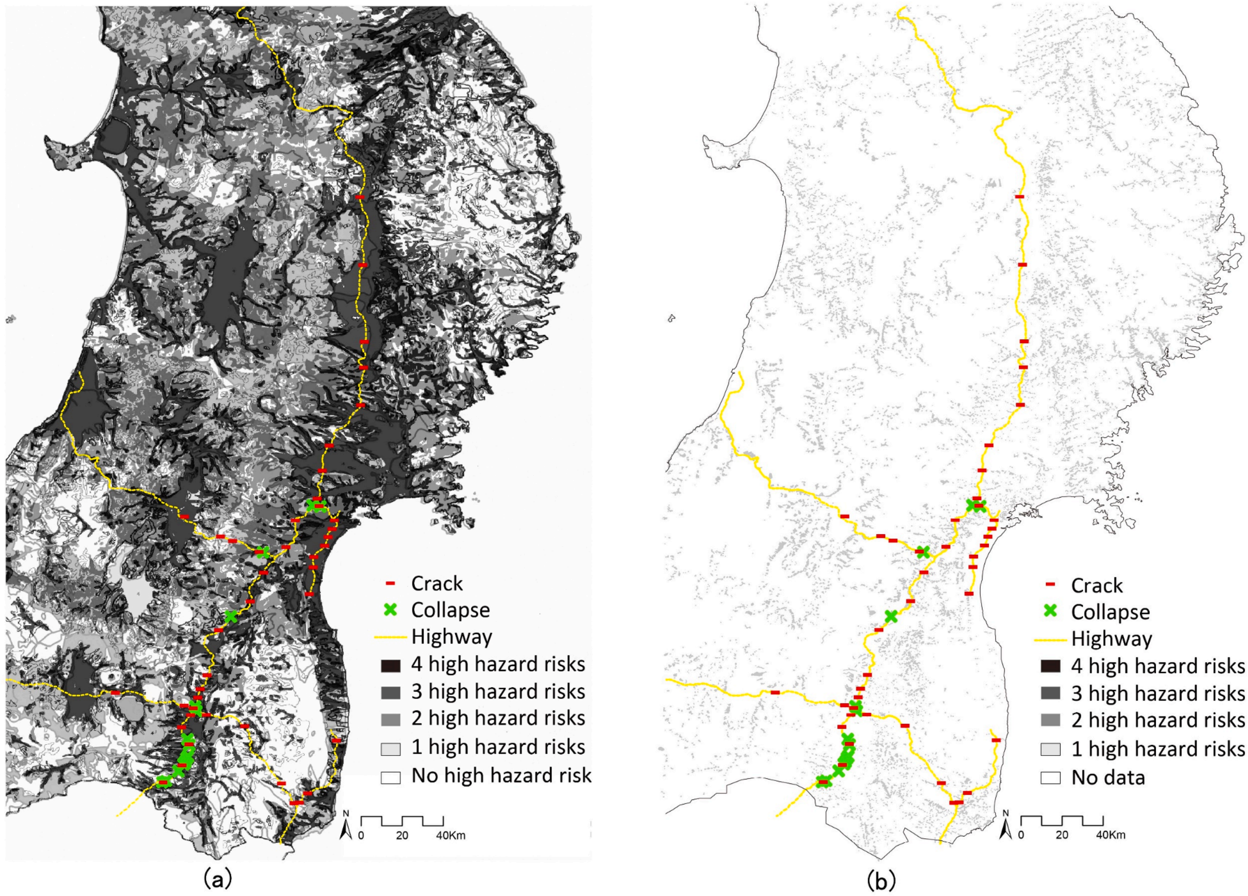

Fig. 7. Map overlay of 60 damaged highway sites with (a) the 1980 JNLA composite risk map, and (b) the 2019 MLIT composite risk map. Note that here the JNLA composite risk map does not include flood risk. This is because according to the guideline of the JNLA environmental inventory, the flood risk mapping result is only applicable at the prefectural and municipal scales, and this risk assessment of damaged highways is at the scale of the entire Tohoku. Also note that the white area on the MLIT composite risk map does not mean that there is no hazard risk; it is where risks are not assessed, hence labeled as "no data".

2020), and there has been a long list of future research agenda. However, public agencies and private enterprises at all levels should carry out multi-hazard risk assessment as soon as possible for compound disaster risk reduction. While we fully recognize that a simple sum of single-hazard risks cannot represent the true multi-hazard risk (Wang, He, & Weng, 2020), we argue that map overlay of individual hazard risk maps—as demonstrated by the 1980 JNLA composite risk map—can still be instrumental as a simple form of multi-hazard risk assessment. Despite the lack of representation of complex interactions of different hazards and the possibility that there can be over- or under-estimations of multi-hazard risk at some locations, map overlay of existing risk maps can be a proxy. In particular, governments and organizations without necessary resources for advanced risk modelling can benefit from conducting such relatively simple and inexpensive multi-hazard risk assessment to reduce compound disasters.

4.2. Risk mapping quality matters

For map overlay to be instrumental for multi-hazard risk assessment, risk mapping quality matters. This importance is highlighted by the contrasting results of the 1980 JNLA and 2019 MLIT composite risk maps. Created by the same overlay approach, the latter performs poorly to identify risky areas where the 3/11 disaster in 2011 has proved to be dangerous. Despite advancements in hazard knowledge and risk modelling since 1980, the MLIT Hazard Map still presents very limited risk information, illustrated by the fact that 98 % of the MLIT composite risk map of Tohoku shows 'no data' (Fig. 7b & 8b). These numerous white areas of 'no data' could be misinterpreted as risk-free.

Unlike the JNLA environmental inventory, where all hazard risks were assessed, the MLIT Hazard Map is a platform of risk mappings by MLIT, as well as local governments. Currently in Japan, different hazard risks are assessed by different national and local agencies working in silos. Because different agencies are only responsible for assessing certain hazard risks, inevitably some geographic areas are left unassessed; while in the JNLA environmental inventory, risk assessment covers every piece of land (i.e., every environmental characteristic is assigned a particular risk level). Furthermore, the MLIT Hazard Map shows only risks associated with selected environmental conditions. For example, landslide risk is only mapped on slopes that are over 30 degrees with built structures downhill; flood risk is only mapped along the major rivers (approx. 10,000 rivers out of 30,000 rivers in Japan) managed by the national government, and only areas that would be inundated under a 100-year flood is shown.

However, the scarcity of risk information on the MLIT Hazard Map does not mean that there is a lack of more comprehensive risk assessments based on environmental classification in Japan. In fact, MLIT has conducted further assessments of landslide and flood risks; yet they are not made publicly accessible. Other agencies have also carried out more detailed risk mappings. For example, the website J-SHIS Map established by the National Research Institute for Earth Science and Disaster Resilience maps earthquake risks of many different scenarios. More recently, some municipalities have simulated the inundation areas under a 1000-year storm event. Despite a wealth of publicly accessible and comprehensive single-hazard risk mappings in Japan, they are scattered on different platforms, not integrated into the MLIT Hazard Map; furthermore, MLIT only selectively discloses results from many risk

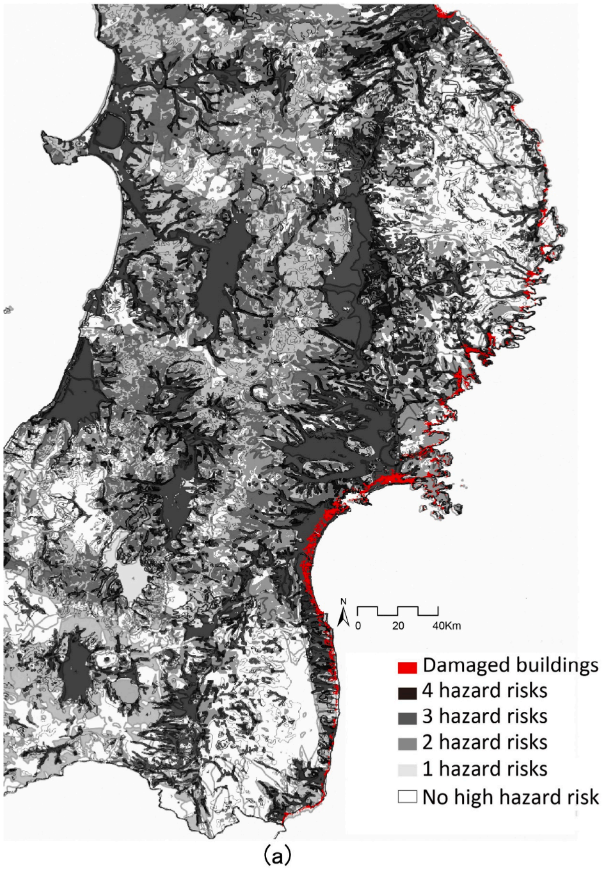

Fig. 8. Map overlay of 251,972 damaged buildings with (a) the 1980 JNLA composite risk map, and (b) the 2019 MLIT composite risk map. Note that here the JNLA composite risk map does not include flood risk. This is because according to the guideline of the JNLA environmental inventory, the flood risk mapping result is only applicable at the prefectural and municipal scales, and this risk assessment of damaged highways is at the scale of the entire Tohoku. Also note that the white area on the MLIT composite risk map does not mean that there is no hazard risk; it is where risks are not assessed, hence labeled as "no data".

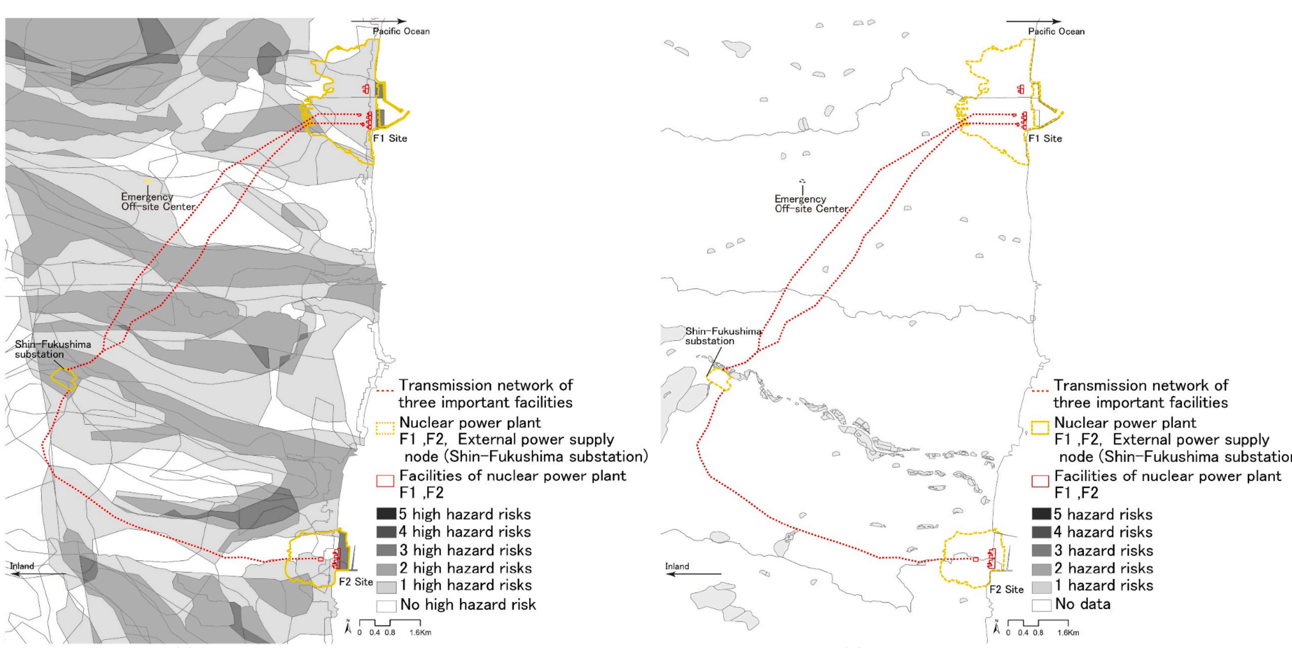

Fig. 9. Map overlay of the Fukushima nuclear power plants and associated facilities with (a) the 1980 JNLA composite risk map, and (b) the 2019 MLIT composite risk map. Note that the white area on the MLIT composite risk map does not mean that there is no hazard risk; it is where risks are not assessed, hence labeled as "no data".

Table 1
The degrees (%) of overlap of 60 damaged highway sites. "Number of (high) hazard risk" means the number of hazard risk the damaged highway site is subject to, according to the 1980 JNLA or 2019 MLIT composite risk maps.

JNLA (1980)		Number of high hazard risk				
		4	3	2	1	0
	Collapse (17)	3 (18 %)	2 (12 %)	6 (35 %)	5 (29 %)	1 (6 %)
	Crack (43)	3 (7 %)	4 (9 %)	16 (38 %)	14 (32 %)	6 (14 %)
	Total (60)	**6 (10 %)**	**6 (10 %)**	**22 (37 %)**	**19 (32 %)**	**7 (11 %)**
MLIT (2019)		Number of hazard risk				
		4	3	2	1	No data
	Collapse (17)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	17 (100 %)
	Crack (43)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	43 (100 %)
	Total (60)	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**60 (100 %)**

Table 2
The degrees (%) of overlap of the total footprint area (ha) of damaged buildings. "Number of (high) hazard risk" means the number of hazard risk the damaged building footprint area is subject to, according to the 1980 JNLA or 2019 MLIT composite risk maps.

JNLA (1980)	Number of high hazard risk				
	4	3	2	1	0
	5 ha (0.2 %)	76 ha (2.3 %)	1846.6 ha (56.7 %)	943.7 ha (29.0 %)	385.5 ha (11.8 %)
MLIT (2019)	Number of hazard risk				
	4	3	2	1	No data
	0 ha (0 %)	0 ha (0 %)	76 ha (2.3 %)	199.4 ha (6.1 %)	2981.4 ha (91.6 %)

assessments. These factors resulted in the MLIT Hazard Map—which is supposed to be an integrated risk database of Japan—performing so poorly for multi-hazard risk assessment.

What makes the MLIT Hazard Map much less informative than the much older risk information extracted from JNLA environmental inventory appears to be political than technical. This political reason seems to be due to the difficulty and the responsibility associated with the disclosure of risk information to the genernal public. An investigation into the politics behind the incompleteness and selective disclosure of risk information on the MLIT Hazard Map is beyond the scope of this study. However, the politics behind the poor risk mapping quality again indicates that the real hurdle to composite disaster risk reduction does not lie in the technical. Despite being most updated and accurate, risk information that is scattered and/or hidden could become under-utilized and therefore futile. An open risk mapping platform that integrates all hazard risk maps and covers every piece of land, like what was done in the JNLA environmental inventory, would make multi-hazard risk assessment much easier and thus more likely to be widely conducted. Therefore, a political will that ensures public accessibility to integrated, comprehensive risk information is key. This means, while research into risk modelling to advance multi-hazard risk assessment is needed, research into the politics of risk mapping is no less important.

Multi-hazard risk assessment based on map overlay requires high-quality, integrated risk mappings of multiple known single hazards. In addition, we also recommend explicitly linking different hazards and their different risk levels to their associated environmental characteristics, as was done in the 1980 JNLA environmental inventory. While modern risk mapping, such as the MLIT Hazard Map, tends to only indicate the risk itself, the JNLA environmental inventory—despite being old and not in a digital format—demonstrates a rather progressive form of risk mapping. Explicitly linking a hazard risk to one or more environmental characteristics (e.g., linking high flood risk to a subsided land area below sea level) allows the general public to appreciate the fundamental mechanisms underpinning the hazard risk. It could serve as an effective means to risk education and communication.

4.3. Strategic ecological planning can reduce compound disasters

If not considered in spatial planning, even the most complex multi-hazard risk assessment would be pointless. Our study echoes Wagner, Merson, and Wentz (2016), which compare the impacts of Hurricane Sandy on the Staten Island against McHarg's Staten Island landuse suitability study. Wagner, Merson, and Wentz (2016) conclude: "McHarg had the foresight to recognize that 86.6 % of the building damages by Hurricane Sandy were located in areas inappropriate for urban development" (p. 43). Similar to Staten Island's land developments that largely disregarded the environmental constraints and took place at vulnerable locations, Tohoku's land developments—including potentially dangerous nuclear facilities—also took place in areas subject to multiple hazard risks.

Tohoku's highways and Fukushima nuclear power plants and associated facilities were constructed in the 1970s ~ 1980s, and most buildings damaged in the 3/11 disasters were erected in the late 1980s and early 1990s. Since most of these developments occurred after the JNLA environmental inventory was done in 1980, it would have been possible to avoid siting them in highly risky locations identified in the inventory. In fact, the 1980 JNLA composite risk map shows that there are actually safer locations with lower hazard risks nearby the Emergency Off-site Center and the Shin-Fukushima Substation (Fig. 9a). The damages to these facilities could have been avoided if they were to be sited 200–300 m away from their riskier locations. If the 1980 JNLA environmental inventory were to be fully utilized in the spatial planning of Tohoku, the damage of the 3/11 disaster could have been significantly reduced.

As mentioned earlier, the 1980 JNLA environmental inventory was

Table 3
The degrees (%) of overlap of the areas (ha) of the Fukushima nuclear power plants and associated facilities. "Number of (high) hazard risk" means the number of hazard risk the damaged area (ha) is subject to, according to the 1980 JNLA or 2019 MLIT composite risk maps.

JNLA (1980)		Number of high hazard risk					
		5	4	3	2	1	0
	F1 (350 ha)	0 (0 %)	0 (0 %)	8 (2 %)	13 (4 %)	284 (81 %)	45 (13 %)
	F2 (150 ha)	0 (0 %)	0 (0 %)	20 (13 %)	6 (4 %)	70 (47 %)	54 (36 %)
	Fukushima Prefectural Nuclear Emergency Off-site Center (1 ha)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	1 (100 %)	0 (0 %)
	Shin-Fukushima Substation (18 ha)	0 (0 %)	0 (0 %)	0 (0 %)	18 (100 %)	0 (0 %)	0 (0 %)
	Total (519 ha)	**0 (0 %)**	**0 (0 %)**	**28 (5 %)**	**37 (7 %)**	**355 (69 %)**	**99 (19 %)**
MLIT (2019)		Number of hazard risk					
		5	4	3	2	1	No data
	F1 (350 ha)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	350 (100 %)
	F2 (150 ha)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	150 (100 %)
	Fukushima Prefectural Nuclear Emergency Off-site Center (1 ha)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	1 (100 %
	Shin-Fukushima Substation (18 ha)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	0 (0 %)	18 (100 %)
	Total (519 ha)	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**0 (0 %)**	**519 (100 %)**

prepared for the development of the third National Land Development Plan (NLDP) of Japan. Unfortunately, this NLDP was not implemented because of the political downfall of the prime minister Kakuei Tanaka, who established JNLA; it was also due to the financial and economic limitations after the Nixon Shock—the social-political-economic impacts on Japan by a set of economic policies implemented by the then US President Nixon in 1971—and the international oil crisis. Japan has yet to see another political leader who understands the importance of holistic, comprehensive environmental assessment underpinning NLDP. Furthermore, the decommission of JNLA in 2001 has led to a return to the conventional, siloed risk assessment and spatial planning by different agencies, as mentioned above. While this lesson is far from new, our study highlights the importance of strategic ecological planning—where landuse suitability analysis is key—for sustainable land development to reduce compound disasters.

5. Conclusion

While the immense natural force—the Tohoku earthquake and tsunami—could not be avoided, our study demonstrates that it would have been possible to minimize the impacts through strategic ecological planning, had the risk mapping results in the 1980 JNLA environmental inventory been considered in Tohoku's land developments. Nevertheless, the 3/11 disaster did instigate some changes in natural hazard management in Japan. While conventional management tends to focus on mitigating higher-frequency, lower-impact events, after the 3/11 disaster, Japan started to raise public awareness of low-frequency, high-impact events. For example, on its website MLIT has informed the public of the possibility of a Nankai Through mega earthquake (M9.1) and tsunami occurring along Japan's southeast coastal areas within the next 30 years. The areas that could be inundated by the tsunami have been mapped and included in the MLIT Hazard Map since 2021. Numerous tsunami evacuation towers have been erected in order to be better prepared for such an extreme event. However, after the 3/11 disaster Japan has continued to experience large disasters. For instance, in April 2016 the southern prefecture of Kumamoto was hit by a series of earthquakes, including a magnitude 7.0 main shock, causing 158 landslides and the collapses of ~ 210,000 buildings (Cabinet Office, 2016). On March 2022 Tohoku again experienced a magnitude 7.3 earthquake, which damaged 3032 buildings. A ~ 0.5 m tsunami followed, but thanks to its rather small magnitude and the newly constructed seawalls after the 3/11 disaster, it did not lead to any damage.

In the face of climate change, not only Japan, but also many other nations in the world are likely to see more compound disasters. While we have demonstrated that map overlay with integrated, comprehensive risk information can be instrumental for multi-hazard risk assessment, we by no means suggest that simple map overlay of single-hazard risk maps works better than complex risk modelling of multi-hazard interactions. However, we caution against over-reliance on such complex risk modelling because it should not be considered the only viable approach to multi-hazard risk assessment. We also caution against a bias towards technological advancement in compound disaster risk management because ever more accurate multi-hazard risk assessment alone is simply not enough. Our study sends a clear take home message that effective compound disaster risk reduction does not lie in the technical.

CRediT authorship contribution statement

Misato Uehara: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Visualization, Supervision, Project administration, Funding acquisition. **Kuei-Hsien Liao:** Conceptualization, Validation, Formal analysis, Investigation, Visualization, Supervision, Writing – original draft, Writing – review & editing. **Yuki Arai:** Conceptualization, Formal analysis, Investigation, Writing – original draft. **Yuta Masakane:** Investigation, Visualization.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix 1. . Map matrixes of 1980 JNLA environmental inventory

1.1 Relative liquefaction risk level matrix of landuse & vegetation map

		Risk level High Low 1234	Liquefact-ion risk
Arctic·alpine zone	Natural Vegetation	High mountain scrub	3
		Alpine heathland and wind-exposed grassland	1
		Snow patch community	1
Subarctic·subalpine zone	Natural Vegetation	*Abies mariesii* association	4
		Betula ermanii community	4
		Aluns maximowiczii-Betula ermanii association	
		Sasa-Betula ermanii community	
		Sasacommunity	1
		Picea glehnii association	4
		Abies mariesii association	4
		Abies mariesii-Tsuga diversifolia community	
		Abies mariesii-Fagus crenata community	
		Q.crispula var. horikawae association	4

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		Risk level High Low 1234	Liquefact-ion risk
		Abies mariesii-Jezoensis var. *hondoensis* alliance	4
	Substitutional Communities	Sasa community	2
		Betula ermanii community	4
		Plant community in clear-cut area	1
Quercus crispula Blume / *Fagus crenata* Region	Natural Vegetation	*Sasa kurilensis-Fagus crenata* alliance	4
		Cyptomeria japonica-Fagus crenata community	
		Sasamorpha borealis-Fagus crenata alliance	
		H.japonica var. *obtusata-Fagus crenata* association	
		Fagus Japonica associaton	
		A. monovar. Glabrum -Tilia japonica community	4
		Chamaeyparis obtusa·Thujopsis dolabrata community	4
		Pinus densiflora community	3
		Polystichum tripteron - Pterocatya rhoifolia community	4
		Quercus dentata community	4
		Alunus japonica community	4
		Alunus japonica-Fraxinus mandshurica var. *japaonica* association	
		Alunus hirsuta var. *sibirica* community	
		Thuja standshii -P.parviflora var. *pentaphylla* community	4
		Thuja standshii -Pinus pravifora community	
		Populus high forest	4
		Populus scrub forest	
		Carpinus tschonoskii community	4
		Ulmus davidaina var. *japonica* association	4
		Quercus crispula community	4
		Quercus crispula -A.mono var. marmoratum community	
		Quercus crispula-Clethra barbinervis association	
		Carprinus laxiflora community	4
		Alnus pendula-weigela hortensis community	4
		Natural scrub forest	2
		Natural grassland	1
	Substitutional Communities	*Fagus crenata-Quercus crispula* community	4
		Castanea crenata-Quercus crispula community	
		Betula platyphylla var. *japonica* community	3
		Betula platyphylla var. *japonica-Sasa* community	
		Vaccinium smallii var. *glabrum* community	2
		Zoysia community	1
		Plant community in clear-cut area	1
		Quercus crispula-Quercus dentata-Quercus serrata community	4
		Weigela hortensis-Hydrangea paniculata community	4
		Weigela decora-Hydrangea paniculata community	
		Carpinus laxflora-Carpinus tuczaninovii community	4
		Pinus densiflora community	3
		Thalictrum filamentosum var. *tenurum* community	
		Sasa kurilensis-Sasa veitchii community	3
Camellia japonica Region	Natural Vegetation	*Abies firma-Illicium anisatum* association	4
		Zelkova serrata community	4
		Machilus thunberigii community	4
		Polystichum polyblepharum-Machilus thunberigii association	
		Pinus densiflora community	3
		Pinus thunbergii community	
		Cleyera japonica-Quercus salicina association	4
		Ardisia japonica-Castanopsis sieboldii association	4
		Willow scrub	3
	Substitutional	*Quercus serrata* community	4
		Pinus densiflora community	3
	Communities	*Pseudosasa japonica-Pleioblastus simonii* community	4
		Miscanthus sinensis community	2
		Pleioblastus chino var. *viridis-Miscanthus sinensis* community -Miscanthus sinensis	
		Field weed community	1
		Plant community in clear-cut area	
	River-side, Moor, Salt marsh and Dune	Salt marsh vegetation	1
		Dune vegetation	1
		Limestone vegetation	2
		Miscanthus sinensis community	2
		Vaccinium oxycoccos-Sphagnum klasse	1
		Moliniopsietalia japonicaeMiyawaki et K. Fujiwara *Moliniopsis japonica Ordnung*	
		Phragmites australis klasse	
		Chrysanthemum arcticum-Chrysanthemum *nipponicum (Franch. ex Maxim.) Matsum.* community	

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		Risk level High Low 1234	Liquefact-ion risk
		Spirodela polyrhiza klasse	
		Duckweed class, *pondweed* class, *Spirodela polyrhiza* class	
		Phragmites japonica community	
		Miscanthus sacchariflorus association	
		Leymus mollis-Carex kobomugi community	
		Chrysanthemum arcticum-Matricaria matricarioides community	
	Plantation and Cultural Land	Evergreen conifer planntation	4
		Cryptomeria japonica-Chamaecyparis obtusa plantation	
		Cryptomeria japonica-Chamaecyparis obtusa-	
		Chamaeyparis pisifera plantation	
		Larix kaempferi plantation	4
		Pinus thunbergii plantation	
		Pinus densiflora plantation	
		Cryptomeria japonica-Larix kaempferi plantation	4
		Robinia pseudoacacia plantation	4
		Phyllostachys bambusoides·P.nigra plantation	4
		Conyza canadensis-Conyza sumatrensis community	2
		Cultivated meadow	1
		Field	1
		Paddy-field and uncultivated paddy-field	1
		Deciduous orchard	2
		Mulberry plantation	
		Seeding paddy-field	
	Others	Urban district, residence, and industrial area	1
		Land construction for residence and factory	1
		Airport	1

1.2. Relative landslide and earthquake risk level of geology map

		Risk level High Low 1234	Earthquake risk	Landslide risk
Sedime-ntary rock	Quaterna-ry	Sand·Gravel·Clay (al)	1	4
		Dune sand (ds)	1	4
	period			
	Cenozoic	Welded Tuff·Volcaniclastic material (wf)	2	2
		Terrace deposit·Diluvial gravel (tr)	3	3
	era			
	Neogene	Sandstone·Mudstone·Mudstone(Green tuff) (Tn)	3	1
		Ancient trimester Sandstone·Mudstone·Mudstone (Tp)	2	4
	period			
	Neogene	Sandstone·Shale·Mudstone (M)	3	4
	period			
	Paleozoic	Limestone (Pls)	4	4
		Clayslate·Sandstone· (P)	4	4
	era			
Igneous rock	Volcanic	Rhyolite (Lp)	4	3
		Andesite (An)	4	2
	rock	Basalt (Bs)	4	4
	Plutonic	Granite (Gr)	4	3
		Gabbro·Diabase (Gd)	4	4
	rock	Serpentinite·Peridotite (Sp)	4	4
Metamorphic		Crystalline schist (Sch)	3	4
		Gneiss (Gn)	3	4
rock				

1.3. Relative slope failure risk level of slope map

Risk level HighLow 1234	Slope failure risk

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Risk level HighLow 1234	Slope failure risk
0° to under 3°	4
3° to under 8°	3
8° to under 15°	1
15° to under 20°	1
20° to under 30°	2
30° to under 40°	3
40° and over	3

1.4. Relative flood risk level of terrain map

	Risk level HighLow 1234	Flood risk
Mountain	Linear steep slope on the mountain	4
	Gentle slope on the mountain	4
Hill	Linear steep slope and Gentle slope on the hill	4
Volcano	Gentle slope on the volcano	3
	Mud flow landforms	3
Upland	Sand gravel upland and rock upland	4
	Lower of diluvial upland	4
	Volcanic ash plateau	4
	Lava plateau	4
Lowland	Linear steep slope on fan	2
	Fan and valley bottom lowland	2
	Delta, tidal flat and marshy valley bottom lowland	1
	Peatland	1
	Sand dune, beach ridge, and sandbank	3

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