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RESEARCH ARTICLE

Quantitative monitoring of changes in forest habitat connectivity following the great eastern Japan earthquake and tsunami

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Abstract

Context In March of 2011 a huge tsunami devastated forest habitats along the coast of Sendai Bay in northeastern Japan. Evaluation and monitoring of the changes in habitat connectivity caused by this disaster are essential for managing the recovery of ecosystems and biodiversity.

Objectives This research is designed to clarify changes in habitat connectivity caused by the tsunami, as well as subsequent changes due to the process of recovery and restoration.

Methods Forest patch distribution maps were constructed from remote sensing data for 2010, just before the tsunami, 2011, immediately after the tsunami, and 2012 and 2016. A binary connection model was employed to generate forest patch network maps for each of the target years, for connectivity distances of 100 m, 800 m and 2500 m. Also, two quantitative connectivity indices, the Integral Index of Connectivity and Class Coincidence Probability were used to assess the changes in continuity.

Results The forest patch network map and quantitative indices analysis both showed that not only had the forest habitats been reduced and fragmented by the tsunami, but that continuity kept declining in the following year. By 2016, however, newly established forest patches connected with extant ones, resulting in a slight recovery in habitat connectivity.

Conclusions The network maps allowed clear visualization of changes in connectivity over the study period, and were backed up by quantitative results from the indices. This method is relevant for conservation of species with diverse mobility and habitat continuity needs, and for management and restoration of coastal ecosystems.

Keywords Connectivity · Great east japan earthquake · Patches network · Disturbance

Introduction

Healthy ecosystems and biodiversity are supported by organisms, materials, energy and information moving through the landscape (Crooks and Sanjayan 2006). Fragmentation and isolation of the habitats that comprise the landscape can impede this movement, resulting in ecosystem degradation and loss of

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biodiversity. Fragmentation of habitats is thus a major threat to healthy ecosystems and biodiversity (Wilcove et al. 1998).

Habitat fragmentation is defined as a process during which a large expanse of habitat is transformed into a number of patches of a smaller total area, isolated from each other by a matrix of habitats unlike the original (Wilcove et al. 1986). Habitat fragmentation has been shown to lead to an increased chance of local extinction (Bakker et al. 1996; Lutz Eckstein et al. 2006; Ewers et al. 2007); and some species may be rendered unable to move or disperse among the isolated habitats (Lindenmayer and Fischer 2007).

Connectivity, as a measure of how much a landscape suffers from fragmentation and isolation, is widely recognized as an essential concept for the conservation of ecosystems (Fagan and Calabrese 2006; Kindlmann and Burel 2008; Vos et al. 2008; Vasudev et al. 2015). Taylor et al. (1993) defined connectivity as “the degree to which the landscape impedes or facilitates movement among resource patches”. Connectivity is especially important when dealing with low-frequency large-scale disturbances that occur once every several hundred years. Tsunami are typical examples of this type of disturbance (Matsumoto et al. 2013; Tomita et al. 2014).

On 11 March 2011, a huge tsunami struck the Sendai region of Miyagi Prefecture, causing enormous damage to coastal forest habitats. Trees were not only knocked down or uprooted, but those that survived the initial physical shock were also later damaged by long emersion in seawater (Tomita and Kanno 2019). Studies using high-resolution satellite images have shown that 90% (4.2 km^2 to 0.5 km^2) of coastal forests in the area were destroyed by the tsunami (Zhao et al. 2013), and there are deep concerns about the impact on the ecosystem (Hara 2014). In addition, in-depth local studies show that the tsunami itself reached agricultural lands inland from the coast, and that after the disaster, various types of forests, including agricultural forests such as farmstead groves, suffered from direct physical damage and withering due to later salt damage (Ujiie et al. 2013; Osawa and Nanaumi 2015). Subsequent human activity, such as evacuation of impacted agricultural areas and felling of remaining trees, also contributed to the overall loss of connectivity.

Fortunately, some remnant patches of forest did survive the tsunami and inundation. Research has shown that following a large disturbance, the remaining species and habitats function as a biological legacy that forms the base for subsequent recovery (Fraterrigo and Rusak 2008; Turner 2010). In the study area as well, remnant patches have been shown to act as a hub for species dispersion (Tomita and Kanno 2019); and broadleaf tree seedlings have newly established in some of the small remnant patches of coastal forest (Hirabuki et al. 2011; Kanno et al. 2014; Tomita et al. 2016).

This research was designed to develop a method for analyzing and monitoring the changes in connectivity experienced in Sendai Bay. Previous studies have demonstrated the effectiveness of remote sensing technology for identifying and analyzing changes in land cover due to tsunami (Römer et al. 2012; Harada et al. 2015; Ishihara and Tadono 2017); and also to subsequent restoration and reconstruction projects that continue to impact the ecosystem (Hara et al. 2016). This research focuses on changes in connectivity. Forest patch distribution maps were created from land cover maps based on satellite remote sensing images. Connectivity among the patches was then modeled as a forest patch network, and calculated and mapped for three distance classes (short: 100 m, middle: 800 m, long: 2500 m). In addition, two indices, Integral Index of Connectivity (IIC) and Class Coincidence Probability (CCP), were employed to qualitatively analyze changes in connectivity for the same three distances. Data for the forest network maps and qualitative analysis were obtained for 2010, just prior to the disaster; and for 2011, immediately afterwards. Measurements were also taken for 2012 and 2016, to show the changes in connectivity caused by subsequent processes of natural recovery and restoration work.

Methods

Figure 1 shows the research methodology used in this study, which is explained in detail in the following sections.

Study area

The study area, shown in Fig. 2, covers the coastal plain in the vicinity of Sendai City, Miyagi Prefecture, along the Pacific Ocean side of the Tohoku Region (Fig. 2a, b). The area designated for connectivity

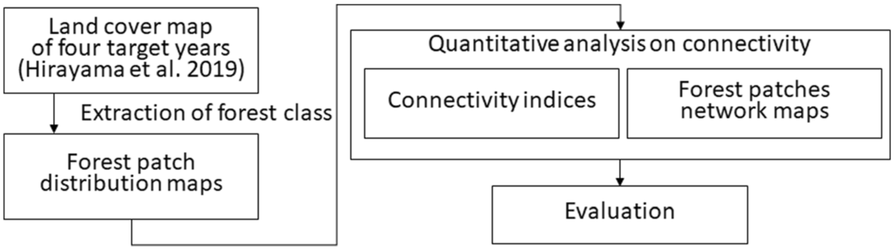

Fig. 1 Flowchart of the research methodology

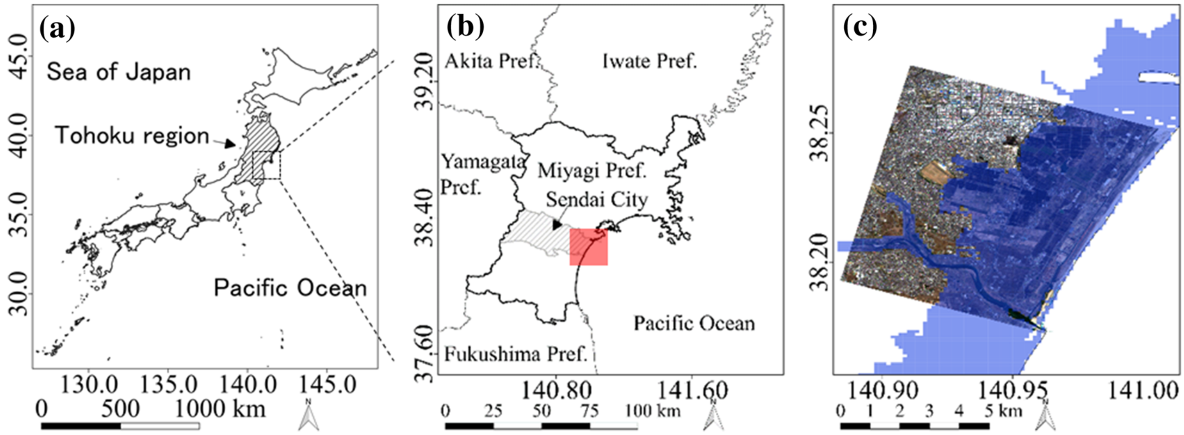

Fig. 2 Location of study area (**a**), with the area for connectivity analysis shown in red (**b**); RapidEye true-color image of the study area and the inundated area shown in blue (c)

analysis is about $80\ \mathrm{km}^2$, and consists of high population density urban sectors in the west, with agricultural land, coastal landforms and residential areas (Fig. 2c). The eastern side of the study area, with flat terrain at an altitude of -1 m to 5 m in the east, was, were heavily flooded by the tsunami (Fig. 2c); (Ministry of Land, Infrastructure, Transport and Tourism 2016), resulting in enormous damage to vegetation and landscapes (Zhao et al. 2013; Hara et al. 2016).

Forest patch distribution maps

The land cover map used in this study was generated as part of our previous research, and used cloudless RapidEye satellite data acquired for 4 April 2010, 13 April 2011, 10 April 2011 and 5 April 2016. (Hirayama et al. 2019). This map was created using a multiple classifier system that was able to reduce the effect of isolated pixels while maintaining high kappa coefficients (0.90 or over), as verified by field surveys and Google Earth images (Hirayama et al. 2018, 2019). The land cover map was utilized to extract forest patch distributions maps for the four target years using R language (raster package).

Connectivity quantification indices

As noted by Saura and Pascual-Hortal (2007), there are no established guidelines for objectively selecting indices for quantitative analysis of connectivity. In this research, IIC was chosen as one of the most commonly employed indices. Many recent studies use IIC only (Clauzel et al. 2015; Hernandez et al. 2015; Huang et al. 2018; Volk et al. 2018), but connectivity studies targeting large-scale disturbances may be difficult to express with a single index, and this research thus utilized a second index, CCP, which views the data from a different perspective than IIC. IIC focuses on the state of the patch, while CCP focuses on the spread of the network (Clauzel et al. 2017).

Previous studies have shown that IIC responds to patch area reduction and disappearance (negative effects on patches); (Pascual-Hortal and Saura 2006) while CCP responds to patch loss and appearance (placement and spatial extent of patches); (Jaeger 2000). In the study area, forest distribution was severely reduced by the disaster. On the other hand, over the past several years natural recovery and subsequent recovery and reconstruction projects have resulted in some forest regeneration. Using these two indices together will allow an appropriate evaluation of both patch reduction and subsequent regeneration.

In this study, IIC and CCP values were calculated at 10 m intervals for distances between 10 m and 3,000 m for the four target year forest patch maps. Based on these results (See "Results for IIC and CCP indices" section, Fig. 5 below) the connectivity distances used for the analysis were set at 100 m, 800 m and 2500 m. In this study, the calculation of the connectivity quantification indices was processed using R language (primarily the rgdal package).

Integral index of connectivity

The forest patches networks were analyzed by using the Integral Index of Connectivity or IIC (Pascual-Hortal and Saura 2006), which has been shown to be able to respond appropriately to any negative effects such as patch area reduction or loss. The IIC calculates the patch area and the connection status between each patch for all patches in the survey area as follows:

$$\mathrm{IIC} = \frac{\sum_{i=1}^{n}\sum_{j=1}^{n}\frac{a_i a_j}{1+nl_{ij}}}{A_L^2}$$

where $a_{(i\ \mathrm{or}\ j)}$ is the area of each patch; nl_{ij} is the connection status (set at 0 if connected, 1 if not connected; set at 0 if i and j are the same patch) between patches i and j, n is the total number of patches in the landscape; and A_L is the total landscape area. IIC values range from 0.0 to 1.0. Higher values indicate a higher the degree of connectivity.

Class coincidence probability

Class coincidence probability (CCP); (Pascual-Hortal and Saura 2006) is defined as the probability that two randomly selected points in a habitat belong to the same network. Also, because these two points belong to the same set of habitat patches and links, CCP is also defined as the probability that two organisms randomly placed in the habitat can find each other (Jaeger 2000). CCP is calculated as follows:

$$\mathrm{CCP} = \sum_{i=1}^{\mathrm{NC}}\left(\frac{c_i}{A_c}\right)^2$$

where NC is the total number of networks in the landscape; c_i is the area of each network; A_c is the total area of patches in the landscape. CCP values range from 0.0 to 1.0. Higher values indicate a higher the degree of connectivity.

Forest patches network maps

Network analysis using landscape elements such as patch distribution has been shown to be effective for connectivity analysis and evaluation (Urban and Keitt 2001). Assuming that organisms move between links in a network, this sort of network is an effective technique for inferring the movement path and range of organisms (Minor and Urban 2008). In this study, a graph-based network was constructed by simulating the distribution of forest patches (patches) and their connection states (links), using an extant binary connection model (e.g. Urban et al. 2009; Saura and Rubio 2010; Guo et al. 2018). In this model, a specific Euclidean distance between patches is set at a connectable distance value. If the measured distance is less than the set value then the patches are considered to be connected. Conversely, if the measured distance is greater than the set value then the patches are considered to be not connected. Based on results of the qualitative analyses, the connectable distance values were set at 100 m, 800 m and 2500 m, and forest patch network maps were generated for each of these values for all four target years.

Results

Forest patch distribution map

The forest patches distribution maps are shown for the entire study area in Fig. 3a–d. These maps follow the changes in forest patches distribution from before the tsunami (2010) to immediately after (2011) to 5 years later (2016). A comparison of the 2010 (Fig. 3a) and

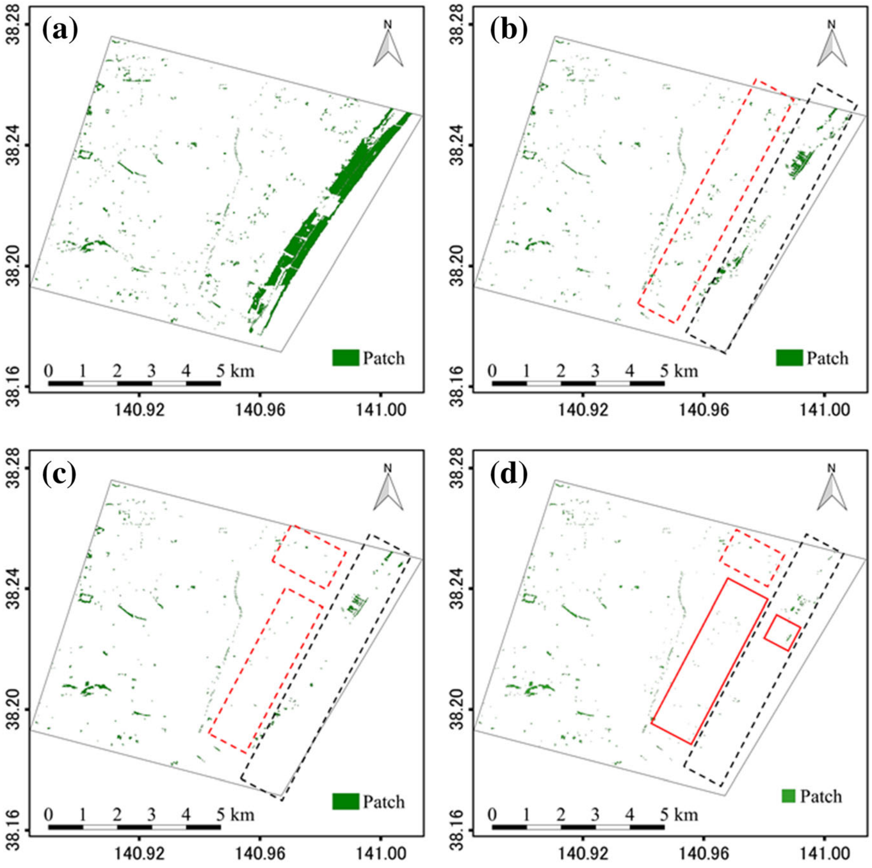

Fig. 3 Forest patches extracted from land cover map for 2010 (**a**), 2011 (**b**), 2012 (**c**) and 2016 (**d**). The black dash line indicates the area where coastal forests were reduced by the tsunami and also subsequently. The red dash line indicates the area where cropland forests were reduced. The solid red line shows where forest patches newly appeared

2011 (Fig. 3b) maps demonstrates that most of the forests stretching along the coast from north to south were nearly completely destroyed by the tsunami. In addition, the remaining forest on the north side of the coast, as well as very small patches of forest on cropland to the west, were further reduced following the tsunami (Fig. 3c, d). On the other hand, by five years later small patches of forest had newly appeared small patches in both the coastal and cropland areas (Fig. 3d).

The data from the above maps is shown in graphic form in Table 1 and Fig. 4. The total number of forest patches continued to decrease immediately following the tsunami, but then increased slightly between 2012 and 2016. Total patch area, on the other hand, continued to decrease over the whole research period. The size of the largest patch showed a sharp drop between 2011 and 2012; and as can be seen in Fig. 4, the recovery in total number of patches between 2012 and 2016 was due chiefly to an increase in smaller patches.

Results for IIC and CCP indices

IIC and CCP were calculated for connectivity distances at 10 m intervals from 10 m to 3000 m (Fig. 5). As a general trend, both values showed a sharp rise in the range of 600 m–1000 m for all the target years, then flattened out at longer distances.

The IIC values for all connectivity distances dropped sharply immediately after the earthquake, and then continued to decline over the research period. In contrast, the CCP values showed a sharp decrease due to the tsunami, but only at shorter connectivity

Table 1 A summary of annual changes in the number of patches and patch size

	Year			
	2010	2011	2012	2016
Number of patches	638	532	350	413
Total patches area (m2)	5854204.1	1209741.7	939477.1	775263.9
Patch size (m^2)				
Max	67.1	67.2	67.2	67.2
Min	9175.9	2274.0	2684.2	1877.2
Average	738.8	738.8	806.0	671.6
Median	2709560.8	18,623.9	50842.4	50238.0

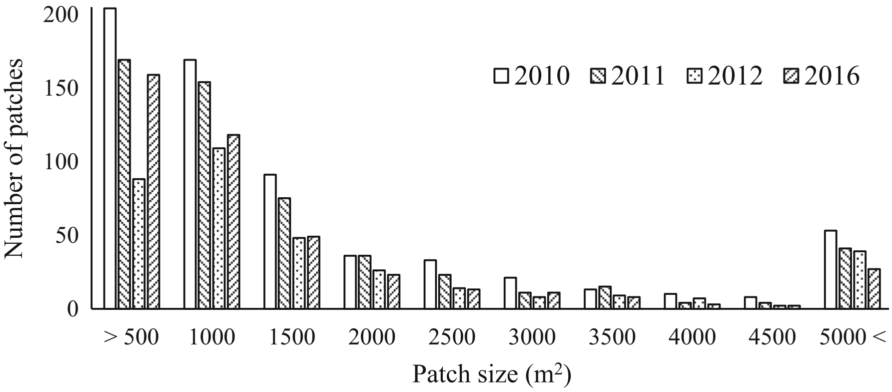

Fig. 4 Number of patches by patch size for each year

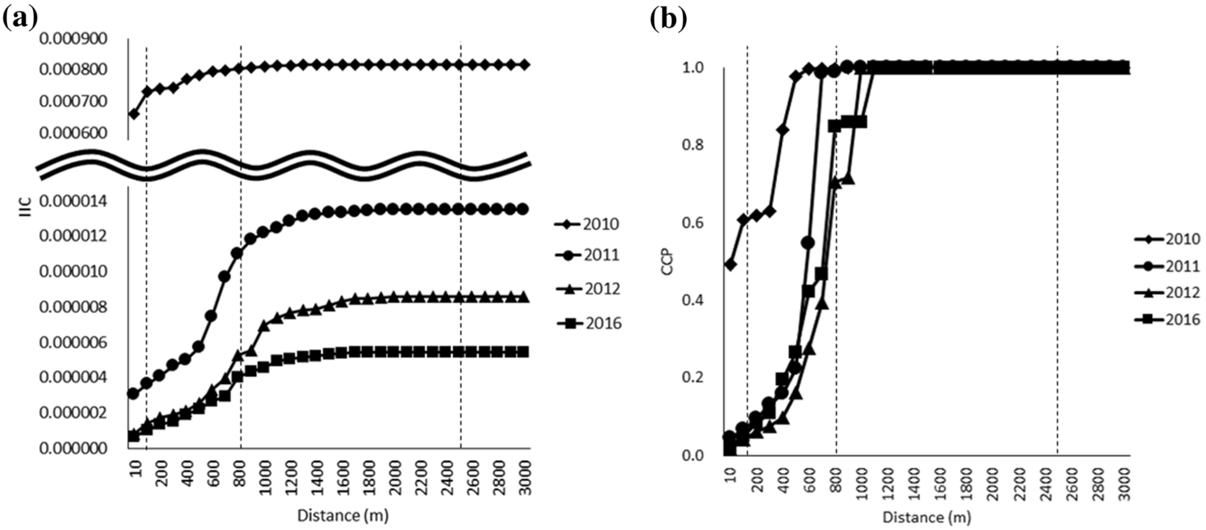

Fig. 5 IIC (**a**) and CCP (**b**) values for connectivity distances of 10 m to 3000 m for 4 target years. Based on these data, connectivity distances for building the networks used in the analysis were set at 100, 800 and 2500 m (indicated by dashed lines)

distances. At distances greater than 800 m the CCP values were maxed out for all target years. Based on this trend the connectivity distances for the analyses were set at 100 m (short), 800 m (middle) and 2500 m. Changes in IIC and CCP connectivity for the three set connectivity distances are shown in

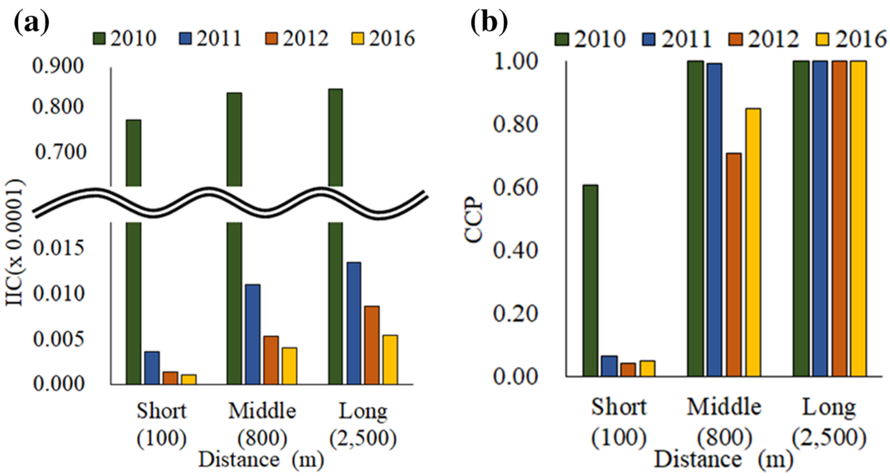

Fig. 6 Changes in IIC and CCP for three set connectivity distances over the research period

Fig. 6. As can be seen, although the IIC value for all three distances continued to, the CCP value began to increase from 2012.

Forest patch networks

Forest patch networks were constructed for each of the three connectivity distances and each of the target years. As was noted above, a connectivity link was recorded when the distance between two patches was equal to or less than the established connectivity distance. The number of links and networks recorded for each target year and each connectivity distance are shown in Table 2. The results are then shown visually in forest network maps, also generated for each target year and each connectivity distance (Fig. 7a-l). These forest patch networks visualize the degree of fragmentation and connectivity for the forest patches in the target zone.

Changes in connectivity over the period 2010 to 2016

The results for the forest patch research, IIC and CCP indices and forest network analysis, were used to visualize and qualitatively evaluate the changes in connectivity seen over the research period.

Changes in connectivity immediately after the tsunami (2010–2011)

As can be seen in Table 1, the total area of forest decreased sharply after the disaster. Although the total number of forest patches showed only a slight decrease, the average patch size plummeted. The largest patch (2709, 560.8 m^2), a continuous belt of forest running parallel to the coast, was completed broken up. The largest patch following the tsunami was only 183,623.9 m^2. Looking at Table 2 and Fig. 7, at the 800 m connectivity distance (Fig. 7e, f), a clear

Table 2 Number of networks and links (parenthesis) by dispersal distances for each year

	Year			
	2010	2011	2012	2016
Short (100 m)	274 (510)	227 (420)	180 (241)	228 (343)
Middle (800 m)	2 (1677)	3(1295)	4 (775)	6 (1103)
Long (2500 m)	1 (1847)	1 (1526)	1 (993)	1 (1281)

The number in parentheses are the links

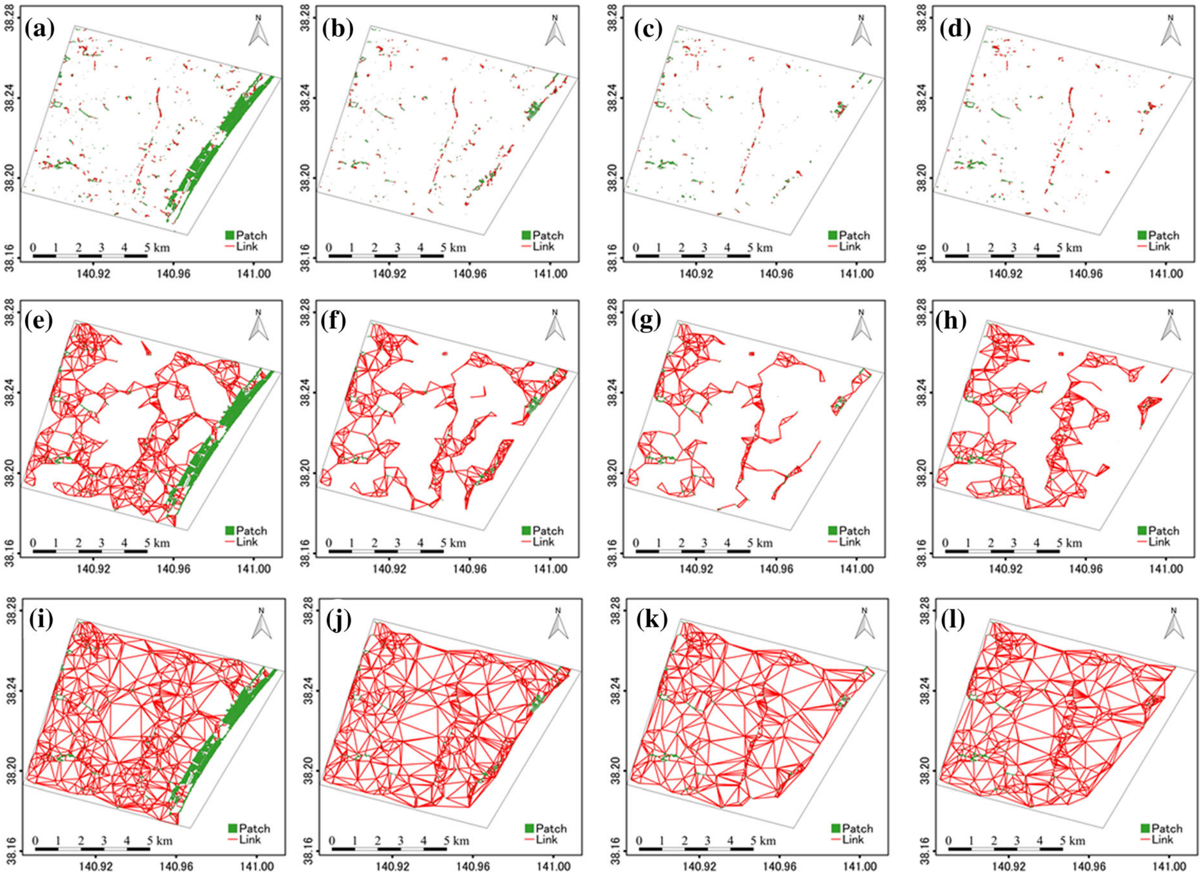

Fig. 7 Forest patches network connected at distance (100 (**a–d**), 800(**e–h**), 2500 (**i–l**) **m**); year of 2010 (**a**, **e**, **i**), 2011 (**b**, **f**, **j**), 2012 (**c**, **g**, **k**), 2016 (**d**, **h**, **l**)

gap can be seen separating the northern and southern sections of the long coastal forest. The connections between these two areas now follow a circuitous route to the west. For the IIC values, an extremely sharp drop in connectivity can be seen for all three distances (Fig. 6a). Values decrease from around 0.800 to between 0.005 and 0.015. The CCP values also show a sharp drop for the short distance, but almost no change for the middle and long distances (Fig. 6b). These results visually and qualitatively document the tremendous fragmentation of habitat caused by the tsunami.

Changes in connectivity after the earthquake (2011–2012)

The number of total forest patches continued to decline in the year following the earthquake (Table 1). Much of this decline was due to a continued loss of small patches, as clearly seen in Fig. 4. The size of the largest patch decreased, but the average patch size increased slightly, also due to reduction of small patches. The number of networks and links for the short distance both decreased sharply (Table 2). For the middle and long distances as well, the number of links clearly decreased. This loss in connectivity is clearly visible in the short distance network maps (Fig. 7b, c). Loss of continuity can be seen in both the coastal forest area and the inland cropland area. In addition, even at the middle distance the northern coastal forest area is seen to be completely cut off from the inland area (Fig. 7f, g). The IIC values show a continued decrease for all three distances (Fig. 6a); while those for the CCP show a clear decline only for the middle distance (Fig. 6b). These calculations provide quantitative backup for the visualization produced by the forest network maps. These results show that continuity kept declining in the year following the tsunami, most likely due to such factors as continued damage from the emersion in salt water.

Changes in connectivity 5 years after the earthquake (2012–2016)

5 years after the earthquake the total area of forest continued to decline, but the number of patches increased (Table 1). As can be seen in Fig. 4, this increase was due mainly to establishment of new small patches in the less than 1000 m^2 range. This trend can also be seen in Table 2. The total number of networks increased for the short distance, and the number of links for all three distances. Newly established forest patches appeared in both the coastal forest and inland cropland areas, and the new patches linked with extant patches, resulting in recovery of forest networks over the whole area. This recovery can be seen for all distances in Fig. 7c, d, g, h, k, l. The IIC data shows a small decrease in connectivity for all three distances (Fig. 6a), reflecting the continued decline in total patch area. The CCP data, however, shows a slight increase for the short distance and a more pronounced increase for the middle distance (Fig. 0.6b), providing quantitative evidence for the increase in connectivity due to appearance of new patches. These results show that 5 years after the tsunami, the appearance of new small patches resulted in a slight recovery in connectivity over the study area.

Discussion and conclusion

In general, Loss of connectivity impedes ecological processes involved in the movement of organisms between habitats and threatens population survival (Wilcove et al. 1998). Furthermore, it can lead to changes in the ecological character of organisms (Tucker et al. 2018). Connectivity monitoring is thus vital for understanding and managing ecological changes following a large scale disruption such as a tsunami. When managing the recovery of a disturbed ecosystem, it is important to keep in mind that the remaining species and habitats will function as a biological legacy that will support the recovery process (Fraterrigo and Rusak 2008; Turner 2010). In this study area as well remnant patches have been shown to act as a hub for species dispersion (Tomita and Kanno 2019). Thus establishing a method for evaluating the connectivity between the remaining patches is an important management priority. The aim of this study was to visually and quantitatively clarify changes in connectivity caused by the tsunami and subsequent recovery and reconstruction projects. The study employed both network maps and two quantitative indices to identify changes in continuity caused during and after the tsunami, and was able to effectively quantify changes connectivity in habitat connectivity caused by the tsunami, as well as subsequent changes due to the process of recovery and restoration.

Visualization of changes in habitat connectivity

Network maps allowed clear visualization of the changes caused by the tsunami, as well as those due to subsequent recovery and restoration. Network construction is considered an effective method for inferring the movement path and range of organisms (Minor and Urban 2008). The forest patch networks constructed from land use data employed in this study allowed visualization of changes in connectivity that can influence how plants and animals move through the landscape. The maps show where former connections have been broken, and where new ones have formed. They also show which habitat patches or group of patches have become isolated within the overall ecosystem. As such they accurately reflect the patterns of habitat fragmentation and changes in connectivity. For example, the continued decrease in forest patches immediately after the earthquake (Fig. 3c, d) is thought to be due to salt damage caused by inundation (Ujiie and Baba 2013). The negative impact on habitat connectivity caused by this inundation can be clearly seen in the middle distance network (Fig. 7f, g).

The ability of the network maps to show changes in forest patch networks for three connectivity distances provides a useful basis for managing species. For example, organisms that stay put or move only short distances can be easily isolated by habitat fragmentation. These species require close connectivity to move about and locate one another. On the other hand, more mobile species are able to move between more widely separated habitat patches. Haas (1995) have shown that small mammals with wider ranges of movement are less effected by habitat fragmentation than those with more restricted ranges. Habitat connectivity has also been shown to influence the movements of woodland nesting birds (Honorato et al 2015). Moreover, these changes in the range of bird movements may affect the dispersal of plant seeds (Perez-Hernandez et al. 2014).

The current patterns of species diversity have been shown to be influenced by habitat connectivity from past decades (Koyanagi et al 2012) or more than 50 years ago (Helm et al 2006). It is thus important to document changes in connectivity starting with pre-disaster and continuing into the future. For this purpose, quantitative analysis using network mapping derived from remotely sensed data has the potential to be an extremely valuable and practical tool.

Quantitative evaluation of changes in habitat connectivity

While network maps are ideal for assessing changes in habitat connectivity, some indexes are able to express these changes quantitatively. IIC, for example, can approximate the negative impact on connectivity as a decrease in index value (Pascual-Hortal and Saura 2006). Another index, CCP, can express the probability of two patches being connected, and also the ease of encounter between organisms (degree of landscape division) from the state of the network in the landscape (Jaeger 2000). Many recent studies use the single index for qualitative analysis (Clauzel et al. 2015; Hernandez et al. 2015; Huang et al. 2018; Volk et al. 2018). Connectivity studies targeting large-scale disturbances, however, may be difficult to express with a single index, and this research thus opted to use both IIC and CCP. These two indices differ in approach. IIC is focuses on the state of the patch, while CCP focuses on the spread of the network (Clauzel et al. 2017). The results clearly demonstrated the effectiveness of this approach. For example, the IIC results showed an overall decline in connectivity that continued throughout the study period. CCP, in contrast, was able to detect newly established forest patches that contributed to a small increase in connectivity at the middle distance level. By combining multiple indices with different properties the research was able to compensate for the advantages and disadvantages of each index and provide deeper insights into the landscape level changed in continuity.

Currently, guidelines for selecting the index to be used for connectivity studies are absent (Saura and Pascual-Hortal 2007). On the other hand, various connectivity analysis software has been developed (Vogt et al. 2007; Saura and Torne 2009; McRae and Kavanagh 2011; Foltête et al. 2012), making it possible for researchers to select multiple indices best suited to their needs. The results of this study clearly demonstrate the benefits of using multiple rather than limited single indices.

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