

Article

Super Typhoon vs. Earthquake as Driving Force of Forest Succession in a Subtropical Tectonically Active Region

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Abstract

This study compared the effects of super typhoons and earthquakes on forest succession at the slopes of the Rokko Mountains in Japan. According to changes in the enhanced vegetation index (EVI), the super typhoon in 1991 caused severe, widespread damage to topographically distinct forest stands across the mountains. A major earthquake in 1995 with a magnitude of $M_j = 7.2$ caused moderate effects on the EVI. The 1994 super typhoon and the 1995 major earthquake exhibited similar spatial damage patterns, with impacts concentrated on the northern slopes. Although the 2018 super typhoon recorded higher wind speeds, there was no reduction in forest stands across the mountains, indicating an increase in forest resilience. Nevertheless, detailed observations revealed localized, patchy impacts in 2018, specifically the death of some evergreen trees on the northern slopes. The 1991 typhoon diminished up to 14% (conf. int. 95%: $\pm 3\%$) of the pre-typhoon EVI values for the most negatively affected forest stands. Hence, the typhoons were thought to be the primary driving force that accelerated the forest succession by eliminating vulnerable trees. This elimination enhanced the increasing dominance of broadleaved evergreen laurel tree species, which are known to have stronger root systems than the vulnerable conifers. In addition, it was revealed for the first time that multiple vegetation types on slopes under the same topographical conditions were commonly damaged by multiple super typhoons within a 27-year period, during which typhoon-enhanced forest succession was strongly pronounced. The findings offer beneficial prospects for proactive climate-resilient forest management and disaster mitigation strategies tailored to slope-specific vulnerabilities. This study is the first to compare the effects of super typhoons and a major earthquake on forest stands.

Keywords: wind damage; forest disturbance; forest restoration



Academic Editors: Pablo Antúnez and Christian Wehenkel

Received: 28 March 2026

Revised: 23 May 2026

Accepted: 25 May 2026

Published: 28 May 2026

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1. Introduction

According to Poorter et al. [1], forest succession is defined as a directional change in species populations, the community, and the ecosystem at a site following an ecological disturbance. Ecological disturbances include natural events such as windstorms. Tropical cyclones are powerful windstorms often accompanied by heavy rainfall. Tropical cyclones mainly occur at latitudes of approximately 10° to 20° in the Pacific, North Atlantic, and South Indian oceans [2]. The tropical cyclones then proceed north or south in the Northern or Southern Hemispheres, respectively. Some tropical cyclones reach and run over land,

and then may disturb the forest stands. The ‘storm-warning zone’ (bofu-iki) is defined as the area where wind speeds reach 25 m s^{-1} or higher. Near Japan, it is not uncommon for regions to remain within this zone for ten hours or more several times a year. Such prolonged exposure to tropical cyclones inevitably leads to catastrophic damage.

Details of forest disturbance caused by tropical cyclones have been well documented by photographs by Kagamihara et al. [3]. After a tropical cyclone hit a western Japanese region, some tree root systems were detached from the soil, and the root systems that remained in the soil rapidly decomposed. The outcome of forest disturbances, such as that mentioned above [3], was detected as changes in ecological indicators such as the normalized difference vegetation index (NDVI) [4], which indicates the health status of green biomass. Tropical cyclone-induced decreases in NDVI were recognized after the observed forest stands had experienced the uprooting of trees, breaking of tree trunks and branches, and defoliation [5]. The enhanced vegetation index (EVI [6]) was employed to accurately identify cyclone-affected forest stands [7]. Unlike NDVI, which is often saturated in high-biomass regions, EVI maintains sensitivity in dense forests, allowing for the precise detection of fallen trees.

A recent review article shows that forest disturbances caused by windstorms, fires, pests, or diseases kill vulnerable trees that eventually release organic matter and inorganic nutrients [8,9]. These processes enable the colonization of diverse taxonomic newcomers, driving a process of ecological succession in which the species most adaptable to the new environment eventually become dominant. These shifts in species composition and the acceleration of succession are accompanied by niche-derived diversity and unique ecosystems [10]. Tropical cyclones and related disasters are common in Japan and often cause forest disturbances [2]. For example, in Tokyo, tropical cyclones occasionally knock down vulnerable trees that die afterward. Fujiwara [11] found that the species composition in the forest had clearly changed between 1950 and 1971, when more than 90% of chinkapin (*Castanopsis cuspidata* (Thunb.)), a broadleaved laurel species, survived. Meanwhile, only 13% of pines and 5% of Japanese cedars (*Cryptomeria japonica* (Thunb. ex L.f.) D.Don) were still standing after being occasionally hit by tropical cyclones. In the south coastal regions of Japan, these processes alter the secondary forest stands originally dominated by human-introduced coniferous trees, typically, pines and Japanese cedars. Eventually, the forest changed to an evergreen laurel forest, which is the climax forest type in the region [12]. Along the east coast of the United States, which shares climatic similarities with the southern coastal regions of Japan, tropical cyclones have been identified as a driving force of forest succession [13].

Besides tropical cyclones, the memory of the 2011 Great East Japan Earthquake remains vivid, and numerous other seismic events continue to cause damage across Japan on an almost annual basis. Earthquakes have also caused significant forest disturbance, observed as decreases in NDVI value as well as the recovery [14,15]. Even though earthquakes have immediate destructive effects on forest ecosystems, they can also be driving forces of forest succession by allowing the surviving tree species to fit in the post-earthquake landscape while vulnerable tree species are eliminated [16]. Moreover, under global climate change, intensifying typhoons represent a growing climate risk rather than merely isolated disturbance events.

Here, a question arises. If an extremely strong tropical cyclone or a major earthquake hits a forest ecosystem, which one has the more significant statistical contribution to vegetative biomass loss, as indicated by changes in EVI value? To compare the effects, changes in EVI before and after disasters were expected to give an answer to the question. Numerous studies have documented the processes of forest disturbance [17] and subsequent recovery [18] related to tropical cyclones. Similarly, some records exist regarding the de-

structive impacts [19] and restoration [20] associated with earthquakes. However, there has been no comparative analysis to date that directly evaluates the destructive power of these two forces at a shared site.

As such, this study was conducted to examine whether either a strong tropical cyclone or a major earthquake resulted in more significant changes in EVI value across forest stands in the Rokko Mountains in western Japan, hypothesizing that the impact of the earthquake would be more profound.

2. Materials and Methods

In 1991, 1994, and 2018, the Rokko mountains were hit by extremely strong super typhoons [21]. Typhoons are a regional name for tropical cyclones [2]. The 1991, 1994, and 2018 typhoons meet the criteria for super typhoon status. Super typhoons are defined as those with surface wind speeds of 130 knots (240 km h^{-1}) or greater [22]. Changes in EVI were obtained for pixels representing $30 \times 30 \text{ m}$ areas in the Rokko Mountains. The EVI values within a period of a single year were compared before and after the 1991, 1994, and 2018 typhoon seasons. To enable the evaluation of the effects of each super typhoon independently from other events, including typhoons, earthquakes, and others, December, January, and February (winter) composite EVI datasets for 1991, 1994 or 2018 were used to minimize the effects of other typhoons and earthquakes in previous years, mitigating possible interactions among multiple typhoons and other events spanning more than a single year [23,24]. Likewise, changes in the EVI in the same area were obtained as effects of the major earthquake that shook the area on 17 January 1995. The before–after comparison was made using EVI values for the 18 January–28 February 1995 composite and the 1992–16 Jan 1995 winter composite to evaluate the immediate earthquake effects. Year-long earthquake processes were also evaluated by comparing the 18 Jan 1995–1996 winter composite EVI values against those from the 1992–16 Jan 1995 winters. The comparisons were made taking topographical changes into account.

The workflow of this research is shown in Figure 1, and it will be described in the following chapters.

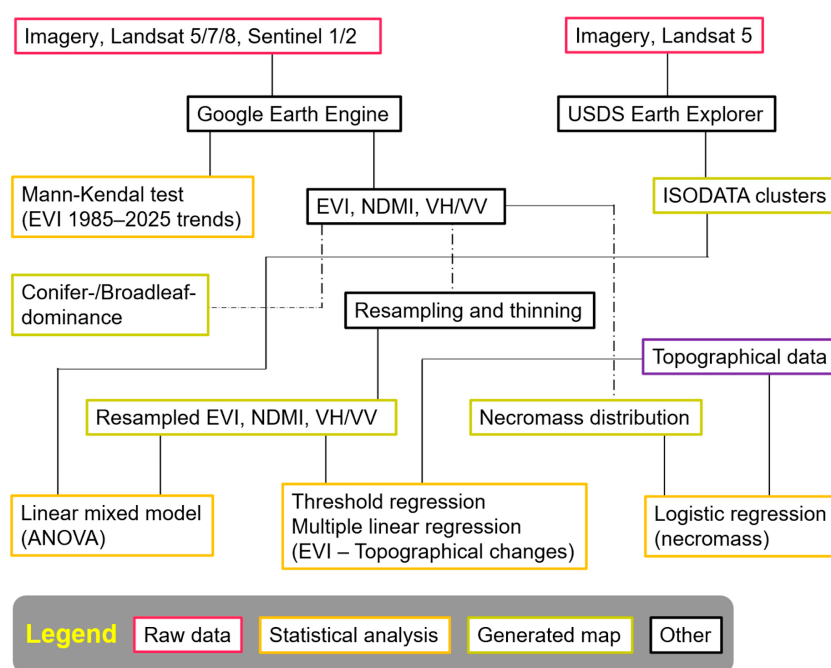


Figure 1. Workflow of this study. The solid and dashed lines do not touch each other at the intersection point.

2.1. Site Description

The current study site is located mainly in Kobe city, Hyogo prefecture, in western Japan (Figure 2). According to Köppen [25], the Rokko Mountains and the surrounding areas shown in Figure 2b belong to the humid subtropical zone (Cfa). The mountains have the highest altitude of 931 m above sea level at 34.7780° N, 135.2637° E in Kobe city, Japan. According to Takahashi et al. [26], almost the entire area of the mountains has a brown forest soil derived from granite [27]. The soil has low fertility while its water permeability is high [26].

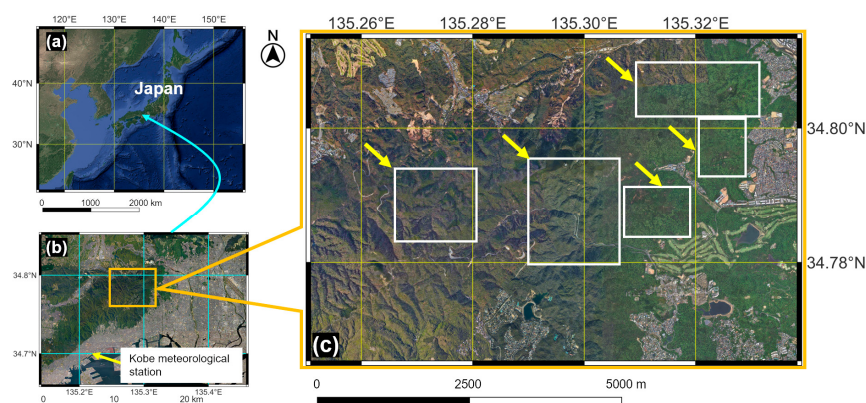


Figure 2. Maps of the study site. Maps (a–c) indicate a broad-scale map of Japan and its surroundings (1000-km scale), location of the Rokko Mountains relative to downtown Kobe to the south, and an aerial photograph of the specific study area, respectively. The white rectangles with yellow arrows indicate areas of analysis of Landsat and Sentinel imagery data.

The mountains have had centuries of deforestation history; they lost a significant number of trees and became bare except for a small area [28]. In the early 1900s, landslides and their subsequent outcomes occasionally damaged downtown Kobe city. Then, to cope with this risk, a reforestation program to restore the Rokko's vegetation was started in 1902 [29,30]. In the last 100 years, limited human activities accompanied by deforestation occurred [31]. The mountains were included in the Setonaikai National Park, established in 1934 [32].

In the reforestation program, multiple tree species were introduced. The most widely introduced was a pine tree species (*Pinus densiflora* Siebold et Zucc.). Another widely introduced tree was *Alnus firma* Siebold et Zucc., a Japan-endemic tree species that fixes atmospheric nitrogen. The program also involved other tree species, including coniferous evergreen species of Japanese cedar (*Cryptomeria japonica* (Thunb. ex L.f.) D.Don) and Japanese cypress (*Chamaecyparis obtusa* (Siebold et Zucc.) Endl.). Some deciduous trees were also introduced. These were zelkova (*Zelkova serrata* (Thunb.) Makino), sawtooth oak (*Quercus acutissima* Carruth.), maple species, and others [30]. To date, depending on the site, most of the initially introduced trees have been substituted by others, such as camphor trees (*Camphora officinarum* Boerh. ex Fabr.), a broadleaf evergreen laurel species. Between 1954 and 2004, evergreen laurel tree species became more abundant than in the past [33].

The area including the mountains and Kobe city was strongly shaken by an earthquake on 17 January 1995. The magnitude values were $M_w = 6.9$ and $M_j = 7.2$ [34]. The effects on the forest stands were also analyzed and compared with those of typhoons.

2.2. Meteorological Data on Typhoons

Super typhoons Mireille, Orchid, and Jebi hit the region in 1991, 1994, and 2018, respectively. Typhoons are tropical cyclones that occur in the northwestern Pacific Ocean [2]. Mireille and Orchid were category 4 super typhoons, the second-most intense typhoon

category [35]. Jebi was a category 5 super typhoon, the strongest one. The nearest meteorological station was the Kobe meteorological station (Figure 2b). The meteorological data from the meteorological station on the 3 days of the super typhoons were retrieved from the Japan Meteorological Agency website (<https://www.jma.go.jp/jma/indexe.html> accessed on 2 May 2026). From the website, meteorological data on 27 September 1991 (Mireille), 29 September 1994 (Orchid), and 4 September 2018 (Jebi) were retrieved (Figure 3). The website also provided the number of typhoons that had struck the region, including Kobe city and the Rokko Mountains. The mean number of typhoons approaching within 300 km of Kobe was 3.8 per year between 1991 and 2018 (standard deviation 1.9). The typhoon numbers in 1991, 1994, 1995, 2000, and 2018 were 4, 2, 1, 0, and 5, respectively.

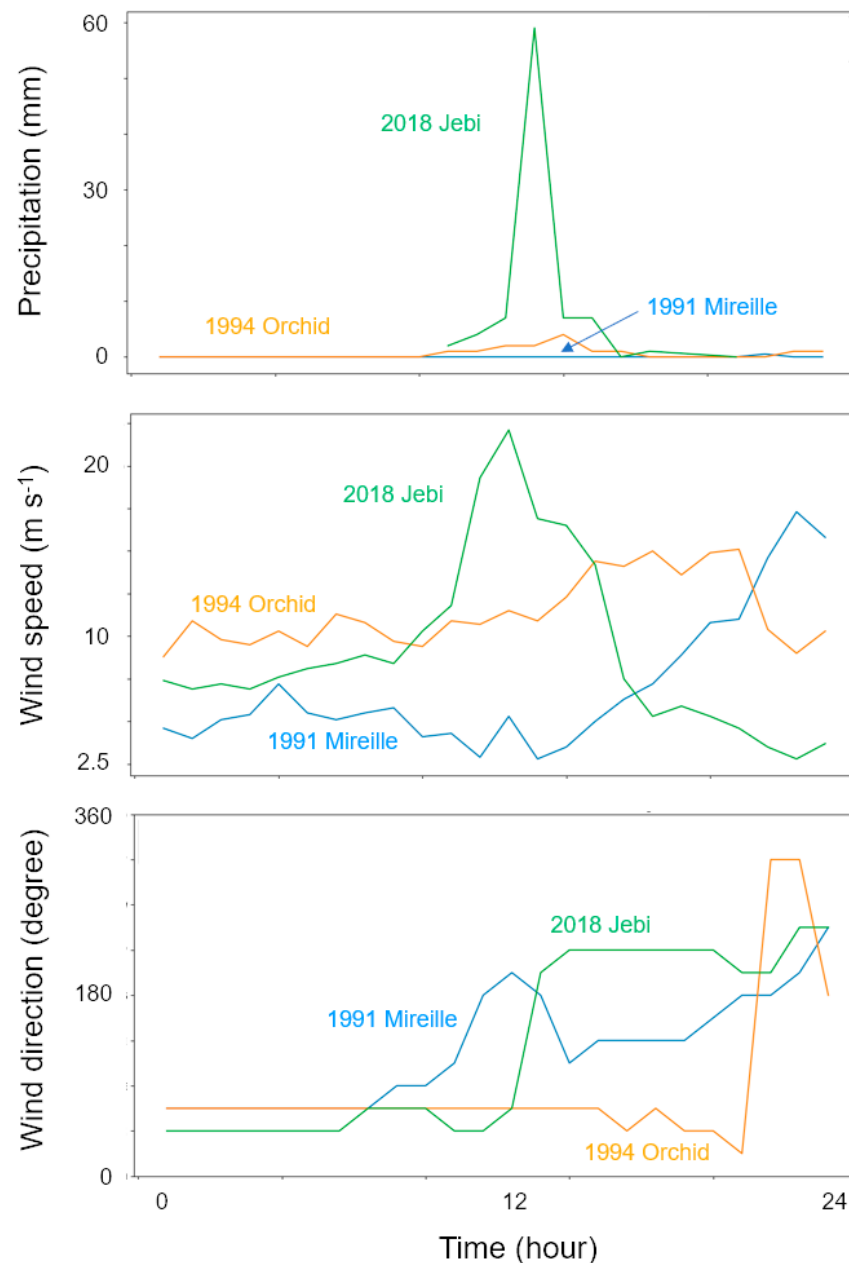


Figure 3. Changes in precipitation, wind speed, and wind direction on 21 September 1991 (Super typhoon Mireille), 29 September 1994 (Orchid), and 4 September 2018 (Jebi) at the Kobe Meteorological Station.

The maximum terrain-adjusted wind speeds on Rokko slopes during the typhoons were evaluated as follows. To evaluate the physical stress imposed by the typhoons,

two datasets were integrated within the Google Earth Engine platform (Map data: Google, DigitalGlobe). The datasets were topographic and meteorological variables. Sin- and cos-converted components derived from wind speeds and directions at 10 m above the surface were obtained from the ECMWF ERA5-Land hourly dataset. Google Earth Engine performed the wind impact simulation and maximum impact extraction.

The course of super typhoon Jebi (Figure 4) was retrieved from the Digital Typhoon database website [36] (<http://agora.ex.nii.ac.jp/digital-typhoon/> accessed on 12 March 2026).

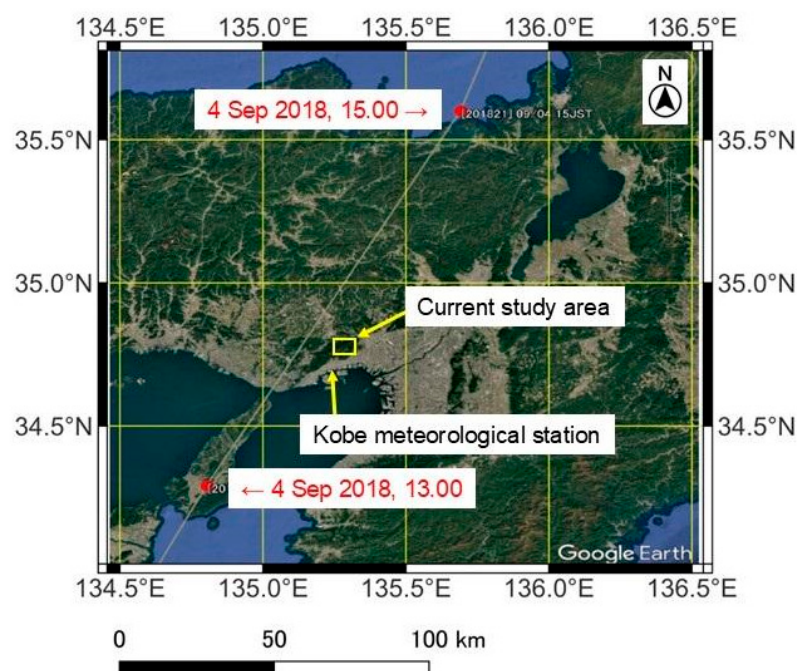


Figure 4. Course of super typhoon Jebi on 4 September 2018.

2.3. Remote Sensing Data

Google Earth Engine was employed to retrieve remote sensing data. For all analysis periods, a median composite was generated to derive representative reflectance values.

To perform a three-decade-long assessment of vegetation changes, for the analysis spanning from the late 1980s to the early 2000s, data from Landsat 5 Thematic Mapper and Landsat 7 Enhanced Thematic Mapper+ collection 2 level 2 were selected. For the contemporary analysis focused on 2015–2019, Sentinel 2 MultiSpectral Instrument level 1C data were utilized (European Space Agency, Paris, France). The collection comprised winter (December, January, February) EVI composite, which integrates data on multiple time series and then fills in the gaps caused by cloud contamination and other uncertainties [37]. This study targeted the winter season to evaluate the physiological state of evergreen trees. To enable the before–after comparisons, the composite of the preceding three years was used as the baseline. For example, to evaluate the 2018 typhoon effects, we compared the 2018–2019 winter composite (observation) against a 2015–2018 winter baseline. Immediate effects of the major earthquake were evaluated by comparing the composite EVI value for 18 January 1995–28 February 1995 against a winter composite baseline for 1992–16 January 1995 winters.

When relying on the Landsat series, surface reflectance data were used, which included atmospheric correction via the USGS LaSRC/LEDAPS algorithms. Cloud masking was performed using the quality assessment pixel bitmask. As for Sentinel-2, top-of-atmosphere reflectance data were processed, with clouds and cirrus removed via the quality assessment 60 and MSK_CLASSI bands. Given the steep and complex topography of the Rokko

Mountains, a rigorous sun-canopy-sensor + C-correction topographic correction was implemented for both Landsat and Sentinel 2 datasets. For each scene, the specific solar geometry (zenith and azimuth) was retrieved from the image metadata. A band-specific C-factor was then estimated through linear regression between the reflectance and local incidence angle within the study area.

The EVI was utilized as a robust proxy for vegetation vigor, calculated as follows:

$$\text{EVI} = 2.5 \times (\text{NIR} - \text{red}) / ((\text{NIR} + 6 \times \text{red} - 7.5 \times \text{blue}) + 1) \quad (1)$$

where red, NIR, and blue are reflectance measurements for red (630–690 nm wavelength), near-infrared (760–900 nm wavelength), and blue (450–530 nm wavelength) light, respectively. The EVI is a vegetation index to enhance the vegetation signal with improved sensitivity in high-biomass vegetation through a reduction in background scatter and atmospheric influences. The EVI is an improved version of the NDVI, which indicates gradients between extremely vegetation-rich and barren areas. The richer the vegetation, the closer the value converges to 1. The lowest value is -1 . While Landsat products were processed as surface reflectance, Sentinel 2 data utilized Level 1C top-of-atmosphere reflectance. To ensure time-series consistency between these different reflectance levels, the EVI's mathematical formulation inherently incorporates the blue band. The blue band serves to stabilize and self-correct atmospheric scattering effects [6], thereby minimizing the discrepancy between top-of-atmosphere and surface reflectance datasets in dense forest canopies.

All image processing, algorithmic corrections, and spatial statistics were performed using the Google Earth Engine cloud platform. Final results were projected into the UTM Zone 53N (EPSG:32653) coordinate system and exported as GeoTIFF images.

2.4. Handling Remote Sensing Data

QGIS 3.2.2. and MultiSpec version 2024.05.16 64-bit for Windows were used to obtain values for the EVI [4] for pixels in the Landsat and Sentinel imagery datasets retrieved from a Google Earth Engine collection. December, January, and February (winter) composite EVI datasets for the 1991, 1994 and 2018 typhoons were used to minimize the effects of other typhoons and earthquakes in previous years when there must have been interaction among multiple typhoons and other events within more than a single year [23,24]. The three-year winter composite image was regarded as the baseline image before the typhoon season or earthquake. The post-typhoon periods for EVI comparison were December 1991–February 1992, December 1994–16 January 1995, and December 2018–February 2019. For 2000, when no typhoon approached the region, the December 1997 – February 2000 and December 2000 – February 2001 composite EVI images were used as the before and after 2000 typhoon season images, respectively. Unavailable pixels were eliminated in the following analyses. Likewise, changes in the EVI in the same area were obtained as effects of the major earthquake that shook the area on 17 January 1995. The before–after comparison was made by obtaining EVI values for the Landsat imagery data.

Regarding the Sentinel imagery, systematic 3×3 pixel resampling was applied. In contrast, Landsat data were analyzed at their native 30 m resolution.

2.5. Moisture Measures Before the Typhoon in September 2018

Normalized difference moisture index (NDMI) composite values [38] for 2015–2019 winters were retrieved from the Google Earth Engine cloud platform. The imagery was acquired by the Sentinel 2 satellite. The NDMI indicates gradients between extremely moist and dry ecosystems. The moister the ecosystem, the closer the value converges to 1. To ensure accuracy in the rugged terrain of the Rokko Mountains, we applied the sun-canopy-sensor + C topographic correction to bands 8 and 11, as in the case of EVI determination.

2.6. Evergreen Conifer- and Broadleaf-Dominance Likelihood Mapping

To characterize the spatial distribution of evergreen forest types in the area, we utilized the Sentinel 2 harmonized reflectance collection for the 2017–2018 winter [39]. First, two spectral indices were calculated to differentiate conifer- and broadleaf-dominant forest stands. Normalized difference red edge (NDRE) was calculated using the near-infrared (band 8) and red edge (band 5) bands to capture vegetation vigor and chlorophyll content during the winter season. Tasseled cap brightness (TCB) was derived via a linear transformation of six multispectral bands (bands 2, 3, 4, 8, 11, and 12) using coefficients optimized for Sentinel 2. TCB was used as a proxy for the overall albedo and structural density of the canopy. To account for the spatial continuous transition between conifer- and broadleaf-dominant stands, we developed a likelihood mapping approach rather than a discrete classification. The NDRE and TCB values were rescaled to a 0–1 range using a unit-scale normalization based on typical local ranges (NDRE, 0.1–0.4 and TCB, 0.12–0.35). The likelihood for each forest type was defined as follows. Evergreen broadleaf likelihood was defined by high NDRE and high TCB values, representing the relatively high reflectance and vigor of broadleaf species (e.g., *Camphora officinarum*). Conifer likelihood was defined by high NDRE and low TCB, reflecting the dark and dense canopy structure of conifers (e.g., *Pinus densiflora*). The resulting likelihood layers were clipped to the study area boundary and masked to include only forested clusters. The final products were exported as GeoTIFFs at a 10 m spatial resolution for subsequent spatial analysis.

2.7. Identification of Necromass After the 2018 Typhoon Season

To detect the severest forest disturbances such as fallen trees and canopy dieback, we integrated multi-modal satellite observations from Sentinel 1 synthetic aperture radar and Sentinel 2 multispectral imagery [40]. Structural changes in the forest canopy were assessed using the HV/VV polarization ratio from Sentinel 1 ground range detected data. To minimize the influence of seasonal humidity variations, we processed winter-only composites (December to February) for the observation period (winter 2018–2019) and the baseline period (winter 2015–2018). A median composite was generated for each period, and the structure loss was quantified by calculating the difference in the HV/VV ratio. A decrease in this ratio indicates a reduction in the volume of vertical and randomized scattering structures, characteristic of tree falls or major structural damage. Physiological stress and moisture reduction were evaluated using the NDMI derived from Sentinel 2 harmonized data. The NDMI difference (moisture drop) was then calculated between the pre- and post-disturbance winter periods. The final identification of dead biomass and fallen trees was performed using a strict dual-threshold approach. Pixels were classified as disturbed only if they exhibited a significant structural decline (structure loss < −2.0 dB) accompanied by a substantial reduction in canopy moisture (moisture drop < −0.1). To eliminate salt-and-pepper noise and isolate meaningful disturbance clusters, a 3 × 3 focal mode filter was applied to the binary classification mask. All processing was executed on the Google Earth Engine platform.

2.8. Topographical Variables for the Landsat and Sentinel Pixels

QGIS 3.22 and MultiSpec version 2024.05.16 64-bit for Windows were used to obtain topographical variable values for the Landsat pixels. Slope angle, slope aspect, and altitude values were determined for the 30 × 30 m rectangle areas represented by the Landsat imagery pixels. The slope aspect values were determined using the following equations:

$$\text{west-east slope component} = \text{wind speed (m s}^{-1}) \times \sin(\theta) \quad (2)$$

$$\text{south-north slope component} = \text{wind speed (m s}^{-1}) \times \cos(\theta) \quad (3)$$

where θ is the wind direction, θ is 0° when the wind direction is north, 90° when east, 180° when south, and 270° when west. Western and southern winds were positive, and eastern and northern winds were negative.

2.9. Vegetation Map

A vegetation map of the study area was obtained from the website provided by the Biodiversity Center of Japan (<http://gis.biodic.go.jp/webgis/> accessed on 26 May 2026). The information was acquired between 1999 and 2012.

2.10. Iterative Self-Organizing Data Analysis Technique Clustering of Pixels in the Landsat Imagery Data

MultiSpec version 2024.05.16 64-bit for Windows was used to classify the area in Figure 2c based on Landsat 5 pixels. To classify the forest stands, an unsupervised classification was performed using the Iterative Self-Organizing Data Analysis Technique (ISODATA). Unlike the standard k-means algorithm, ISODATA is a dynamic clustering process that automatically adjusts the number of clusters through iterative splitting and merging. During each iteration, clusters with a standard deviation exceeding a predefined threshold are split into two, while pairs of clusters with close spectral distances are merged. This process continues until the statistical distribution of the pixels reaches a stable state, allowing for a more objective representation of the complex forest structure and topographic variations in the Rokko Mountains. Clustering was carried out at 99% or greater pixels that did not change class membership; the minimum cluster size was represented by 4 pixels. Then, 10 clusters were generated in the imagery representing the area shown in Figure 2c. The Landsat 5 imagery datasets were acquired for 18 March 1991, 5 May 1991, and 23 March 1993. The dataset for 18 March 1991 had a 4% cloud cover, and the others had 0%. Images for bands 1 (blue), 2 (green), 3 (red), 4 (near-infrared 1), 5 (near-infrared 2), and 7 (mid-infrared) were used. The band 2 image (green) for 23 March 1993 was eliminated due to an unknown computer glitch. Eventually, 17 grayscale images were used for ISODATA clustering by applying the above conditions.

2.11. Statistical Analysis

Sentinel data carried by comma-separated-value files provided by MultiSpec for Windows were 3×3 resampled on the Google Colaboratory platform. Sentinel and Landsat data were subjected to spatial thinning on Google Colab.

XLStat version 2021.4.1 (Addinsoft Inc., Paris, France) was used for stepwise multiple regression analysis. Changes in EVI or winter EVI were described as dependent variables by topographical variables and NDMI serving as independent variables. These processes identify the topographical variables most significantly associated with changes in EVI. A 5-fold cross-validation was adopted. In stepwise multiple regression analysis, $p = 0.05$ for inclusion and 0.10 for removal were adopted for independent variable selection. A variance inflation factor < 10 was used as the threshold for selecting independent variables.

The linear mixed-effects model analysis of variance, logistic regression analysis, threshold regression analysis, Global Moran's I test for detecting spatial autocorrelation, and Mann–Kendal increase/decrease test for detecting significant increasing/decreasing trends of EVI were conducted on Google Colab. In the linear mixed-effects models, changes in EV were treated as the dependent variable. The ISODATA categories and the disaster events (typhoon and earthquake) were involved as independent variables. In analyzing composite EVI values for the 1990–1991, 2003–2004, and 2017–2018 winters, the ISODATA categories and the periods were used as independent variables. For the linear mixed-effects models, post hoc pairwise comparisons applying Tukey's HSD test were performed.

Threshold regression analysis was performed to identify significant topographical variables influencing (changes in) EVI. In the threshold analysis, (changes in) EVI value and topographical variables were involved as the independent and dependent variables, respectively. A 5-fold cross-validation was used.

Logistic regression analysis was performed with a 5-fold cross-validation to examine the effects of topographical conditions on the occurrence of necromass. In the analysis, the occurrence of necromass was used as the dependent variable. The topographical variables and NDMI were used as the independent variables.

The Mann–Kendall trend test was applied to the winter and annual EVI composites from 1985 to 2025 across the five rectangular areas in Figure 2c.

3. Results

This study compares the impacts of typhoons and major earthquakes. In the following subsections, details of the results and mechanisms of the results will be described.

3.1. Typhoon Rain and Wind

In the 1991, 1994, and 2018 typhoon seasons, the Rokko Mountains and the surrounding region were more severely subjected to strong winds than in 1995 and 2000, when a single and no typhoon hit the region, respectively (Figure 5). In 1995, when the major earthquake occurred, the region experienced relatively calm winds throughout the year.

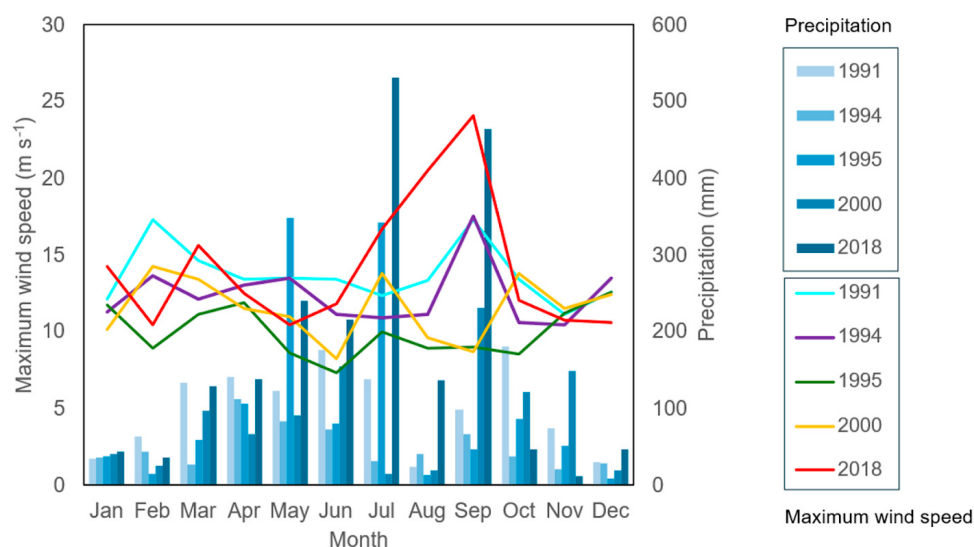


Figure 5. Precipitation and maximum wind speed for 12 months in 1991, 1994, 1995, 2000, and 2018 at the Kobe meteorological station.

3.2. ISODATA Clusters

ISODATA clustering resulted in 10 clusters. According to Figure 6, the distribution pattern of the 10 clusters does not match the map of vegetation types. This mismatch was unexpected. While we expected that specific forest stands would be more or less vulnerable to strong winds than the others, the results of this study indicated that multiple, obviously different forest stands on similar topographical conditions had a common vulnerability to the typhoons, seemingly by wind rather than rain, as well as to earthquakes, which are described later.

Results of ISODATA clustering are provided in Table 1. Ten clusters were generated based on the reflectance values for visible light and moisture-related infrared light. In the computation, cluster 1 was eliminated by the MultiSpec software because of the negligible number of pixels [41]. The clusters show gradients of bright–dark canopy appearance and

dry-moist ecosystems. Cluster 2 was the brightest and driest among the nine clusters. Cluster 10 was the darkest and most moist.

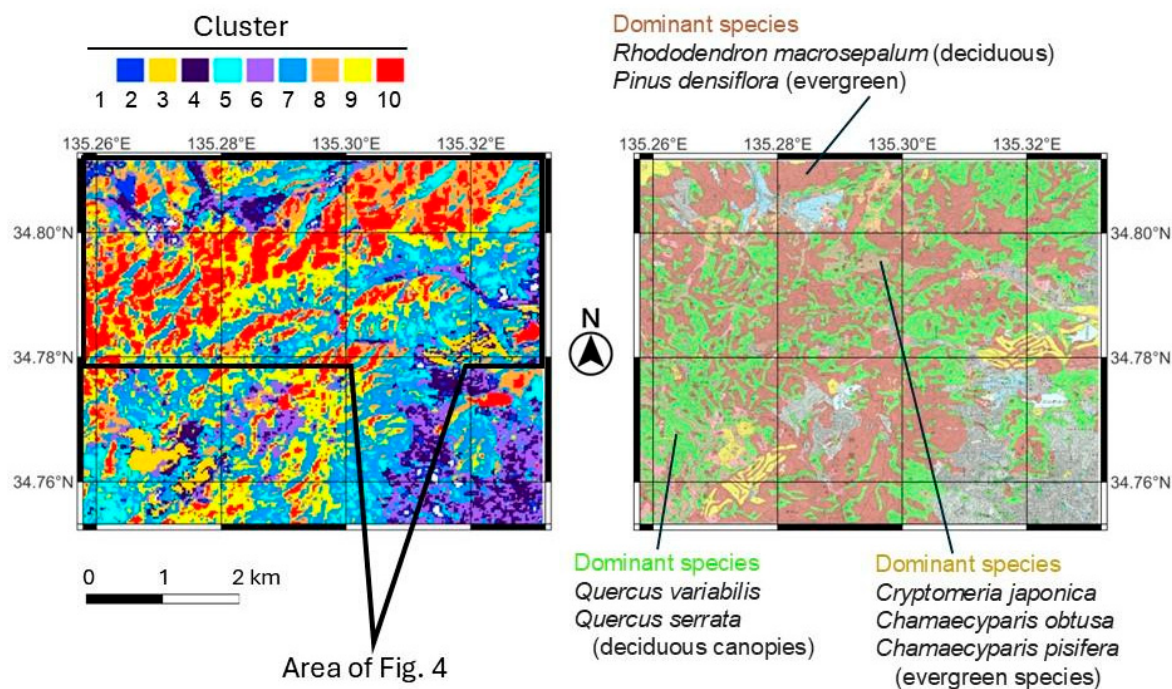


Figure 6. ISODATA clusters and vegetation types in the area from Figure 2b.

Table 1. ISODATA clusters generated by analyzing Landsat 5 imagery datasets on 18 March 1991, 5 May 1991, and 23 March 1993. The values indicate reflectance for the bands of the sensors of the Landsat 5 satellite.

Cluster	Visible Light			Near Infrared	Short-Wave Infrared	
	Blue	Green	Red		1	2
1	0.161	0.192	0.217	0.278	0.270	0.228
2	0.147	0.168	0.189	0.247	0.227	0.194
3	0.132	0.144	0.162	0.230	0.188	0.157
4	0.152	0.169	0.182	0.216	0.207	0.191
5	0.160	0.175	0.195	0.244	0.221	0.208
6	0.138	0.152	0.169	0.215	0.191	0.167
7	0.130	0.141	0.158	0.209	0.174	0.149
8	0.128	0.138	0.149	0.196	0.162	0.141
9	0.128	0.137	0.151	0.190	0.159	0.141
10	0.126	0.133	0.141	0.170	0.145	0.132

According to Figure 7, the clusters were located on distinct slopes within the mountain range. Through spatial thinning, the sample size was reduced to 825 for each period/year to ensure that the *p*-value for Moran’s I reached 0.05 or greater when handling the topographical variables and NDMI. Clusters 2 through 4 were excluded during this process because their relatively small sample sizes caused a significant inflation of the standard error. Consequently, these clusters were omitted from the subsequent analyses. Cluster 10 primarily faces west, while the other clusters face east. Regarding latitudinal orientation, clusters 2, 8, and 10 are situated on north-facing slopes, whereas the others occupy south-facing slopes. Slope steepness ranges between 33° and 38°, with cluster 10 having the gentlest inclines. In terms of altitude, cluster 9 is located at the highest elevation, followed by cluster 10. Notably, these clusters at higher altitudes tend to be the moistest during the winter season.

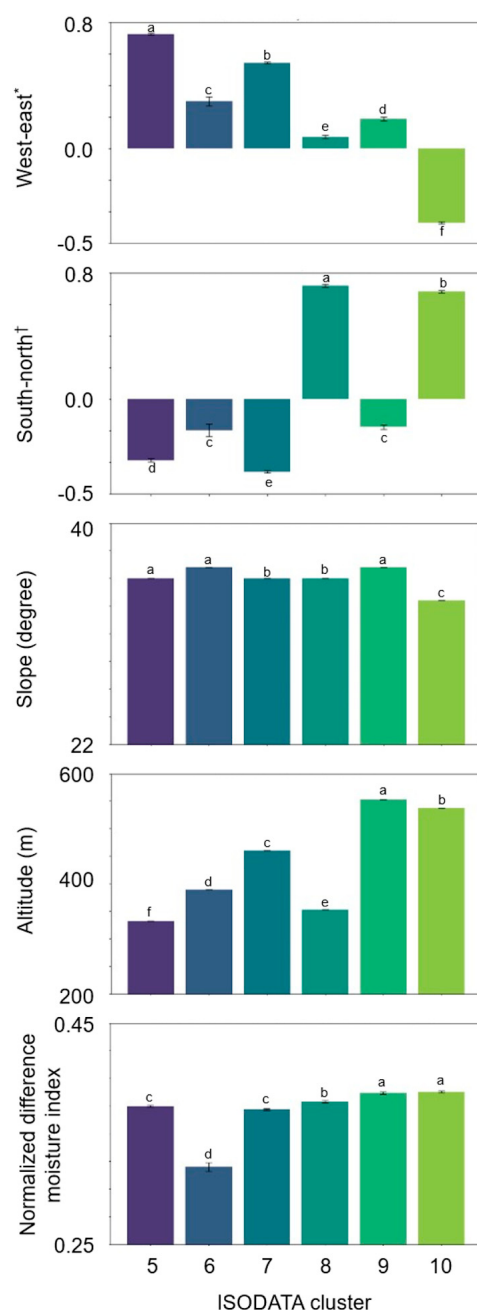


Figure 7. Topographical profiles, mean canopy heights, and normalized difference moisture index values in December 2017 to February 2018 (winter) for the ISODATA clusters (standard error). For each variable, values with the same letter do not differ significantly ($p > 0.05$) according to analysis of variance and Tukey's HSD test. * West-east: west = -1 , east = 1 , north or south = 0 ; † South-north: south = -1 , north = 1 , west or east = 0 .

3.3. EVI Trends Revealed by Mann–Kendall Trend

Figure 8 presents the results of the Mann–Kendall test. In the five rectangular plots (Figure 2c), a general increasing trend in biomass has been observed over the last four decades. The rate of increase in EVI for the winter period (December to February) exceeds that of the annual average. This disparity suggests an expansion or increased dominance of evergreen vegetation within the mountains.

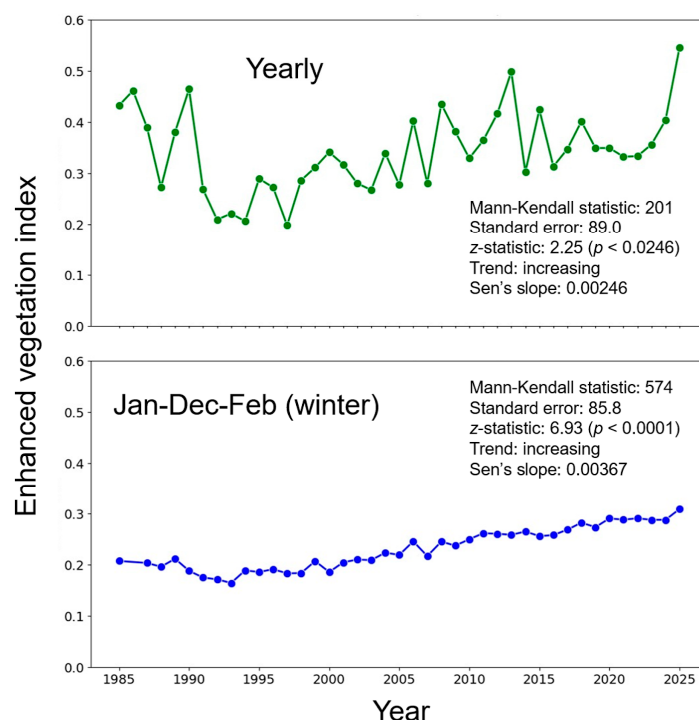


Figure 8. Annual and winter (December–February) changes in the enhanced vegetation index within the rectangular areas shown in Figure 2c. The winter of 1986 (December 1985 to February 1986, (**bottom**)) was excluded because only a single Landsat 5 image was available, and it yielded no valid pixels due to heavy cloud contamination.

3.4. EVI Trend During the 1991, 2003, and 2018 Winters

Figure 9 illustrates the EVI values for clusters 5 through 10, derived from EVI composites spanning from December to the following February for the years 1990–1991, 2003–2004, and 2017–2018. During spatial thinning based on Moran's I, we observed that achieving a p -value greater than 0.05 for certain years or disasters would have required an extreme reduction in sample size (e.g., fewer than 200 cases). Given that Moran's I values remained below 0.4, we opted to maintain 825 cases for each event to ensure sufficient statistical power while minimizing spatial autocorrelation. The relative differences in EVI values among the clusters have remained consistent throughout this 27-year period. A ubiquitous increasing trend in EVI was also observed across all clusters. Clusters 5 and 7, which are predominantly situated on the southeastern slopes (Figure 7), exhibit higher EVI values, whereas clusters 8 and 10, primarily located on the northern slopes, show lower values.

3.5. Changes in EVI Before and After the Disasters

Figure 10 illustrates the changes in EVI for each cluster following the super typhoons and the major earthquake. The 1991 super typhoon was the most devastating, while the 1995 earthquake exhibited immediate effects on EVI value, but the effects clearly differed among the clusters and between the short-term and year-long periods.

While response patterns vary across clusters, the magnitude of damage has generally declined since the severe impact observed in 1991. Clusters 5 and 7, located on the southern slopes, suffered substantial damage during the 1991 typhoon. However, they exhibited robust biomass accumulation following the 1994 typhoon and the 1995 earthquake. In contrast, clusters 8 and 10 on the northern slopes showed a divergent trend. Although their damage in 1991 was relatively minor, they experienced a loss of photosynthetic tissue one year after the 1994 typhoon and 1995 earthquake—a period during which other stands showed gains. All these clusters demonstrated higher resilience during the 2018 typhoon,

maintaining EVI levels that were unexpectedly superior to those recorded in 2000, a year characterized by the absence of major natural disturbances.

Figure 11 indicates spatial changes in EVI values before and after the 1994 typhoon season. A visually perceivable trend is that the north-facing and northwest-facing slopes experienced the greatest decreases in EVI value in the 1994 typhoon season. The spatial patterns of EVI changes following the 1994 typhoon exhibited a visual similarity to the damage patterns observed one year after the 1995 earthquake. This similarity suggests a potential linkage between the impacts of these two successive disturbances.

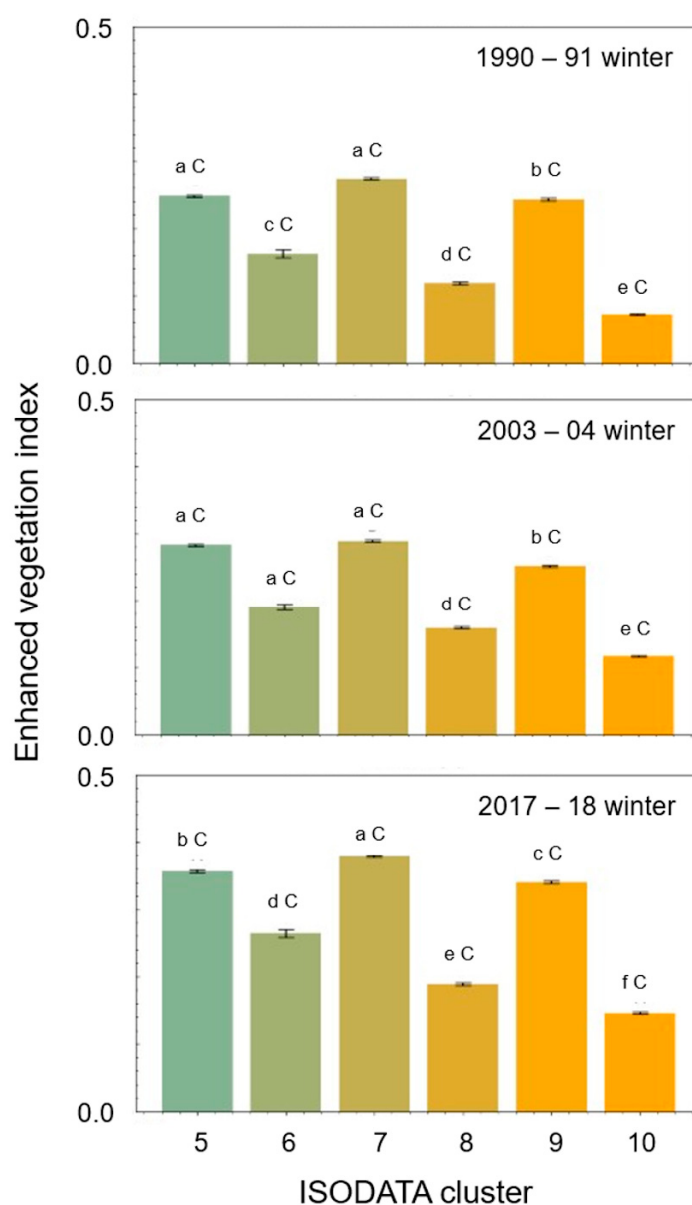


Figure 9. EVI values for clusters 5 to 10 in 1990–1991, 2003–2004, and 2017–2018 winters (December–February). Error bars indicate standard errors. Values with the same letter do not differ significantly ($p > 0.05$) according to analysis of variance and Tukey’s HSD test. Lowercase letters indicate significant differences between clusters within the same year, while uppercase letters indicate significant differences between years within the same cluster.

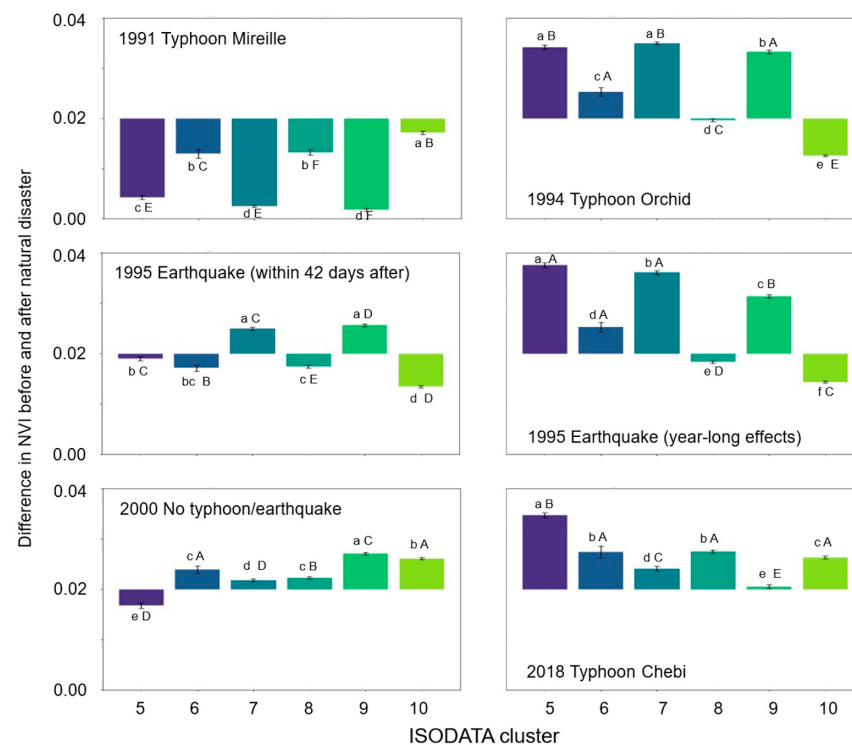


Figure 10. Changes in enhanced vegetation index before and after the disasters. Error bars indicate standard errors. Different lowercase letters indicate significant differences among clusters within the same analysis category at $p = 0.05$, while different uppercase letters represent significant differences among categories within each cluster.

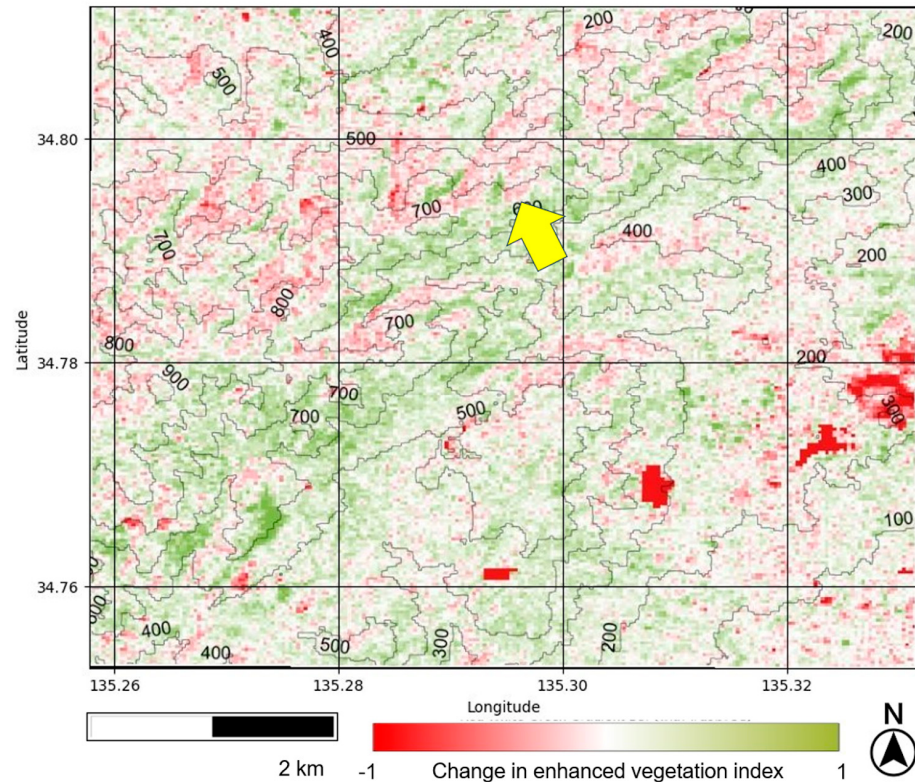


Figure 11. Changes in enhanced vegetation index value between the winters of 1991–1994 (December, January, February) and 1994–1995, when the region experienced the category 4 super typhoon Orchid in September. The yellow arrow indicates the location of the 2018–2022 time-series comparison using precise cm level images.

The 1994 typhoon primarily impacted the northern slopes, although its peak intensity was lower compared to the 1991 and 2018 typhoons. The 1991 typhoon showed a distinct spatial bias, with strong winds concentrated on the western slopes and minimal impact on the eastern side. In 2018, both northern and western slopes were subjected to high-velocity winds, while the eastern slopes again experienced relatively calm winds.

Table 2 presents results that were obtained by conducting threshold regression analysis. The analysis was restricted to datasets where spatial autocorrelation was sufficiently low (Moran's I , $p > 0.05$). In the winter preceding the 1991 typhoon season, the threshold model revealed a distinct ecological boundary located slightly north of the south-facing slopes, where EVI values exhibited a rapid transition. Integrating the results from Figures 7 and 9, the consistently low winter EVI for clusters 8 and 10 on the north-facing slopes over the past 30 years indicates that the biomass of photosynthetic evergreen trees was lower there than on the south-facing slopes, where biomass is more abundant. In contrast, for the winters following the 1991 and 1994 typhoons, as well as the 2000–2001 winter following the disaster-free summer/autumn, the collapse of the model (indicated by negative R^2 values) demonstrated that such distinct ecological boundaries were no longer detectable.

Table 2. Results of threshold regression analysis for EVI (changes) in association with topographical factors.

Metric	1990–1991 Winter	1991 Typhoon	1994 Typhoon	2000–2001 Winter (No Disaster)
Mean R^2 (SD *)	0.478 (0.139)	−1.048 (0.996)	−0.094 (0.202)	−0.732 (0.362)
Most influential variable	South–North [†]	South–North	South–North	Altitude (m)
First split point	0.624	0.830	0.380	495
Delta mean EVI	0.163	0.016	0.030	0.0146

* SD: Standard deviation of 5-fold cross validation; [†] South–North: south = −1, north = 1, west or east = 0.

To investigate whether a continuous gradient existed in the absence of a distinct boundary, we conducted a multiple linear regression analysis (Table 3). The results were as follows. Consistent with the results of the threshold regression analysis, the multiple regression models confirm that winter EVI representing evergreen biomass was strongly dictated by slope orientation (South–North) as of the winter of 1990–1991. In contrast, the rapid EVI decline during the 1991 typhoon season was difficult to describe by the topographical variables through linear models, as in the case of the threshold regression results. This lack of predictability likely reflects the extensive biomass loss across a broad area of the mountain range (Figure 10). Meanwhile, during the 1994 typhoon season, strong wind pressure specifically affected the north-facing slopes (Figure 12), leading to predominant evergreen biomass degradation in those areas. However, by 2000—a year without major disasters—these topographical trends were no longer detectable even through this linear model, suggesting a rapid and fundamental transformation of the vegetation structure over the preceding decade.

Table 3. Results of multiple linear regression analysis for EVI (changes) in association with topographical factors.

Category	Model	Adjusted R^2	Significant Independent Variable	Coefficient (Most Significant Variable)
1991 winter	1	0.604	South–North *	−0.118
	2	0.766	South–North, West–East	−0.107
	3	0.789	South–North, West–East, Altitude	−0.104
	4	0.798	South–North, West–East, Altitude, NDMI [†]	−0.103
1991 typhoon	1	0.101	South–North	0.015
	2	0.124	South–North, West–East	0.014
	3	0.132	South–North, West–East, Altitude	0.014

Table 3. Cont.

Category	Model	Adjusted R ²	Significant Independent Variable	Coefficient (Most Significant Variable)
1994 typhoon	1	0.278	South–North	−0.020
	2	0.472	South–North, West–East	−0.018
	3	0.502	South–North, West–East, NDMI	−0.018
2000	1	0.104	Altitude	4.31×10^{-5}
no disaster	2	0.118	Altitude, South–North	4.26×10^{-5}

* South–North: south = −1, north = 1, west or east = 0; † NDMI; Normalized difference moisture index.

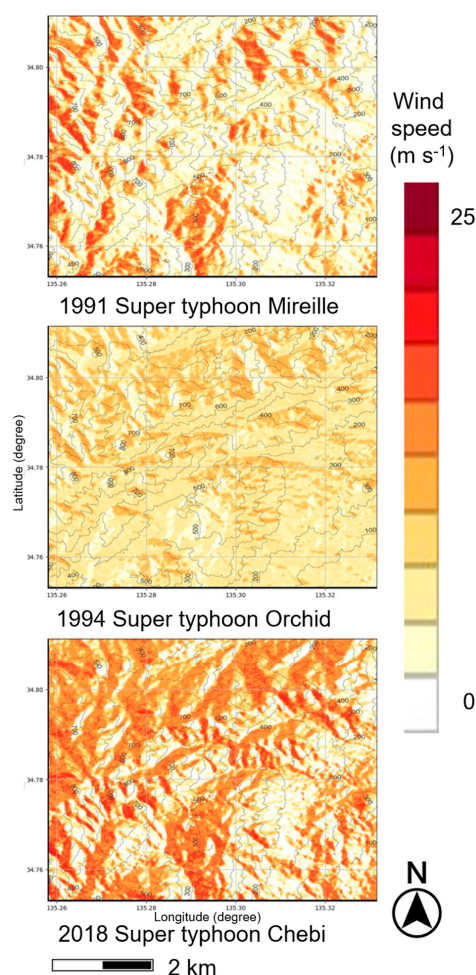


Figure 12. Maximum wind speeds for the slopes within the Rokko Mountains study area during three super typhoons: 1991 (Mireille), 1994 (Orchid), and 2018 (Chebi).

3.6. Aspect-Dependent Divergence in Long-Term Forest Succession

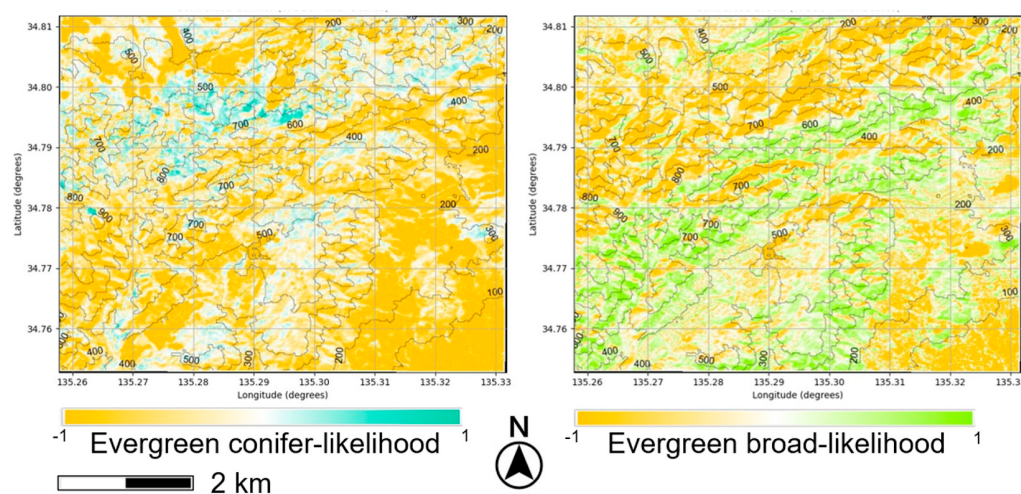
Regarding the detection of necromass, which consists of non-living woody debris such as fallen trees and dead branches, the characteristics of its spatial distribution are presented in Table 4. After spatial thinning to achieve $p > 0.05$ for Moran's I, the number of cases totaled 284. Among the 284, 83 pixels represented necromass, while the others were non-necromass. A recall of 0.09 indicates that the criteria for necromass detection were stringent. Consequently, the model likely captured only the most definitive occurrences. Nevertheless, the ROC AUC of 0.74 indicates that the significant factors dominate the spatial risk of occurrence. In particular, the slope orientation (South–North) emerged as the dominant determinant, completely surpassing other factors with an odds ratio exceeding 5.0. This implies that following the 2018 typhoon season, necromass was five times more likely to occur on the north slopes than on the south slopes.

Table 4. Results of logistic regression analysis for the occurrence of necromass within the five rectangular areas shown in Figure 2c.

Variable	Coefficient	Standard Error	z	$p > z $	Odds Ratio	95% Confidence Interval (Odds)
Constant	−1.29	1.48	−0.874	0.382	0.274	0.015–4.993
Altitude	0.003	0.001	2.688	0.007	1.003	1.001–1.005
West–East *	−0.133	0.326	−0.409	0.683	0.875	0.462–1.657
South–North †	1.63	0.388	4.213	0.000	5.117	2.394–10.94
NDMI 2017–18 winter	−4.76	3.611	−1.318	0.187	0.009	0.000–10.16
Slope degrees	−0.013	0.016	−0.815	0.415	0.987	0.957–1.018

* West–East: west = −1, east = 1, north or south = 0; † South–North: south = −1, north = 1, west or east = 0; Cross validation results (Average $\pm$ standard deviation); Accuracy: 0.76 ± 0.02 , Precision: 0.42 ± 0.26 , Recall: 0.09 ± 0.06 , F1-Score: 0.15 ± 0.09 , ROC AUC: 0.74 ± 0.04 .

Figure 13 indicates the likelihood of coniferous versus broadleaf tree occurrence within the evergreen tree-dominated areas of the current study area. The results reveal that coniferous evergreen forest stands persist primarily on the north slopes. In contrast, broadleaf evergreen species had been expanding their distribution on the south slopes. This suggests a successional shift from the original coniferous plantations, composed mainly of pine (*Pinus*) and cedar (*Cryptomeria*), toward a dominance of broadleaf evergreen species, such as *Quercus*, particularly on the south slopes.

**Figure 13.** Evergreen conifer likelihood (left) and evergreen broadleaf likelihood (right) in 2017 December–2018 February winter for the pixels representing the landcover types.

Other evidence of the typhoons as a driving force of forest succession is shown in Figure 14. The area is located on the northmost slope in the largest rectangle in Figure 2c. On the northern slope, evergreen trees recognized in February 2018 were lost after the 2018 super typhoon in September, which then resulted in the canopy gaps seen in the springs of 2020 and 2022. Tables 2 and 4 also indicate that the evergreen canopies in clusters 8 and 10 underwent the most significant structural degradation [42] following the 2018 typhoon. This supports the hypothesis that these clusters lost a portion of their evergreen members during the event, even though entire areas of these clusters gained evergreen biomass (Figures 9 and 10).

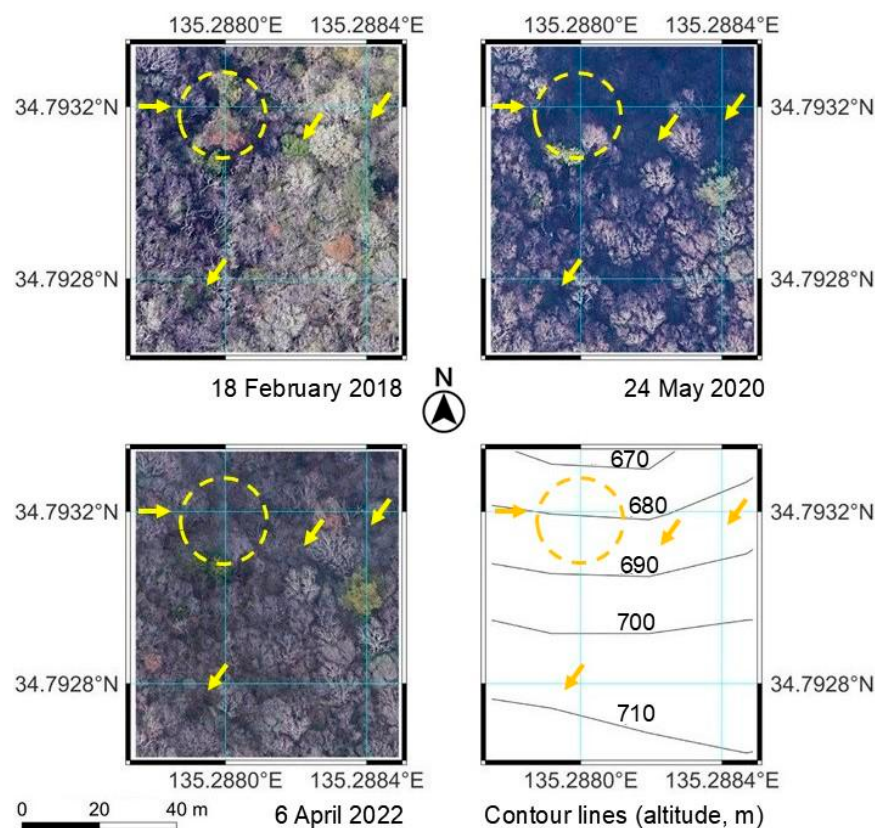


Figure 14. Changes in canopy appearance in the area indicated by the yellow arrow in Figure 11. The yellow/orange circles and arrows indicate evergreen canopies that existed before the September 2018 super typhoon, but disappeared after the typhoon.

4. Discussion

For the first time, the effects of super typhoons and a major earthquake on forest stands were compared. Then, the 1991 typhoon was the most destructive. The major earthquake moderately disturbed the evergreen biomass on the northern slopes. Though the 2018 typhoon was the strongest among those generated within the past 30 years, the evergreen forest stands revealed more resilience compared to 1991. However, after the 2018 typhoon, damage was still distributed on the northern slopes in small and scattered patches. The mechanisms, processes, and related topics of the findings are discussed below.

4.1. Effects of the Super Typhoons

According to Figures 10 and 11, evaluating the effects of super typhoons as the differences in EVI value before and after the periods of approximately a single year was valid if the typhoon-frequent months of July to October were included within the period. Within a comparable period of 1 year or so, a super typhoon-induced forest disturbance was observed between October 2017 and October 2018 in Hong Kong. The NDVI loss was largely attributed to the super typhoon [17]. A similar typhoon effect was recognized as the difference before and after the 2004 typhoon season in western Japan when Japanese cypress trees lost above-ground biomass more significantly than in 2003 [43]. The 1991 and 1994 typhoons must have disturbed the forest stands mainly by wind (Figures 2 and 10–12), while some other windstorms were accompanied by rain with stronger effects on the trees than wind [44].

When there were multiple vegetation types, Lu et al. [45] reported that broadleaf forest stands were more vulnerable to a typhoon than coniferous forest stands in northeastern China. Conversely, Isamoto and Takayama [46] found that broadleaved trees were damaged

less than coniferous trees, including pines, Japanese cedars, and Japanese cypress. Contrary to these instances of damage on specific vegetation types, the multiple forest stands on similar topographical conditions were found to have had a common vulnerability to the strong winds of the 1994 typhoon and earthquakes (Figure 10).

4.2. Linkages Between Forest Succession in the Rokko Mountains and Typhoons

In southern coastal Japan, including Kobe, typhoon-induced forest succession was observed. In a plantation plot in Tokyo, the survival, extinction, and generation of each individual tree were recorded. The human-introduced pines and Japanese cedars were killed at a high ratio by typhoons, whereas an evergreen laurel tree species of chinkapin survived more significantly than the coniferous cohabitants. Thus, the evergreen laurel-dominant community was established [11]. Similar changes in forest community structure are thought to have been accelerated by typhoons on the Rokko Mountains, especially in the 1990s or beforehand.

Tree community censuses have been conducted in the Rokko Mountains. Between 1954 and 2004, according to the censuses, evergreen laurel tree species became more abundant [33]. Changes in tree community structure within a later period, between 1974 and 2019, again demonstrated the increasing dominance of laurel tree species [30]. From these instances, it is clear that the mountains have been experiencing perceivable changes in tree community membership. As suggested by the dark color of cluster 10's profile and the gaps in the canopies in the early 1990s (Table 1) and the early 2020s (Figure 14), typhoons were highly likely to be the driving force of the forest succession.

Figures 8 and 9 show that clusters 5 and 9 lost EVI values of 13% and 14% during the typhoon seasons in 1991, while the values were positive after the 2018 typhoon season. The 40-year trend was the increasing EVI for the forest stands in the five rectangles in Figure 2c. Figures 10 and 12 also show that the forest stands were more tolerant to the strong winds of the 2018 typhoon than in the early 1990s, although the wind speeds were greater on 4 September 2018 (Figures 3 and 12). The 2018 typhoon season indicated no damage as mean changes in EVI value. In a 100 × 100 km area in the current region of western Japan, including the Rokko Mountains, Takahashi and Saito [47] found that mainly south slopes on mountains lost an NDVI of 0.050 or greater. Therefore, it is possible that forest stands on the Rokko Mountains had already become tolerant enough to the upslope winds before.

Shortly before approaching the Rokko Mountains, the typhoon damaged an experimental forest of Japanese cypress [48]. In the plantation plot, 10% of Japanese cypress trees died due to the typhoon damage. On the same day, in another prefecture, the 1991 typhoon also disturbed multiple forest stands, among which the least affected were forest stands of a broadleaf species, *Quercus acutissima* [46]. The rate of damaged trees in the *Q. acutissima* stands was 13%. A comparable rate of 15% was recorded for mixed forest stands with laurel tree species such as *Castanopsis* and *Quercus* trees. Pine tree stands were more severely disturbed, resulting in 37% damaged trees. Furthermore, the Japanese cypress and Japanese cedar forests were even more seriously damaged than the pine tree stands. The pine, cedar, and cypress trees introduced to the Rokko Mountains would have been more severely damaged on every slope of the Rokko Mountains due to weak root systems to support the above-ground biomass [49], which is not necessarily advantageous to the leveraging force of strong winds of typhoons [50].

4.3. Differences Between the South and North Slopes

A novel finding of this study was that multiple vegetation types on the north-facing slopes were commonly damaged (Figures 6, 7 and 11). This trend coincides with the findings by Ikami et al. [51], who conducted a study in the Mie Prefecture. There, two forest

stands on south- and north-facing slopes, covering 1.6 ha and 1.9 ha, respectively, had 937 and 969 Japanese cedar (*Cryptomeria japonica*) trees. Over the ten-year period from 2013 to 2023, the south slopes lost 12 trees to windthrow, whereas the north slopes lost 48. A chi-square test yielded a chi-square value of 21.2. The odds ratio was 4.02. This result is close to the odds ratio of 5.12 observed for evergreen necromass occurrence on the north slopes of the Rokko Mountains in this study.

The south and north slopes of the mountains can be different in the intensity of air pollution effects in the south coastal Japanese mountains, such as Mount Gokurakuji in Hiroshima [52] and the Rokko Mountains [53]. In these mountains, pine trees on the south slopes are more significantly affected by air pollution that causes soil acidification [54]. Meanwhile, evergreen laurel tree species are relatively more tolerant than Japanese cedar and Japanese cypress introduced in the Rokko Mountains reforestation program [55]. Thus, less sensitive evergreen tree species could become more dominant due to their relatively greater tolerance to soil acidification [30]. Also, there may be differences in soil fertility on the south and north slopes of the Rokko Mountains due to differences in solar irradiance per unit area [56]. In the warmer region of Queensland, Australia, after cyclone Larry in 2006, there was a significantly higher percentage of tree falls in less fertile, granite-based sites compared with more fertile, basalt-based sites [57]. Soils of the Rokko Mountains are also granite-based. It is worth investigating if the soil of clusters 8 and 10 are more oligotrophic than the others, and whether or not the poor soil nutrient status resulted in the poor forest restoration.

4.4. Effects of the Earthquake

When compared with the typhoon effects, moderate changes in EVI before and after the earthquake were recognized (Figure 10). The 1995 earthquake-induced landslide areas were distributed as small patches covering 0.1 to 1% of the areas analyzed by Kawabe et al. [58]. Furthermore, trees partially uprooted in major earthquakes can survive and grow [59]. These factors were possible causes of the moderate EVI losses for clusters 8 and 10. The results also indicated that the earthquake caused minor loss of foliage and small branches, and then the biomass recovered during the following summer, unlike the 1991 typhoon. Thus, the significant decreases in EVI in the 1991 typhoon are likely due to more frequent lethal trunk break and uprooting (Table 4, Figure 14).

In some cases, the uprooting of trees detaches the root systems from the soil [60]. This root-damaging impact must have occurred in the Rokko Mountains as a result of the 1995 earthquake. Especially, tree species with relatively weak root systems, such as Japanese cedars, were likely to be the majority of the victims [49]. Some damaged trees could have survived, although these were subjected to difficulties in taking in water and nutrients from the soil. Moderately damaged trees are expected to be more vulnerable to subsequent disasters, especially heavy rain. This possibility must not be ignored. The comparison of the leverage effect of wind on tree canopies and the mechanical impact of earthquakes, primarily on the root systems, remains to be made.

4.5. Perspective of Disaster Mitigation

By buffering direct rainfall via canopies, absorbing water in the root systems that prevents immediate water downflow, and holding soil structure with roots, forests have the function of preventing landslides [61]. This function can be crippled by heavy rain, as well as by strong winds and earthquakes. From 8 to 10 August 2014, at the Kobe meteorological station, a precipitation of 267 mm and a maximum hourly wind speed of 14.6 m s^{-1} were recorded. These conditions were thought to have caused landslides after forest disturbance [3]. The landslides mainly occurred on the northern slopes of the Rokko

Mountains [29]. The distribution pattern of landslides reported by Okimura [29] overlaps well with that of the poorly restored clusters 8 and 10 (Figure 4).

The northern slopes had relatively more vulnerable trees, at least to the 2018 typhoon that pushed tree canopies and caused tree fall, as indicated in Table 4 and Figure 14. Intensive rainfall in August 2014 must have washed soil away from the root systems of partially uprooted but surviving trees. Some root systems of previously disturbed trees are likely to be more easily washed because roots detached from the above-ground biomass decompose rapidly [62], and then the land stability declines [49]. These underground processes related to forest succession are thought to have been associated with the 2014 landslides, the 1995 earthquake, and the typhoons. The mechanism of landslides after the 2014 heavy rain must be clearly different from that of the earthquake that resulted in landslides mainly on the south and east slopes [63,64].

The findings provide beneficial insights into adaptive and climate-resilient forest management strategies in regions increasingly threatened by super typhoons and seismic activities. The persistent vulnerability observed on the north-facing slopes highlights the need for slope-specific, proactive management. As a management strategy to foster climate-resilient forests, a topography-dependent conversion approach is possible. On vulnerable north-facing slopes, active forest management should prioritize the gradual conversion of legacy, weak-rooted coniferous plantations into deep-rooted evergreen broadleaved forests. This can be achieved through selective thinning of conifers to accelerate the natural recruitment of native laurel species, which showed greater tolerance to both windthrow and soil acidification in this region. Conversely, on south-facing slopes where forests have already achieved a certain level of wind tolerance, a passive restoration approach or minimal intervention could be applied to reduce management costs. Incorporating such topographically tailored silvicultural practices will assist forest managers in transforming vulnerable monocultures into structurally diverse, ecologically resilient ecosystems capable of withstanding the intensifying compound disturbances of the Anthropocene.

4.6. Limitations and Prospective of This Study

This study relied on changes in EVI value for the forest stands in winter. Therefore, the information is on evergreen tree species. In the succession processes, however, some deciduous tree species should have certain roles. Unfortunately, due to frequent disturbance by clouds at imagery acquisition times in the summer, no summer imagery data of adequate quality were available. The unavailability of information on canopies in the respective summers, including canopies of deciduous tree species, was a disadvantage.

Another clear disadvantage of this study is spatial resolution. As we relied mainly on Landsat and Sentinel imagery datasets, detailed outcomes and post-processes of the natural disasters were unseen, except for those shown in Figure 14. Supplementing ground truth data is favorable, if available. Therefore, new census data are highly anticipated to enhance the validation of the models adopted in this study. In this context, EVI serves as a comprehensive indicator of vegetative response observed as overall spectral reflectance rather than distinguishing between different types of physical damage, such as simple defoliation versus long-term structural loss.

The effects of spatial autocorrelation were not entirely canceled out. However, the presence of opportunistic tree species that invaded during the succession process added structural heterogeneity to the forest canopy (Figure 14). This diversity likely moderated the spatial autocorrelation (Moran's $I < 0.4$) and contributed to the small recall rate (0.09) in the necromass detection, as the model primarily captured the most severe damage where topographic vulnerability overrode individual tree resilience.

Analyzing details of the listed aspects in Sections 4.2–4.4 will generate useful knowledge. Tracking future changes in the forest stands will be valuable by analyzing aspects of physicochemical soil characteristics [65], airborne depositions [53], tree census, and cm level resolution canopy appearance. The mountains have clear records of deforestation and reforestation. Thus, they are a good study site for extracting knowledge on processes and results of deforestation and reforestation, in addition to natural disaster prevention and the resilience of the forests.

It is highly plausible that the 1995 earthquake interacted with subsequent typhoons, and we acknowledge the difficulty in isolating their individual impacts. However, future exploration of the mechanical links between extreme weather and tectonic activity may provide a more comprehensive understanding of forest succession and offer critical insights for disaster management.

5. Conclusions

For the first time, this study bridged the identified knowledge gap by directly comparing the destructive impacts of tropical cyclones and a major earthquake at a shared site. Contrary to our initial hypothesis that the earthquake would exert a more profound impact, the temporal analysis of EVI demonstrated that the 1991 super typhoon was the most significant driving force of forest succession on a landscape scale. While the 1995 earthquake had only moderate effects on forest stands on northern slopes, the entire mountain range revealed an increase in long-term resilience against subsequent typhoons. This study uncovered hidden topographic vulnerabilities: we revealed a common vulnerability across diverse vegetation types under consistent topographical conditions during the 1994 typhoon and the 1995 earthquake. This central finding proves that forest disturbance and subsequent successional resilience are heavily dictated by slope-specific dynamics rather than tree species diversity alone.

The most vulnerable forest stands had multiple vegetation types, including deciduous, evergreen, coniferous, and broadleaved trees. Because typhoons kill trees, especially those that have weak root systems, the northern slopes were highly likely to experience forest succession accelerated by the typhoons functioning as a driving force thereof. Indeed, according to precise cm level Google Earth images, some evergreen tree canopies confirmed in February 2018 on a northern slope disappeared following the super typhoon in September 2018.

Moderate effects of an $M_j = 7.2$ earthquake in 1995 on EVI were recognized. The earthquake did not cause significantly large landslides that exposed soil. Thus, the root systems of the most typhoon-vulnerable forest stands were not significantly affected by the mechanical force primarily on the root systems. Changes in EVI showed that the 1991 super typhoon more seriously disturbed the vulnerable forest stands by killing the weakest trees. These processes are thought to have enhanced the forest succession by substituting vulnerable trees with indigenously dominant tree species, typically broadleaved evergreen laurel trees such as oaks. The south slopes must differ from the north slopes in multiple ecological aspects. These differences are worth investigating based on the findings and discussion of this study. The Rokko Mountains are a good study site because of their unique history, geographical conditions, and ecosystem restoration processes.

The study area is characterized by frequent heavy rainfall, in addition to typhoons and earthquakes. Unlike the stable forest regeneration patterns observed in tectonically inactive tropical regions, forests in this landscape undergo restoration through frequent physical disturbances and subsequent successions. Furthermore, the details of these successional processes differ significantly between south- and north-facing slopes. The fact that the odds of necromass occurrence on northern slopes remain five times higher than on southern slopes, even a century after plantation, warrants serious attention for future disaster

management. On a landscape scale, typhoons have exerted more destructive impacts than the 1995 earthquake. Moreover, the frequency of typhoons is significantly higher. Therefore, disaster mitigation strategies for typhoon events must account for the current successional status, which is inherently characterized by slope-specific vulnerability, as tropical cyclones have become increasingly intense in recent years.

Author Contributions: Conceptualization, R.D. and T.P.; methodology, R.D. and T.P.; software, R.D.; validation, R.D.; investigation, R.D.; resources, R.D.; data curation, R.D.; writing—original draft preparation, R.D. and T.P.; writing—review and editing, R.D. and T.P.; visualization, R.D. and T.P.; funding acquisition, T.P. All authors have read and agreed to the published version of the manuscript.

Funding: This project is financed by FCT—Foundation for Science and Technology through project UID/04020/2025 (CinTurs).

Data Availability Statement: As the Google Earth Engine asset, the geotiff file is available at 10.17632/jzbh453yg5.2. The MultiSpec project file for the five rectangle areas is included.

Conflicts of Interest: The authors declare no conflicts of interest.

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