IMPACT OF RESTORATION WORKS AND ECOSYSTEM CONSIDERATIONS ON VEGETATION RECOVERY FOLLOWING THE 2011 TSUNAMI: A REMOTE SENSING APPROACH

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KEY WORDS: large-scale infrequent disturbance, vegetation recovery, UAV remote sensing, NDVI

ABSTRACT: The Great East Japan Earthquake of March 11, 2011, caused a massive tsunami that severely affected coastal vegetation in Eastern Japan. Over the 10 years, restoration efforts were undertaken to reconstruct large seawalls and restore the coastal forest. These restoration works, combined with considerations for ecosystem preservation, influenced the pathways of vegetation succession, resulting in diverse patterns of vegetation regeneration. This study aimed to assess the effects of restoration works and ecosystem considerations on vegetation recovery after the tsunami using remote sensing techniques and normalized difference vegetation index (NDVI) analysis, which serves as an indicator for primary production potential. The study site, located in Miyagino-ku, Sendai City, Japan, encompasses an ecotone comprising a sandy beach, coastal forest, and back marsh. The vegetation physiognomy within the study site was classified into three zones based on their distance from the shoreline: sandy beach, pine scrub, and pine forest. Each zone was further divided into two areas, distinguished by the extent of ecosystem consideration. Within the sandy beach zone, one area contained small rocks as the remnants of a temporary road, while the other area remained unaffected by restoration works. The pine scrub zone comprised an area focused on preserving biodiversity through sandy substrate conservation and the other area dedicated to restoring the coastal forest by elevating the substrate with compacted sandy mineral soil of hills containing clay substance. The pine forest zone included an area dedicated to biodiversity conservation and the other area where land elevation was carried out to restore the coastal forest. The large seawall restored lies between the sandy beach and the pine scrub zone. To examine changes in NDVI within each zone between one year after the tsunami and the completion of restoration work, NDVI images were generated using color-infrared imagery acquired in 2012 and multispectral imagery acquired in 2020. By comparing changes in NDVI between the two areas within each zone, we assessed the impact of different degrees of ecosystem consideration on primary production potential. In the sandy beach zone, both areas exhibited a slight and similar increase in NDVI between 2012 and 2020, suggesting negligible influence from the construction of temporary roads on sandy beach vegetation recovery. Within the pine scrub zone, the NDVI showed a larger range and increase rate in the area focused on conserving the sandy substrate, likely due to the vigorous growth of naturally regenerated pines. Conversely, numerous unhealthy planted pines were observed in the land elevation area. In the conservation area of the pine forest zone, the NDVI showed a significant increase compared to the land elevation area, suggesting rapid vegetation regeneration through biological legacies such as remnant trees and rhizomes following the tsunami. Conversely, the land elevation area with limited years since construction exhibited only marginal NDVI increase. The results highlight the importance of different restoration approaches and their impact on primary production potential. These findings contribute to the development of effective strategies for future ecological restoration projects in coastal regions affected by tsunami disturbances.

1. INTRODUCTION

On March 11, 2011, the Great East Japan Earthquake caused a massive tsunami with a maximum run-up height of 40.4 m, and severely impacted the coastal ecosystems of Eastern Japan (Mori et al., 2011; Shimada, 2016). In Sendai City, northeastern Japan, the tsunami changed drastically the sand-dune coastal ecotone, including sandy beaches, dunes, coastal forests, and back marshes (Hirabuki et al., 2011). Although large areas of coastal forest, mainly comprising Pinus thunbergii Parl. (Japanese black pine), were disturbed and destroyed by the tsunami, small patches remained in narrow comb-like stripes running perpendicular to the shoreline and the direction of the tsunami (Hirabuki et al., 2011; Hara et al., 2016; Tomita et al., 2016). The area and number of these remnant forest patches decreased continuously after the tsunami, and it caused fragmentation and a reduction of continuities of the forest at the landscape scale (Hirayama et al., 2020). On the other hand, studies for vegetation at stand scale after the tsunami have reported various types of vegetation recoveries. For example, two years after the tsunami, a higher density of coastal herbs was observed in the disturbed area of the coastal forest than in the sandy beach, although the species composition was similar (Oka and Hirabuki, 2014). The unevenness of the ground surface caused by the uprooting of trees increases the species diversity of plants (Onza et al., 2014). Additionally, vegetation recovered autonomously after the tsunami, replacing pioneer plant species with biennial and perennial plant species three years after the disturbance (Kanno et al., 2014). The various-sized trees survived after the tsunami, including the Japanese black pines and broad-leaved trees (Tomita et al., 2016; Tomita and Kanno, 2019).

While vegetation recovered autonomously in the disturbed coastal area of Sendai City, large-scale reconstruction works have progressed to restore the coastal forest and seawall (Kurosawa, 2021). The Ministry of Land, Infrastructure, Transport, and Tourism, Japan (MLITTJ), reconstructed seawalls at 7.2 m altitude and ca. 32.9 m in base width, extending about 9.6 km along the shoreline of Sendai City. The Forestry Agency, Japan (FAJ) created vast land elevation areas behind the seawall based on the criterion of 3.2 m altitude and more than ca. 200 m in width. As a result, extensive areas of recovering ecosystems and sandy substrate for the growth of coastal plants were mounded and replaced with sandy mineral soil of hills containing clay substance. The Japanese black pines were planted in these land elevation areas to restore the coastal protection forests.

On the other hand, in a part of the reconstruction area in Sendai City, the MLITTJ and FAJ took recovering ecosystems and the emergence of threatened species after the tsunami into consideration, following the opinion of the committees. For example, the MLITTJ utilized the temporal road during the seawall reconstruction and set back a part of the reconstructed seawall. The FAJ also established the two types of areas, preserving the remnant ecosystem after the tsunami and maintaining the original sandy substrate in the dunes without land elevation. In recent years, there has been increasing literature regarding vegetation and species composition in land elevation areas. Coastal plants in the land elevation areas of the coastal forest emerge d scarcely (Mabuchi et al., 2020; Yamanouchi et al., 2020; 2021). Similar species composition characterized by many exotic plant species seemed on the land elevation areas regardless of the vegetation history of the coastal forest before the tsunami, while community diversity enhanced in the preserved remnant coastal forest (Kanno et al., in press). These researches have indicated that the reconstruction works negatively affect the recovery of vegetation and plant diversity as one of the ecosystem functions, but ecosystem consideration during the works reduces the effects. However, exploring how these works and considerations influence the potential of primary production at the stand scale in the sand-dune coastal ecotone is still necessary.

This study employed a remote sensing technique to examine the effects of ecosystem considerations during the restoration works on the changes in primary production potential. Normalized difference vegetation index (NDVI) images, which serve as an indicator for primary production potential, were generated using color-infrared imagery acquired in 2012 and multispectral imagery acquired in 2020. By comparing changes in NDVI, we assessed the impact of different degrees of ecosystem consideration on primary production potential.

2. MATERIALS AND METHODS

2.1 Study Site

The study site (780 m x 320 m) in Miyagino-ku, Sendai City, Japan, encompasses the sand-dune coastal ecotone comprising a sandy beach, coastal forest, and back marsh (Fig. 1). The vegetation physiognomy within the study site was classified into three zones based on their distance from the shoreline: sandy beach, pine scrub, and pine forest (Kanno et al., in press). Each zone was further divided into two areas, distinguished by the extent of ecosystem consideration. Within the sandy beach zone, one area contained small rocks as the remnants of a temporary road, while the other area remained unaffected by the restoration works. The pine scrub zone comprised an area focused on conserving biodiversity through sandy substrate preservation and the other area dedicated to restoring the coastal forest by elevating the substrate with compacted sandy mineral soil of hills containing clay substance. The pine forest zone included an area dedicated to biodiversity conservation and where land elevation was carried out to restore the coastal forest. Therefore, each zone includes the affected and conserved areas from the restoration works (Fig. 2). The enormous restored seawall lies between the sandy beach and pine scrub zone.

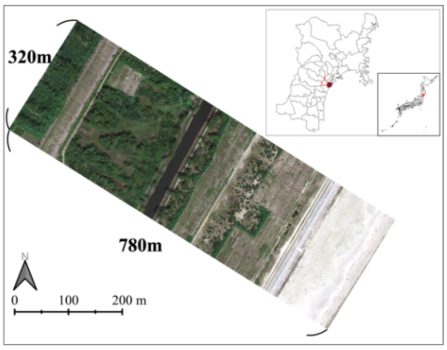

Figure 1. General location (upper right side on the figure) and true-color image of the study site. The image was obtained on August 24, 2020.

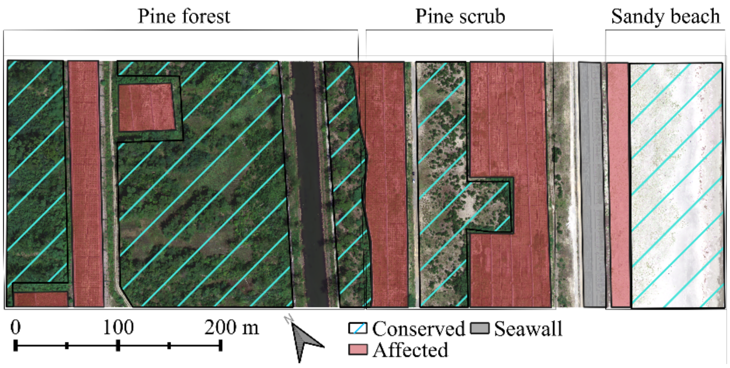

Figure 2. Arrangement of the affected and conserved areas in each zone in the study site.

2.2 Data

Color-infrared (CIR) imagery and multispectral imagery were utilized to examine changes in normalized difference vegetation index (NDVI) between one year after the tsunami and the completion of restoration work (Fig. 3). The CIR imagery was obtained on July 10, 2012, and has 10 cm/px in ground sampling distance (GSD). The multispectral imagery (hereafter, UAV imagery) was obtained using P4 Multispectral (DJI, Inc.) on August 26, 2020, and has 4 cm/px in GSD. The UAV imagery was downsized to 10 cm/px in resolution and geometrically corrected to match the CIR imagery using ArcMap 10.8.1 (ESRI, Inc.).

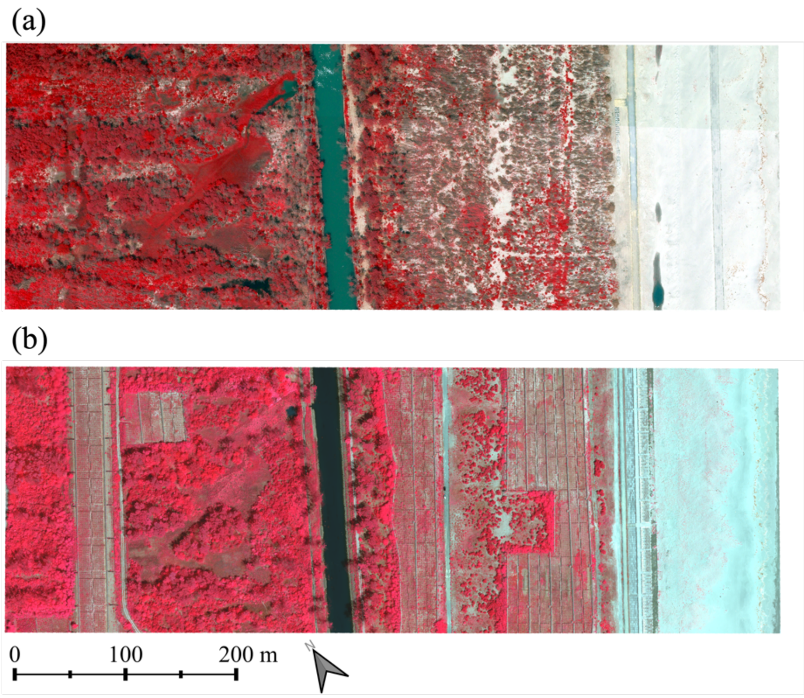

Figure 3. The CIR (a) 2012 and UAV (b) 2020 imagery in the study site. Each imagery was represented by the false color (near-infrared as R, red as G, green as B).

2.3 Shadow Elimination

The presence of shadows within the imagery can reduce or lose information on the imagery, increasing the error of vegetation indices (Zhu and Woodcock, 2012; Zhang et al., 2015). Therefore, the canopy shadow index (SI) was calculated and used as the threshold to eliminate the shadows (Saei and Abkar, 2004). SI for each imagery was defined in the following equations.

$$SI = \sqrt[3]{(255 - G_{cir})(255 - R_{cir})(255 - NIR)} \quad (1)$$

where G_{cir} = digital number of brightness in the green band of the CIR imagery
R_{cir} = digital number of brightness in the red band of the CIR imagery
NIR = digital number of brightness in the near-infrared band of the CIR imagery

$$SI = \sqrt[3]{(1 - B)(1 - G_{uav})(1 - R_{uav})} \quad (2)$$

where B = reflectance in the blue band of the UAV imagery
G_{uav} = reflectance in the green band of the UAV imagery
R_{uav} = reflectance in the red band of the UAV imagery

Shadows within the imagery became darker, the SI values larger. The threshold for each imagery was determined by referencing the SIs for the shadow and other areas in the imagery (Fig. 4).

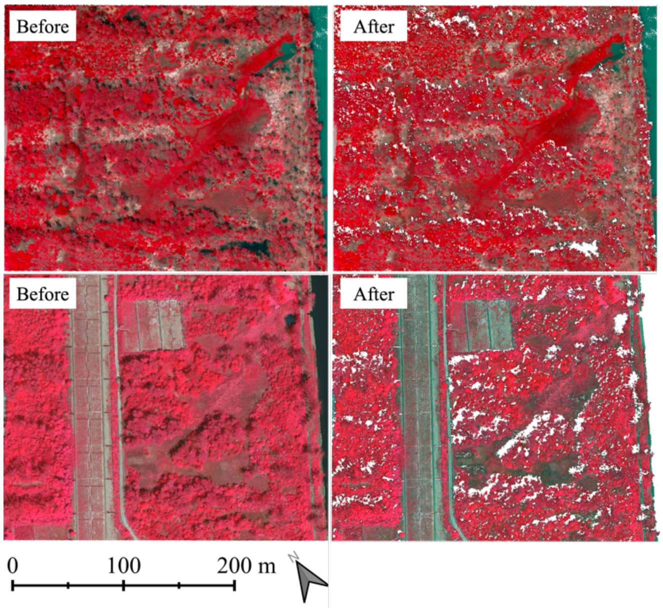

Figure 4. Results of the shadow elimination in the CIR (upper row) and UAV (lower row) imageries. The thresholds were 234 and 0.965 in the CIR and UAV imageries, respectively.

2.4 Vegetation Index

The NDVI for each imagery was calculated based on the digital number of the CIR imagery and the reflectance of the UAV imagery using ArcMap 10.8.1. The NDVI was calculated following the equation.

$$NDVI = \frac{NIR - RED}{NIR + RED} \quad (3)$$

where NIR = digital number or reflectance in the near-infrared band of the imagery
RED = digital number or reflectance in the red band of the imagery

By comparing changes in NDVI between the two areas within each zone, we assessed the impact of different extents of ecosystem consideration on primary production potential.

3. RESULTS AND DISCUSSION

Throughout the study site, NDVI values were higher in 2020 than in 2012, as shown in Figure 5. In 2012, one year after the tsunami, the effects of the restoration work had not reached the study site, and patches with moderately high NDVI appeared in the pine scrub zone and abundantly in the pine forest zone. These patches mainly resulted from regenerated coastal plants in the pine scrub zone and survived trees in the pine forest zone, as reported by the previous studies (e.g. Kanno et al., 2014; Oka and Hirabuki, 2014; Onza et al., 2014; Tomita et al., 2016). In 2020, after the completion of restoration works, there were few occurrences of patches with high NDVI values in the affected areas of both the pine scrub zone and the pine forest zone. However, such patches were more apparent in the conserved area of each zone. These phenomena suggest that the ecosystem considerations in the restoration work positively affected the recovery of the primary production potential, not only for the recovery of plant diversity (e.g. Kanno et al., in press).

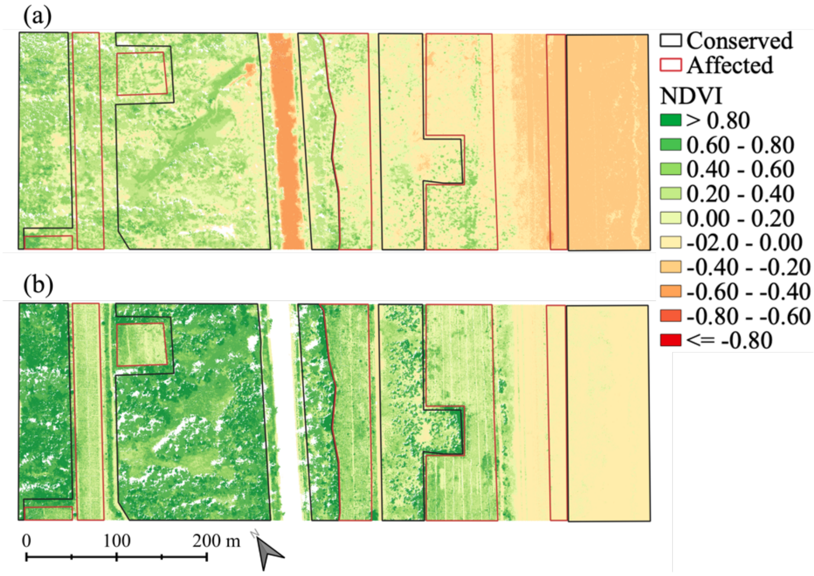

Figure 5. The NDVI of the study site in 2012 (a) and 2020 (b).

In the sandy beach zone, both areas exhibited a slight and similar increase in NDVI between 2012 and 2020 (Fig. 6, Table 1), suggesting negligible effects from the construction of temporary roads on sandy beach vegetation recovery in the viewpoint of the potential for primary production. In the pine scrub zone, the NDVI showed a more extensive range and increase rate in the area conserving the sandy substrate, likely due to the vigorous growth of naturally regenerated pines and coastal plants. On the contrary, the planted pines with a small-sized crown with low NDVI were frequently observed in the land elevation area (pers. comm.). In the conservation area of the pine forest zone, the NDVI displayed a significant increase compared to the land elevation area, suggesting a rapid increase in the leaf area of the vegetation. This drastic recovery was probably through biological legacies such as surviving trees and rhizomes following the tsunami (Franklin et al., 2000; Kanno et al., 2014; Tomita et al., 2016). Conversely, the land elevation area with limited years since construction exhibited only marginal NDVI increase.

In each zone's conservation area, the higher NDVIs appeared in descending order of distance from the shoreline, likely due to harsh environmental conditions such as sand blows and salt spray that inhibit plant growth near the sea. From the viewpoint of the potential for primary production, ecosystem conservation on the landward might significantly affect the recovery.

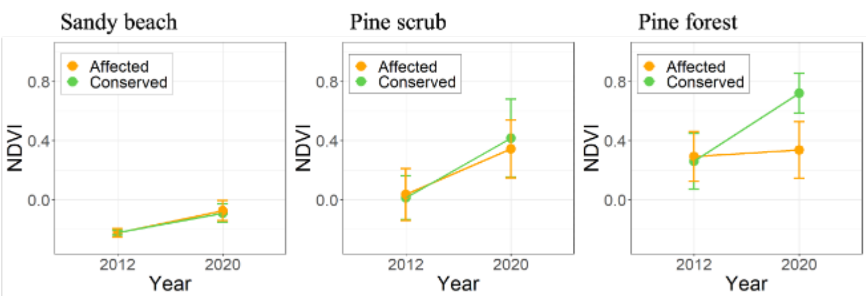

Figure 6. Changes of NDVI between 2012 and 2020 in the affected and conserved areas in each zone. Circles and error bars indicate the mean and standard deviation, respectively.

Table 1. Summary of NDVI in the study site.

	2012					2020				
	Area (m^2)	No. pixels	Mean±SD	Min	Max	Area (m^2)	No. pixels	Mean±SD	Min	Max
Sandy beach										
Affected	47.261	472524	-0.224±0.029	-0.538	0.000	47.261	472520	-0.073±0.068	-0.308	0.673
Conserved	216.880	2154746	-0.222±0.017	-0.522	-0.044	216.880	2154751	-0.091±0.062	-0.396	0.529
Pine scrub										
Affected	255.874	2558036	0.037±0.175	-0.714	0.810	255.874	2558041	0.345±0.195	-0.380	0.900
Conserved	134.672	1346313	0.014±0.148	-0.333	0.673	134.672	2558041	0.430±0.264	-0.358	0.917
Pine forest										
Affected	103.534	1035120	0.292±0.166	-0.846	0.826	103.534	1035118	0.338±0.192	-0.281	0.899
Conserved	551.431	5512954	0.260±0.190	-0.548	0.875	551.431	5512961	0.718±0.139	-0.514	0.940

4. CONCLUSIONS

We performed stand-scale remote sensing using very high-resolution imagery to assess the effects of ecosystem considerations during the restoration works on the potential for primary production changes. The results highlight the importance of ecosystem considerations in the restoration works and their effect on the potential for primary production. These findings contribute to developing effective strategies for future ecological restoration projects in coastal regions affected by tsunami disturbances.

5. ACKNOWLEDGEMENTS

We are grateful to the Forestry Agency, Japan for making the survey possible. This research was supported by JSPS KAKENHI 20K12260 and in part by 23H00528.

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