COMPARISONS OF THE CROWN NDVI AND HEIGHT GROWTH OF PINES BETWEEN THE PRESERVED AND LAND ELEVATION AREAS USING UAV REMOTE SENSING

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ABSTRACT: Remote sensing (RS) is a valuable tool for monitoring plant growth as it allows for the acquisition of multispectral bands, including near-infrared, enabling the assessment of photosynthetic productivity. Unoccupied aerial vehicles (UAVs) offer the advantage of low-altitude image acquisition, facilitating ultra-high-resolution individual-level observations with superior spatial accuracy, leading to more precise plant growth assessments.

After the 2011 massive tsunami along the coastal sand dune of Sendai City, Japan, the Forestry Agency established a narrow preservation area on the natural sandy substrate and undulating landform to maintain autonomous recovery of biodiversity. On the other hand, many elevation areas were created, where a large amount of sandy mineral soil of hills containing clay substance was embanked and compacted as the basement of the coastal protection forest. Evaluating the growth of naturally regenerated pines (*Pinus thunbergii*) in the preservation area and comparing it with planted pines in the elevation area is crucial for determining appropriate substrate maintenance and land elevation methods. Therefore, we aimed to compare pine growth in the preservation and elevation areas using the vegetation index, which indicates chlorophyll content and leaf area, as well as height growth rate. Volumetric water content beneath the topsoil was also measured as an abiotic environmental indicator in both areas.

To generate multispectral ortho mosaics of the study site (approximately 140 x 130 m) in Okada Shinhama, Miyagino-ku, Sendai City, a UAV (P4 Multispectral; DJI, Inc.) was flown at an altitude of 30 m above the ground in December 2021. Ground control points (GCPs) were marked with aerial signs, and their positions were determined using RTK-GNSS measurement. The acquired images were processed using Pix4DMapper, a photogrammetric software. The normalized difference vegetation index (NDVI) was calculated based on reflectance in the red and near-infrared bands of the multispectral ortho mosaic using ArcMap.

Twenty-four pines were arbitrarily selected in each area, resulting in 48 pines, and their locations were determined using RTK-GNSS measurement. To calculate the relative height growth rate, the annual shoot length of stem and tree height were measured for all pines. To assess the potential photosynthetic productivity of each pine at an individual level, the polygon representing the pine crown was created using ArcMap. The median NDVI of pixels within the crown was then calculated. Additionally, at 40 arbitrarily selected points in the study site, the volumetric water content (m^3/m^3) at a soil depth of 10 to 20 cm was measured using a soil moisture sensor (TEROS-12; METER Group, Inc.). In the elevation area, the soil layer corresponded to the surface of the heavily compacted embankment, which was experimentally covered by on-site sand.

The comparison of pines in height between 40 cm and 160 cm revealed lower NDVI values in the elevation area compared to the preservation area. In the elevation area, lower NDVI values corresponded to lower relative height growth rates. The volumetric water content beneath the topsoil was higher in the elevation area, characterized by compacted mountain sand than in the preservation area. In the elevation area, submerged conditions often occurred, and then the low permeability of the soil may have increased the volumetric water content and negatively impacted the photosynthetic activity and height growth of the pines.

1. INTRODUCTION

Remote sensing (RS) is a valuable tool for monitoring plant growth as it allows for the acquisition of multispectral bands, including near-infrared, enabling the assessment of photosynthetic productivity. Unoccupied aerial vehicles (UAVs) offer the advantage of low-altitude image acquisition, facilitating ultra-high-resolution individual-level observations with superior spatial accuracy, leading to more precise plant growth assessments (Robinson et al., 2022; Yang et al., 2022). UAVs mounted with multispectral cameras can acquire information of plant health using vegetation indices such as the Normalized Difference Vegetation Index (NDVI) and the Normalized Difference Red Edge Index (NDRE) at the individual-level. Many studies using UAVs have been implemented in forest ecology and forestry. For example, structure from motion (SfM), a photogrammetric technique using images acquired by the UAV, based individual tree detecting can be a practical approach to map canopy-dominant trees (Young et al., 2022). Tree canopy images acquired by the UAV can be used to assess liana infestation at least as accurately as traditional ground data (Waite et al., 2019). The RGB images, acquired by a low-cost UAV, and deep learning can map the spatial distribution of palm species (Ferreira et al., 2020). Canopy-based metrics, calculated using UAV images, can be at least as effective as traditional ground-based metrics for measuring the effects of local competition on tree growth (Vanderwel et al., 2020). Combination of UAV-based multispectral images and target detection algorithms such as Faster R-CNN and YOLO can be to monitor the occurrence of pine wilt disease and obtain the distribution of infected trees at an early stage (Yu et al., 2021).

In the coastal area of Sendai City, Japan, severely affected by the 2011 tsunami following the Great East Japan Earthquake (Hara et al., 2016; Shimada, 2016), several studies reported autonomous vegetation recovery resulting from biological legacies such as buried seeds and surviving plants, including Japanese black pines (*Pinus thunbergii*), within a few years after the tsunami disturbance (Hayasaka et al., 2012; Hirabuki et al., 2011; Kanno et al., 2014; Ohbayashi et al., 2017; Oka and Hirabuki, 2014; Suzuki, 2016; Tomita et al., 2014). To conserve biodiversity and vegetation recovered after the tsunami, the Forestry Agency, Japan (FAJ) established the preservation area in a small portion of the total restoration area by preserving the original sandy substrate and undulating landform. Except for this, along the shoreline of Sendai Bay, vast land elevation areas (hereafter, elevation areas) were created based on the criterion of 3.2 m altitude and more than ca. 200 m in width by the FAJ. In this construction work, a large amount of sandy mineral soil of hills containing clay substrate was embanked and heavily compacted to elevate the basement of the coastal protection forest. Then, Japanese black pine saplings were planted preferentially in order to reduce the damage caused by sand blows, salt spray, storm surge, and tsunamis to settlements and farmlands (Furuta and Seino, 2016; Kurosawa, 2021, 2016; Nishihiro et al., 2014). As a result, coastal ecosystems and vegetation recovering from the 2011 tsunami were devastated.

This study aimed to compare the growth of Japanese black pine juveniles in the preservation and elevation areas using the vegetation index, which indicates chlorophyll content and leaf area, as well as height growth rate. Volumetric water content beneath the topsoil was also measured as an abiotic environmental indicator in both areas.

2. METHODS

The study was carried out in a coastal sand dune in Sendai City, Miyagi Prefecture, northeastern Japan (N38.233762, E140.995363; Fig. 1). The beach ridge is ca. 400 m wide and undulates with maximum dune top of ca. 5 m above sea level, and on the interior side Japanese black pine (hereafter, pine) dominated, homogeneous-aged (ca. 30 years old) plantation was severely disturbed by the Great East Japan Earthquake and Tsunami (Tomita et al., 2016) and autonomously recovered vegetation was also disturbed by the reconstruction works.

The study site (approximately 140 x 130 m) was set in this coastal sand dune and was composed of the preservation area and the elevation area (Fig. 1). The sandy substrate and undulating landform of the sand dune were preserved in the preservation area. In contrast, sandy mineral soil of hills containing clay substance was embanked and heavily compacted in the elevation area, although on-site sand was experimentally covered in ca. 10 cm depth to rehabilitate the ground surface. Individuals of pine in the preservation area were naturally regenerated before and after the 2011 tsunami, while those in the elevation area were planted in Spring 2019.

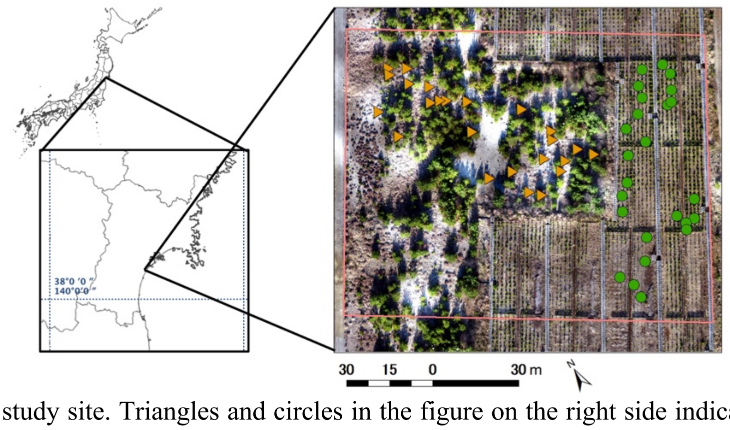

Figure 1. Location of the study site. Triangles and circles in the figure on the right side indicate the arbitrarily selected juveniles of Japanese black pine in the preservation and elevation area, respectively. Figures on the left side were created based on the GSI map.

To generate multispectral ortho mosaics of the study site, a UAV (P4 Multispectral; DJI, Inc.) was flown at an altitude of 30 m above the ground in December 2021. Ground control points (GCPs) were marked with twenty aerial signs, and their positions were determined using RTK-GNSS measurement. The acquired images were processed using Pix4DMapper version 4.6.4 (Pix4D S.A., Inc.), a photogrammetric software, to generate multispectral ortho mosaics of the study site (grid sampling distance: 0.92 cm/px). The normalized difference vegetation index (NDVI) was then calculated based on reflectance in the red and near-infrared bands of the multispectral ortho mosaic using ArcMap 10.8.1 (ESRI, Inc.). The NDVI was calculated following the equation.

$$NDVI = \frac{NIR - RED}{NIR + RED} \qquad (1)$$

where *NIR* = reflectance in the near-infrared band of the multispectral ortho mosaic
RED = reflectance in the red band of the multispectral ortho mosaic

In December 2021, twenty-four pine juveniles were arbitrarily selected in each area, resulting in a total of 48 pine juveniles, and their locations were also determined using RTK-GNSS measurement (Fig. 1). To calculate the relative height growth rate (RHGR), the annual shoot length of the stem was measured for all pine juveniles in December 2022 (Fig. 2). The RHGR was calculated following the equation.

$$RHGR = \frac{\ln(H + H_S) - \ln(H)}{t_2 - t_1} \qquad (2)$$

where H = height of the pine juveniles in December 2021
H_s = annual shoot length of stem of the pine juveniles in December 2022
t_2 = observation date in December 2022
t_1 = observation date in December 2021

Figure 2. The annual shoot of the stem the pine juvenile (a) and the polygons representing a crown of the arbitrarily selected pine juveniles (b).

To assess the potential photosynthetic productivity of each pine juvenile at an individual level, the polygon representing the crown of pine juveniles was created using ArcMap 10.8.1 (Fig. 2). The median of NDVI within the crown was then calculated. Additionally, at 40 arbitrarily selected points in the study site (Fig. 3a), the volumetric water content (m^3/m^3) at a soil depth of 10 cm to 20 cm was measured using a soil moisture sensor (TEROS-12; METER Group, Inc.). In the elevation area, the soil layer corresponded to the surface of the heavily compacted embankment, experimentally covered by on-site sand.

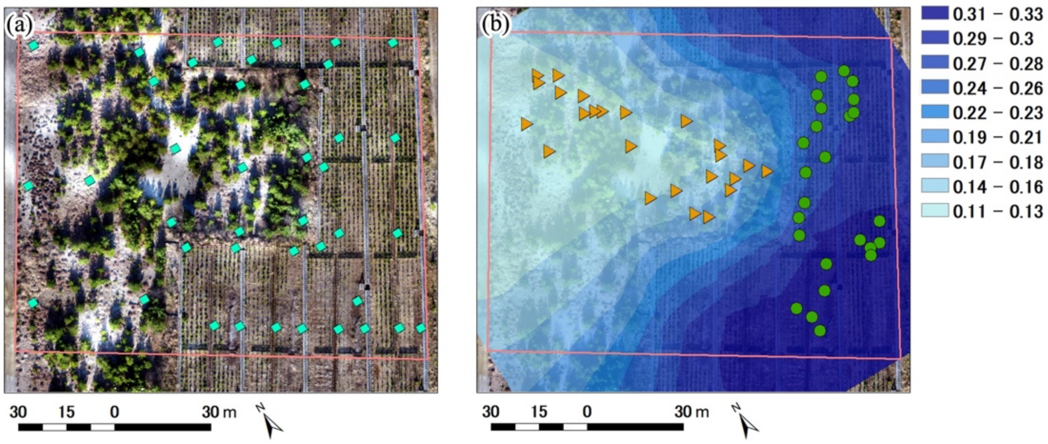

Figure 3. Location of the sampling points for the volumetric water content (m^3/m^3) beneath the topsoil (a) and contour map of the volumetric water content (b). For triangles and circles, see Fig. 1.

3. RESULTS AND DISCUSSION

As shown in Figs. 3 and 4, the volumetric water content beneath the surface was significantly higher in the elevation area (mean ± SD: 0.307 ± 0.046 m^3/m^3, n = 25) than in the preservation area (0.109 ± 0.025 m^3/m^3, n = 15). This result may be explained by the fact that the embanked basement soil of the elevation area was characterized by heavily compacted mineral soil of hills containing clay substance. As a result, a higher volumetric water content than the preservation area could be observed in the elevation area. This also accords with earlier studies in afforestation areas for the pines (Ono et al., 2021, 2018), which showed that the soils compacted by heavy construction equipment become harder physically and decrease water permeability. Also, the submerged condition was often observed in the elevation area in our study site.

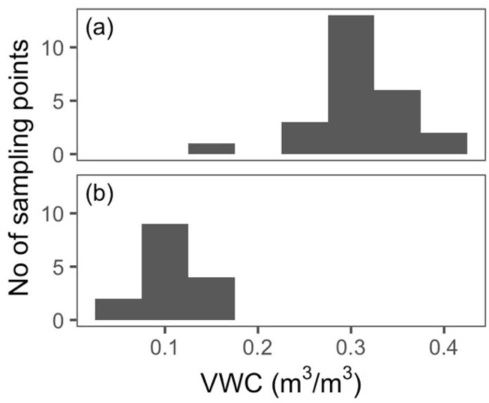

Figure 4. Histogram of the volumetric water content beneath the topsoil (VWC) in the elevation area (a) and the preservation area.

NDVI of the crowns of pine juveniles was significantly lower in the elevation area (0.406 ± 0.123) than in the preservation area (0.772 ± 0.033). The comparison of the pine juveniles in height between 40 cm and 160 cm also revealed lower NDVI values in the elevation area compared to those in the preservation area (Fig. 5a). These findings might indicate that the lower NDVI implies lower photosynthetic productivity caused by a small total leaf area and low chlorophyll content in the leaves of the pine juveniles in the elevation area. Particularly in the elevation area, the more extensive range of NDVI for the pine trees compared to those in the preservation area suggests a possibility of spatially heterogeneous growth conditions of the pine juveniles. Previous studies have shown that i) soil compaction by heavy construction equipment increases soil hardness and then causes the inhibition of root growth of the pine juveniles (Ono et al., 2021), and ii) submerged condition also reduces root growth, inhibits leaf formation and expansion, and decreases the rate of photosynthesis by reducing chlorophyll content (Kozlowski et al., 1991). It is possible that these phenomena could account for some aspects of the results.

In the elevation area, lower NDVI values corresponded to lower relative height growth rates (Fig. 5b). This rather interesting result could be due to the low photosynthetic productivity of the pine juveniles, probably resulting from the reduction of total leaf area and leaf chlorophyll content by the soil compaction and submerged condition. In the preservation area, on the other hand, the NDVI of the pine juveniles showed higher values around 0.8 although the relative height growth rate varies. A possible explanation for this might be that the variation in height growth of the pine juveniles in the preservation area has been affected by other factors such as competition with other individuals rather than photosynthetic productivity. Another possible explanation for this is that the taller pines allocate photosynthetic products to the increase and growth of the lateral shoots. Further studies, which take these variables into account, will need to be undertaken.

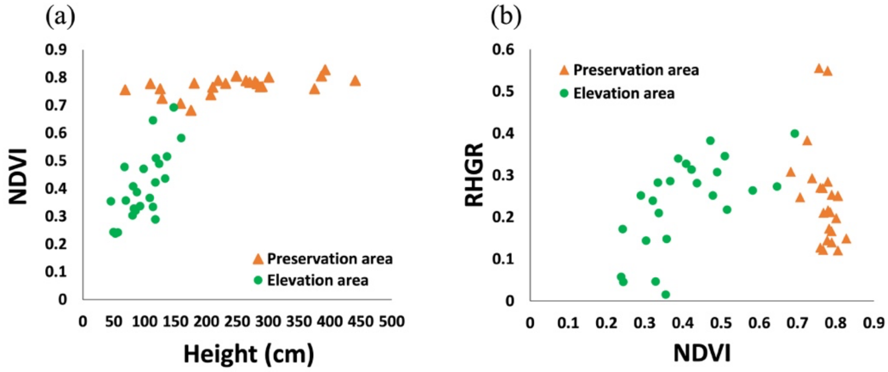

Figure 5. Relationships between NDVI and height (a), and between RHGR and NDVI of the pine juveniles.

4. CONCLUSIONS

We performed an individual-level UAV remote sensing to assess the growing status of *P. thunbergii* juveniles in the early regeneration stage on a severely disturbed coastal sand dune. This study has identified that the NDVI of the pine juveniles in the elevation area was lower than that in the preservation area and positively corresponded to the height growth. This phenomenon is probably due to the reduction of leaf growth resulting from the inhibition of root-system development by basement soil compaction. Notwithstanding the relatively limited sample size, this work offers valuable insight i) into the utilization of the substrate originating from sand dunes rather than the compacted mineral soil of hills containing clay substance for the restoration of coastal forests and ii) into the usefulness of the UAV remote sensing technique in individual- or habitat-level assessment of growth and photosynthetic characteristics of tree species.

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