Master's Thesis of Geography

Changes in soil, vegetation, and landforms after large-scale disturbance in the Sindu coastal dune

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Abstract

The Sindu dunefield, one of the largest, well preserved coastal dunes in South Korea, experienced a substantial artificial disturbance. Unlike occasional vegetation removals at a small scale, the impacts of the disturbance in October 2019 resembled those of natural disturbances such as overwash. Complete devegetation and ground flattening, using excavator and bulldozer, were carried out for the area of 1.2ha at the foredune of Sindu.

In this research, changes of the disturbed foredune were investigated after the disturbance. To compare the disturbed area with other undisturbed zones in geographical and ecological contexts, I monitored the Sindu dunefield at a fine temporal resolution for a year. The main uniqueness of this research is that the dune system was extensively surveyed and analyzed. Disturbed foredune studies usually have been dealing with either dune plants or landforms. In the Sindu, however, the edaphic, vegetational, and geomorphological data were widely collected.

The study includes three main contents. Firstly, changes in each factor (soil, vegetation, and landforms) were investigated. Soil properties were changing at various speeds and directions. Some pioneer species were identified in the disturbed foredune. The process and the incipient stage of foredune landform regeneration were observed. Next, the original statistical methods for the data analysis were presented. Multivariate statistical methods were newly combined and interpreted for specific purposes. Lastly, appropriate field survey methods were suggested for long-term monitoring of a disturbed coastal dune.

With proper study materials, collected by proper monitoring method, and analyzed with appropriate statistical methods, the dune study will provide helpful knowledge for coastal management in this era of rapid disturbance regime change.

Keyword : Coastal dune, Disturbance, Foredune, Soil, Vegetation, Landforms

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Table of Contents

List of Figures

List of Tables

Chapter 1. Introduction

1.1. Study background

Coastal sand dunes are valuable ecosystems providing various ecosystem services. To borrow the expressions of Costanza (1997), disturbance regulation, water supply, sediment retention, nutrient cycling, and recreation can be the ecosystem service of coastal dunes. Of these, the disturbance regulation function got the attention in this research. Coastal dunes, located between a coastal system and a land system, play the role of buffer zones between two different systems (Martínez et al., 2008). Due to their relative position, coastal dunes protect the land system from disturbances, such as wave erosion and storm overwash. At the same time, these natural disturbances destruct the coastal dune system (Ricthie and Penland, 1990; Claudino-Sales et al., 2008).

In this era of rapid climate change, it is often anticipated that the frequency, intensity, and duration of disturbance events will increase in the future (Meehl and Tebaldi, 2004; Webster et al., 2005; Moritz et al., 2012; Allen et al., 2015). However, we are still far from understanding how this altered disturbance regime affects the ecological and geomorphic dynamics of coastal systems (Hesp and Martínez, 2007; Bowler et al., 2018). Intense and frequent disturbances threaten the resilience of a coastal dune system (Houser et al., 2015), and multiple disturbances may affect some coastal systems in a short period (Debusschere et al., 1991; Claudino-Sales et al., 2008). Therefore, predicting the patterns of such dynamics will help to develop appropriate management strategies before unprecedented, large-scale disturbances start to occur (Turner, 2010). Nevertheless, the ecological recovery of disturbed coastal dunefield has not been sufficiently studied (Houser and Hamilton, 2009).

In October 2019, an unprecedented incident occurred at Sindu coastal dune. For ca. 1.2ha (11,830m^2) of the foredune area, complete devegetation and landform flattening were carried out by the Taean Province Office. The name of the work was "Restoration of the foredune at the Sindu coastal dune," and the foredune area was *restored* by an excavator and bulldozer. The two main justifications of the work written in the planning document were "for more erosion and sedimentation to occur" and "for the convenience of tourists." The former reason, one of the central discourses discussed at Sindu, was to some degree scientific and logical. Because sand movement induced by aeolian processes is a necessary part of the dune in some perspectives, a dune area has been devegetated to induce greater aeolian activity (Martínez et al., 2013). As most Sindu dunefield is covered with vegetation and stabilized very well, words about revitalizing morphological dynamics have been coming out.

Nevertheless, the second reason was not persuasive enough. The hidden meaning of "the convenience of tourists" was to increase the tourists' satisfaction, primarily through providing a desert−like landscape. Although many tourists wish to see a bare dunefield, there is room for criticism in disturbing the Natural Monument with heavy machinery.

There is no need to further discuss whether this incident was right or wrong. Instead, from the researcher's point of view, I would like to accept it as an excellent opportunity to study a disturbed coastal dune system. The results of the artificial disturbance fairly resembled an outcome of natural washover in that all the plants were removed, and the foredune landforms were flattened as if a giant wave swept by.

1.2. Purpose of the research

This study aims to monitor changes of the disturbed foredune system in comparison with the undisturbed dune areas. Under the assumption that the results of the artificial disturbance in October 2019 were similar to those of natural disturbance, the disturbed area was thought to be an experimental plot. Other undisturbed areas, on the contrary, gave standard data as control plots.

The word 'System' does not mean everyday language (eco)system. As the academic terminology 'Ecosystem' does, the foredune system includes many factors: in this research, soil, vegetation, and landforms. These factors separately define the foredune system and closely interact with each other, making ecological and geomorphological processes of the system. Therefore, to fully understand the changes of the disturbed foredune, monitoring all these factors is essential.

Soil properties, plant species compositions, and elevation of the disturbed area were thought to change. Due to the short study period, this work could not conclude the eventual destination of the transition. However, the data collected were enough to present the changing phenomenon itself. Furthermore, some statistical methods were proposed based on the data collected. These methods can be adopted in another long-term, well-designed monitoring project. Lastly, proper monitoring methods for a disturbed coastal dune were suggested in retrospect to this study.

Chapter 2. Literature Review

2.1. Studies on the Sindu coastal dune

Many geographers and ecologists have intensively studied Sindu in the 21st century. The research purposes can be divided into two big groups: description and explanation. Geomorphological features (Seo, 2002; Kim, Seo, and Park, 2008), vegetation (Ahn, 2003; Oh et al., 2005; Choi et al., 2006), and spatial distribution of soil properties (Yu et al., 2005; Yu et al., 2012) have been described in detail. The distribution of dune plants has usually been explained with geomorphological (Kahng, 2006; Song and Choi, 2007) or soil (Song et al., 2005) characteristics. Kim (2004) explained the spatial distributions of various plant species with both geomorphological and edaphic variables. Aeolian sand transport was well described and explained by Rhew (2001) and Ryu (2002).

Few studies have been published regarding the changes of the system after a disturbance. The recovery of vegetation was described by Lee et al. (2020) and explained by Kim et al. (2019). Otherwise, no research about the resilience of Sindu was found.

2.2. A coastal dune and disturbance

The best situation for studying the dune recovery is scarce: a researcher should know the specific situation of a dune system before a disturbance, a considerable disturbance should occur at the exact position, and long−term monitoring should go along after the disturbance. Since this kind of lucky case does not appear to a researcher (but see McLean and Shen, 2006), most papers only deal with post−disturbance regeneration pathways.

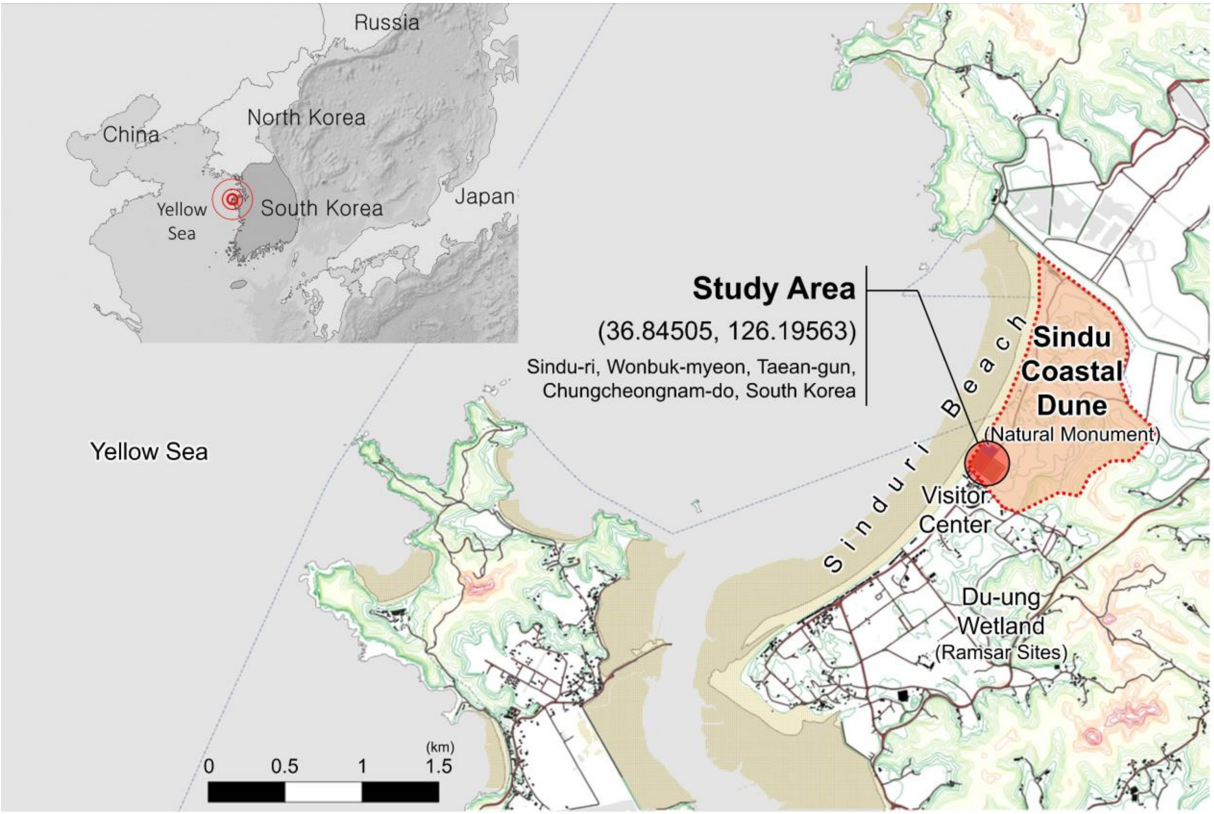
Vegetation recovery at a disturbed coastal dune has been studied for a long time. Although few studies provide results about dune plant regeneration after natural disturbances (e.g., Hayasaka et al., 2012), many researchers have monitored the dunes after artificial disturbances. After an unavoidable artificial disturbances like sand mining and tourists' trampling, vegetation regenerations were studied by Hylgaard (1980) and Partridge (1992). Intended artificial disturbances, that is, devegetation, gave controlled research areas to Wiedmann and Pickart (1996), Pickart et al. (1998), Kollmann et al. (2011), and Marchante et al. (2011).

Many researchers have also studied geomorphological recovery (Thom and Hall, 1991; Hesp, 2013; Houser et al., 2015). In this case, real natural disturbances were usually the initiation of the studies. Moreover, unlike vegetation recovery research, long−time (more than a decade) monitoring had been implemented. Furthermore, landform restorations intervened by a human were widely studied after natural disturbances (Feagin, 2013; de Jong et al., 2014).

2.3. Knowledge gap

As described above, most studies dealing with the recovery of the coastal dune focus on only vegetation or geomorphology. Psuty and Silveira (2010) and Pickart (2013) proposed that both physical and biological components should be considered for a regeneration study at the coastal dune. Furthermore, changes in edaphic characteristics are also crucial for regeneration since soil properties are important determinants of the vegetation distribution in a coastal dune (Kim and Yu, 2009). Soil, vegetation, and landforms are key components forming dune processes in geomorphological and ecological perspectives: therefore, an integrative approach should be pursued.

Hylgaard (1980) criticized that the regrowth of dune vegetation is just 'physical recovery' and said 'ecological recovery' must be achieved for true recovery. The latter should involve many vegetational factors such as species, frequencies, cover, production, reproduction, and interrelationship with other environmental factors (Hylgaard, 1980). Further from here, I would like to emphasize that every factor (soil, vegetation, and geomorphology) of a coastal system should be considered as they change altogether. This integrative approach helps to attain proper coastal management (Martínez et al., 2008).



[Figure 1]

The location of the Sindu coastal dune

Chapter 3. Materials and Methods

3.1. Site description

The Sindu dune, located on the Yellow Sea coast of South Korea, is one of the country's largest, well-preserved temperate coastal dunes (Figure 1). It is 1.2km along the coastline and 0.5 ~ 1km inland, with a total area of 1km^2 wide. Although the dunefield area was 4km long and 0.5 ~ 1.5km inland several decades before (Kim and Yu, 2009), the rapid development of tourist facilities in the 1990s destroyed much of its area (Seo, 2012). The rest preserved area, now called "Taean Sindu-ri Coastal Dune (태안 신두리 해안사구)" was designated as a Natural Monument No. 431. The reasons for the designation are as follows: desert-like unique landscape, act as the breeding area of birds, valuable coastal landforms, well preserved, and is paleoenvironmental research area.

To be more specific, Shin (2009) proposed four ecosystem services of the Sindu coastal dune. The first one is "coastal sand storage and coastline protection." As located in the middle of the ocean and land, the Sindu dune, like other coastal sand dunes, protects the coastline from disturbances such as storm surge (Seok et al., 2015). Describing the sand storage service, Seo (2001) defined the Sindu as "The Warehouse of coastal sands."

The second ecosystem service is "habitats for organisms." For example, 40 families, 92 genera, 108 kinds of plant species inhabit Sindu (Choi et al., 2006), and many rare species (e.g., *Lilium callosum*, *Glehnia littoralis*, *Orobanche coerulescens*, et cetera.) were reported there (Oh et al., 2005). Mongolian racerunner (*Eremias argus*) is the most well-known endangered reptile species living at the Sindu, and the dunefield is the largest ant-lion habitat in Korea.

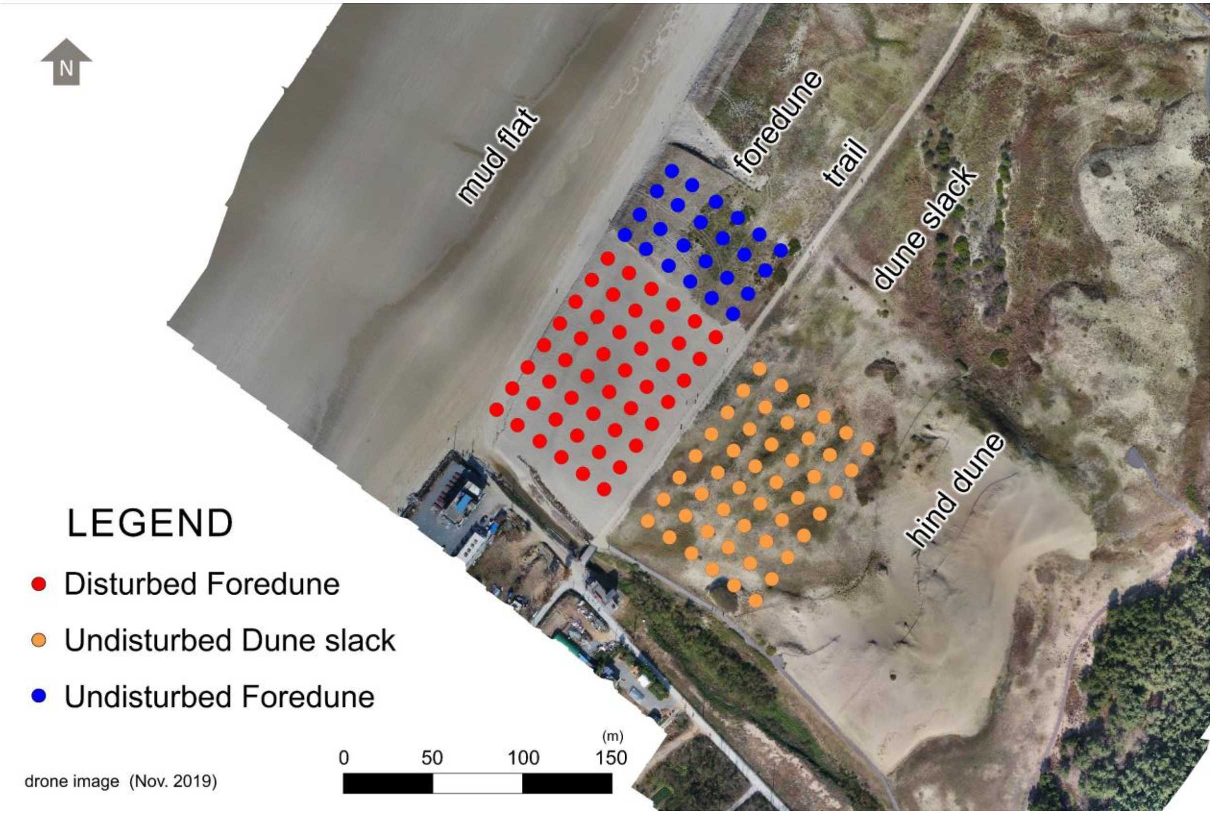
The third service is "groundwater storage." Groundwater stored under the coastal dune is freshwater, unlike saltwater of the sea. The density difference occurred here generates the boundary between fresh water and seawater, and they do not mix. Furthermore, in the monsoonal season (summer) of Korea, a volume of the groundwater at the Sindu expands, and the residents can use water for agriculture (Kim, Seo, and Park, 2008)

The last one is "scenic value." Sindu today is still beautiful, and many tourists visit for its scenery, but unlike these days, it was once famous for its desert-like scenery. From the 1980s, dune plants rapidly expanded, and in the late 1990s, most areas of Sindu were covered with vegetation (Seo, 2002). Due to the loss of its desert-like landscapes, some tourists were disappointed with the fully vegetated dunefield and interviewed "It was just a grassland, not a desert." or "No sandhill was observed." (Seo, 2012). So the last ecosystem service has been partly undermined.

Sindu is called 'the textbook of a coastal dune,' as almost every geomorphological feature of a temperate coastal dune is observed (Park and Yu, 1979). Reported topographical features are embryo dune, foredune ridge, sand hummock, barchan dune, ripple mark, hind dune, U shape dune, hairpin dune, depression hollow, relict dune, and so on (Korea National Park, 1998). Foredune - dune slack - hind dune continuum is well developed, and in the rainy season, temporary wetlands are formed at the dune slack area (Kim, 2021). The Du-ung wetland, one of the Ramsar sites, is located between the hind dune and the mountain behind. Since most of these features are in natural conditions, the Sindu coastal dune is a good area for geographical and ecological studies (Kahng, 2006), and more than ten theses were published in a decade after 2000 (Seo, 2001; Rhew, 2001; Ryu, 2002; Park, 2003; Shin, 2002; Kim, 2004; Choi, 2004; Ko, 2005; Kwon, 2005; Yu, 2005; Hong, 2009).

Although the Sindu is known to be well preserved, there have been constant interventions by humans. In the 1990s, when the Sindu dunefield began to develop, external soils were used for unpaved road construction, and *Oenothera biennis* and *Conyza bonariensis* were introduced, which were unnatural to grow in the normal succession process of the Sindu (Seo, 2012). Cars, trampling, and camping by visitors induced the vegetation destruction in the 2000s.

After Sindu was designated as a Natural Monument in 2001 and dune conservation programs were implemented in earnest, indiscreet and unpredictable interventions by humans disappeared. Systematic and planned interventions, however, are still in progress. Typical and one of the most significant artificial disturbances that occurred at the Sindu is the 2012 vegetation removal. Kim et al. (2019) described the incident as an "extensive" and "drastic" vegetation removal as every plant species (both native and invasive plants) across 11ha area of the Sindu was devegetated. Otherwise, several small-scale vegetation (usually invasive species) removals have been implemented throughout the Sindu dunefield. However, the unprecedented artificial disturbance, accompanying complete devegetation and landform flattening, occurred in October 2019.



[Figure 2]

Three research areas

3.2. Fieldwork design and data collection

3.2.1. Fieldwork design

In the Sindu dunefield, three areas were selected for this thesis research: disturbed foredune, undisturbed dune slack, and undisturbed foredune (Figure 2). The disturbed foredune was an experimental plot covering the broad area impacted by the artificial disturbance. The undisturbed dune slack is located behind the disturbed foredune area. Both areas were equal in size, and the same number of survey points were distributed. The undisturbed foredune was a foredune showing the natural state of the Sindu foredune area since no artificial disturbance has occurred there. The disturbed foredune before the disturbance was hypothesized to be similar to this area. Therefore, it was a control plot in comparison with the disturbed foredune.

The number of total survey points was 120: 48 for the disturbed foredune and the undisturbed dune slack each and 24 for the undisturbed foredune. Since another artificial disturbance occurred at the northeast side of the undisturbed foredune prior to the 2019 disturbance, no more survey points could be installed further. A 1-meter long steel bar was installed at each survey point, and every fieldwork was performed just beside the bar.

3.2.2. Analysis of soil properties

I collected soil samples of two periods: the winter, two months after the disturbance (December 2019) and the summer (August 2020) when dune plants fully entered the disturbed foredune. Approximately 200g of sub-surface (2cm below the ground) soil was collected at each survey point. At the lab, soil properties related to vegetation growth were analyzed: soil moisture content, soil organic matter, acidity, electronic conductivity, exchangeable cations (Na^+, Ca^{2+}, K^+, Mg^+), nitrate (NO_3^-), phosphate (PO_4^{3-}), and grain size variables (mean, sorting, medium sand, fine sand, very fine sand).

Soil Moisture Content

After the soil sampling, the first thing did was to eliminate the soil moisture from the raw soil samples. Soil water was dried at 105° c for 24h with the oven (model: Daihan Scientific Oven - W0F05105), and the sample's weight was measured before and after the dehydration. The soil moisture content was calculated with the formula down below:

$$\text{Soil Moisture Content} = 100 \times (\text{Weight}_{wet} - \text{Weight}_{dry}) / \text{Weight}_{dry}$$

Soil Organic Matter (SOM)

Approximately 15g of the dried soils were put to the crucibles and ignited at 600° c for 6h with the furnace (model: Fisher Scientific Isotemp Muffle Furnace). 600° c and 6h are known to be enough for accurate loss of ignition method, or the LOI method (see Hoogsteen et al., 2015). SOM was calculated with the formula down below:

$$SOM = 100 \times (Weight_{dry} - Weight_{ignite}) / Weight_{ignite}$$

Acidity (pH)

5g of the dried soil sample with 25ml of distilled water (1:5) were added to a conical tube. The tubes were then sufficiently shaken with the Flask Shaker at 80rpm for 1h. Next, well-mixed suspensions were centrifuged (model: Vision Scientific Table-top Centrifuge - VS-5500N) at 3000rpm for 7min and filtered with the Whatman No.42 paper filters. The pH of the filtered extracting solution was measured with the pH meter (model: Trans Instruments Professional Benchtop pH Meter - BP3001).

Electronic Conductivity (EC)

The preprocessing methods were exactly the same with pH solution, but the measuring instrument was different (model: Lutron hand-held EC meter - YK-2001PHA).

Exchangeable Cations

4g of the dried soil sample with 40ml of 1N Ammonium acetate solution[1] (1:10) were added to a conical tube. The tubes were then sufficiently shaken with the Flask Shaker at 70rpm for 1h. Next, well−mixed suspensions were centrifuged at 3000rpm for 7min and filtered with the Whatman No.42 paper filters. The filtered extracting solutions were analyzed with the Inductively Coupled Plasma Atomic Emission Spectrometer (model: Perkin−Elmer ICP−AES – OPTIMA 8300) at the National Center for Inter−University Research Facilities of Seoul National University to quantitatively analyze the Na^{+}, Ca^{2+}, K^{+}, and Mg^{+} ions. No adjustment was applied to the result since the dried soil was analyzed, not the raw soil.

[1] 1N Ammonium acetate solution: 77.08g of NH_4Ac + add distilled water and make it 1000ml in volume (NH_4OH and CH_3COOH for making exact pH7 solution are not needed since the acidity of the solution has no substantial effect on measuring exchangeable cations (Cumbara et al., 2019).)

Nitrate (NO_3^-)

8g of the dried soil sample with 40ml of 2M Potassium chloride solution[2] (1:5) were added to a conical tube. The tubes were then sufficiently shaken with the Flask Shaker at 90rpm for 30min. Next, well−mixed suspensions were centrifuged at 3000rpm for 7min and filtered with the Whatman No.42 paper filters. 10ml of the filtered extracting solution was put into a smaller conical tube and heated at 45° c for 30min. Then 0.4ml of Phenate Buffer[3] and 0.2ml of

Reducing Solution[4] were added and mixed with the Vortexer. Heat the solution at 45° c for 30min again, and cool with cold water for 10min. 0.4ml of Sulfanilamide+NED[5] were added next and mixed. 30min of reaction time is needed at the lab temperature. Lastly, the color of the reacted solution was measured at 543nm wavelength with the spectrophotometer (model: EMCLAB Instruments Spectrophotometer - EMC−11D−V). The color absorbance values measured from the spectrophotometer were compared with the colors of standard Nitrogen solutions. 0, 0.01, 0.05, 0.1, 0.2, 0.5, 1, 2, and 5ppm Ammonium nitrate solutions were made and color reacted with same procedure. The absorbance values of each standard solution were linearly modeled to estimate exact NO_3^- concentration from specific absorbance values. No adjustment was applied to the result since the dried soil was analyzed.

[2] 2M Potassium chloride solution: 150g of KCl + add distilled water and make it 1000ml in volume

[3] Phenate Buffer: 1.8g of 99% Phenol + 15ml of Sodium hydroxide + add distilled water and make it 100ml in volume

[4] Reducing Solution: 25ml of the Stock Hydrazine[4−1] + 5ml of the Copper Solution[4−2] + add distilled water and make it 50ml in volume

[4−1] Stock Hydrazine: 1.2g of Hydrazine sulfate + add distilled water and make it 250ml in volume

[4−2] Copper Solution: 0.04g of Cupric sulfate + add distilled water and make it 100ml in volume

[5] Sulfanilamide+NED: the Sulfanilamide[5−1] : the NED[5−2] = 1 : 1

[5-1] Sulfanilamide: 5g of Sulfanilamide + 50ml of 12N Hydrochloride + 500ml of distilled water

[5-2] NED: 0.5g of N-1-Naphthylethylenediamine dihydrochloride + add distilled water and make it 500ml in volume

Phosphate (PO_4^{3-})

5.7g of the dried soil sample with 40ml of the Bray II Solution[6] (1:7) were added to a conical tube. The tubes were then sufficiently shaken with the Flask Shaker at 90rpm for 2min. Next, well-mixed suspensions were centrifuged at 3000rpm for 5min and filtered with the Whatman No.42 paper filters. 10ml of the filtered extracting solution was then mixed with 1.0ml of the MA Solution[7] and 0.1ml of the AA Solution[8]. After the vortexing, heat the solution at 45° c for 30min. Lastly, the color of the reacted solution was measured at 675nm wavelength with the spectrophotometer. The color absorbance values measured from the spectrophotometer were compared with the colors of standard Phosphorus solutions. 0, 0.05, 0.1, 0.2, 0.5, 1, 2, 5, and 10ppm Phosphorus solutions were made and color reacted with same procedure. The absorbance values of each standard solution were linearly modeled for the estimation of exact PO_4^{3-} concentration from specific absorbance values. No adjustment was applied to the result since the dried soil was analyzed.

[6] the Bray II Solution: 15ml of 1N NH_4F solution + 25ml of 0.5N

Hydrochloride + add distilled water and make it 500ml in volume

[7] the MA (Molybdenum−Antimony) Solution: 244ml of 36N Sulfuric acid + 21g of Ammonium Molybdate + 0.6g of Antimony potassium tartrate + add distilled water and make it 2000ml in volume (add approximately 1000ml of distilled water first for the prevention of exothermic reaction caused by sulfuric acid and water)

[8] the AA (Ascorbic Acid) Solution: 3g of Ascorbic acid + 100ml of distilled water (or 95% Ethyl alcohol)

Grain Size Distribution

The ignited soil was used for the grain size analysis because SOMs were mostly removed. The laser diffraction method was used for the analysis (model: Beckman Coulter Laser Diffraction Particle Size Analyzer – LS 13320, with the Aqueous Liquid Module). The results were analyzed with GRADISTAT Version 8.0, and the grain sizes were scaled with a geometric scaling, not an arithmetic scale since the former suits high content of <1mm particles (Blott and Pye, 2001). The mean size, sorting, and medium sand, fine sand, and very fine sand content were extracted from the results.

3.2.3. Vegetation survey

At each survey point, living vascular plants were surveyed with a 1x1m quadrat. Nomenclature followed Korea National Arboretum (2017), and each species' cover rates were estimated based on the aerial cover method (Fehmi, 2010). Although this method emphasizes dominant and/or tall plants, just one or two small individuals might be determined as outliers during the statistical analysis, and no tall plants like willow trees were living at the plot surveyed.

The vegetation survey started in May; the time plant species started to establish in the disturbed foredune area. Other surveys were carried out in June, July, September, and the last survey was in October when the above-ground part of the plants withered in earnest. In August, heavy east Asian monsoonal rain affected the whole country, so I could not go to the study area for the survey.

3.2.4. Geomorphological survey

Highly accurate Real-Time Kinematic (RTK) GPS, based on Virtual Reference Station (VRS) method, was used to get precise elevation (above the sea level) of the survey points. Trimble R2 GPS receives signals of base GPSs installed by the National Geographic Information Institute and measures almost exact altitude, with an accuracy of under 1cm. From December 2019 to October 2020, I visited Sindu 11 times for the geomorphological survey, once a month on average. Through this, the absolute elevation variable was made at high temporal resolution.

Because ordinary coastal sand dunes are dynamic in sand erosion and sedimentation, the accretion rate variables were calculated with the absolute elevation variable. As the northwesterly wind is dominant at Sindu through October to early April, active sand movement occurs during that period (Park and Yu, 1979; Seo, 2001). Yu et al. (2005) named that time "Active moving sand period," unlike the period from late April to September, named "Inactive moving sand period." So in this research, the absolute elevation variable was split into two groups by period: the former and the latter period of Yu et al. (2005). In addition, simple linear regression analysis using time as an independent variable and the absolute elevation variable as a dependent variable was conducted for each period and at each survey point. The regression coefficients were extracted and used as the accretion rate variable. The positive regression coefficient indicates sand accretion as time goes by, and the negative one means erosion.

3.3. Statistical analysis

3.3.1. Soil property data analysis

The soil properties of the disturbed foredune were compared with those of the undisturbed foredune for the winter (two months after the disturbance) and the summer (10 months after the disturbance), respectively. The subject of analysis was 14 soil variables, in two areas, for two periods.

First, to check the changes of individual soil properties of the disturbed foredune in comparison with those of the undisturbed foredune, the Mann-Whitney U test (also known as Wilcoxon rank-sum test) was employed. Since many soil properties were not normally distributed and had several outliers, a rank-based nonparametric statistic was more appropriate, and therefore, function 'stats::wilcox.test' of R was used.

Second, the overall soil property changes were quantitatively summarized with the original statistical method. As a preliminary, Principal Component Analysis (PCA) was used for the dimension reduction. Function 'stats::princomp' of R summarized numbers of vectors into a few Principal Components (PCs). In this research, PC1, PC2, and PC3 were selected to summarize the soil variables. The criteria for segregation between selected and unselected PCs were established considering the 'knee' of the scree plot and the explaining variances of each PC integrally.

Next, I plotted the three PCs on a 3-D Euclidean space. For comparing the disturbed foredune and the undisturbed foredune of the winter and the summer, Analysis of Similarities (ANOSIM) was adopted. ANOSIM uses a dissimilarity matrix with many groups as an object and is a multivariate version of Analysis of Variance (ANOVA). It is very similar to Permutational Multivariate ANOVA (PERMANOVA), but one difference is that ANOSIM is a method for a rank-based nonparametric test. PERMANOVA could be used with raw dissimilarity matrix (or the transformed one), but PC1, PC2, and PC3 had some extreme outliers, which were not desirable for PERMANOVA.

With ANOSIM for the Euclidean distances in the 3-D plot, how the PCs overlap or not each other can be quantified. As two groups of points (e.g., the disturbed foredune of the winter and the undisturbed foredune of the winter) more overlap each other, the R-value decreases, and the *p*-value increases (Legendre and Legendre, 2012). If less overlap, the former increases, and the latter decreases. These values help quantitatively show the degree of soil property difference between the two groups.

3.3.2. Vegetation data analysis

I had a total of 15 species composition data (three research areas and five times vegetation surveys). With these, Indicator Species Analysis was conducted first. The Indicator Value is decided based on the two concepts: specificity and fidelity. The former is the highest when the species is present in the target area but not elsewhere, and the latter is the highest when the species is present in all survey points of the target area (Borcard et al., 2018).

Next, PERMANOVA was adopted for the data to check whether species compositions of the disturbed foredune were statistically different from those of the undisturbed foredune. If different, how different was quantified. PERMANOVA is widely done with the 'Vegan::adonis' function in R, but 'RVAideMomoire::pairwise.perm.manova' was implemented instead for the convenience of pairwise analysis. The species composition data were transformed to a dissimilarity matrix using the Bray–Curtis index.

ANOSIM, explained earlier, was not used since some rare species were eliminated beforehand: *Zoysia sinica* and *Carex kobomugi* were found at 0 ~ 2 survey points, and *Vitex rotundifolia* was found only once. A more traditional method, Multi–response Permutation Procedure (MRPP), could be used for the comparison. MRPP, however, sometimes mistakenly judges the two groups of data with different within–group dissimilarities (Peck, 2016). The data for the undisturbed dune slack and the undisturbed foredune had no problem: but the average within–group distance of the disturbed foredune was 0.64 for the first survey and increased to 0.85 for the last survey, which induced hesitation for using MRPP. Therefore, PERMANOVA, more robust and having no same issue, was used instead.

To figure out statistically different species compositions, I used *p*-values of PERMANOVA. Usually, *p*-values under 0.05 are thought to be statistically significant, but in this case, *p*-value adjustment was necessary. Since more than 100 relationships were tested, some of the testings having a *p*-value lower than 0.05 could be judged significant by chance, increasing the type I error rate (Peck, 2016). For problem-solving, the method proposed by Benjamini and Hochberg (1995) was used to adjust the criterion. Although this method is less strong than traditional adjustment methods like the Bonferroni correction, it helps to reduce the false discovery rates (*sensu* Benjamini and Hochberg, 1995; termed after Sorić, 1989)

The diachronic changes of the species compositional difference were quantified with PERMANOVA R^2. The higher the R^2, the better the two groups of species composition were distinguished by the group variable (the factor variable). Conversely, low R^2 indicates similarity between two vegetation data.

Chapter 4. Results

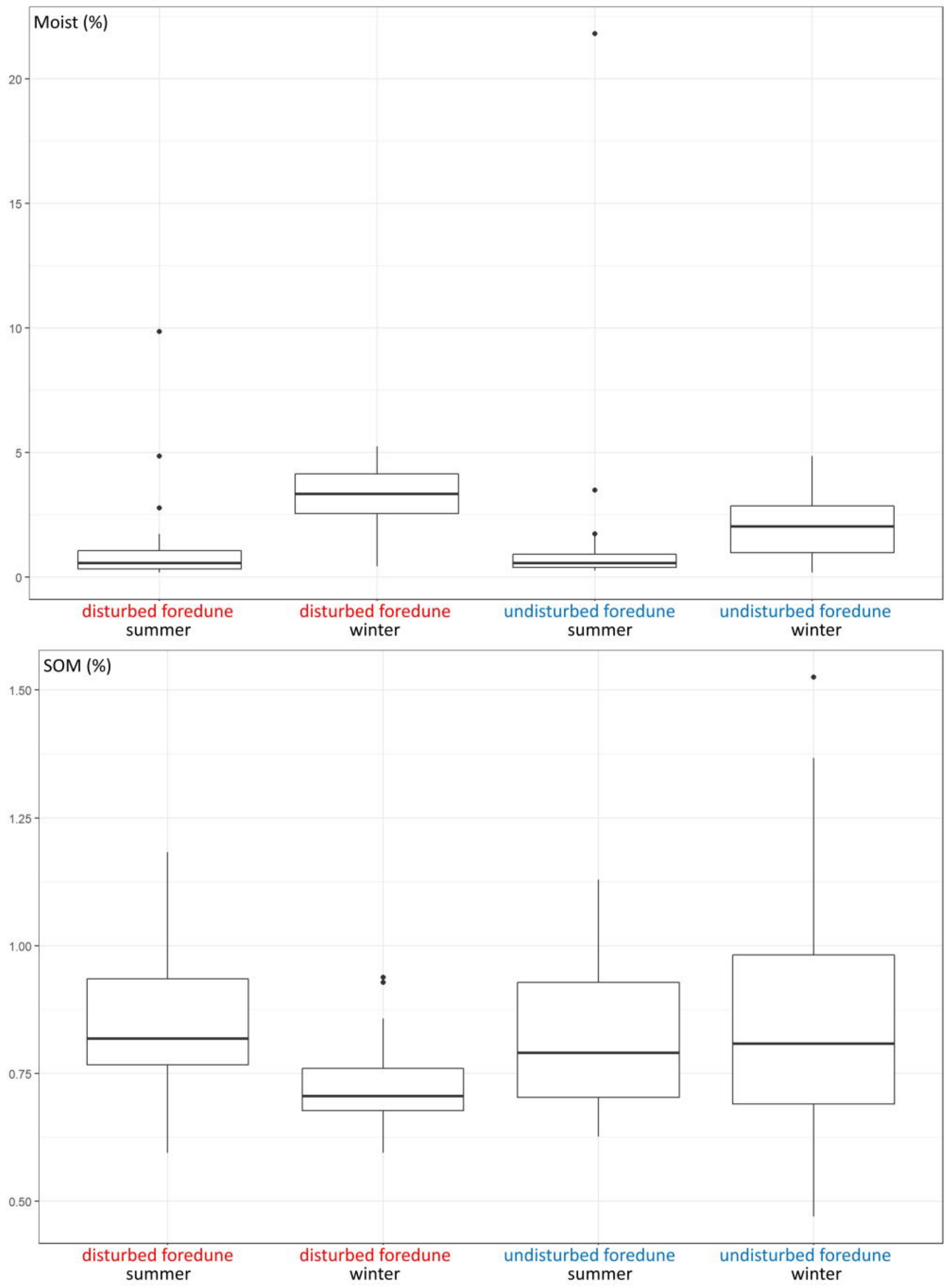
4.1. Soil property

4.1.1. Soil property of coastal dune system

The soil property of the Sindu coastal dune is one of the most important factors defining the dune system. Although vegetation and landform dynamics of the dune are easily observed by eyes, and of course, they are crucial factors, invisible soil property is also an indispensable research subject. Based on a biogeomorphic point of view, soil property determines the distribution of dune plants, and at the same time, is changed under the influence of dune plants. Furthermore, the fact that soil property is determined by surrounded geomorphology is well known, but little research emphasizes that soil property affects landform generation (but see Nolet, 2020). In short, the dune area’ s vegetation, landform, and soil form feedback loops (Kim and Yu, 2009).

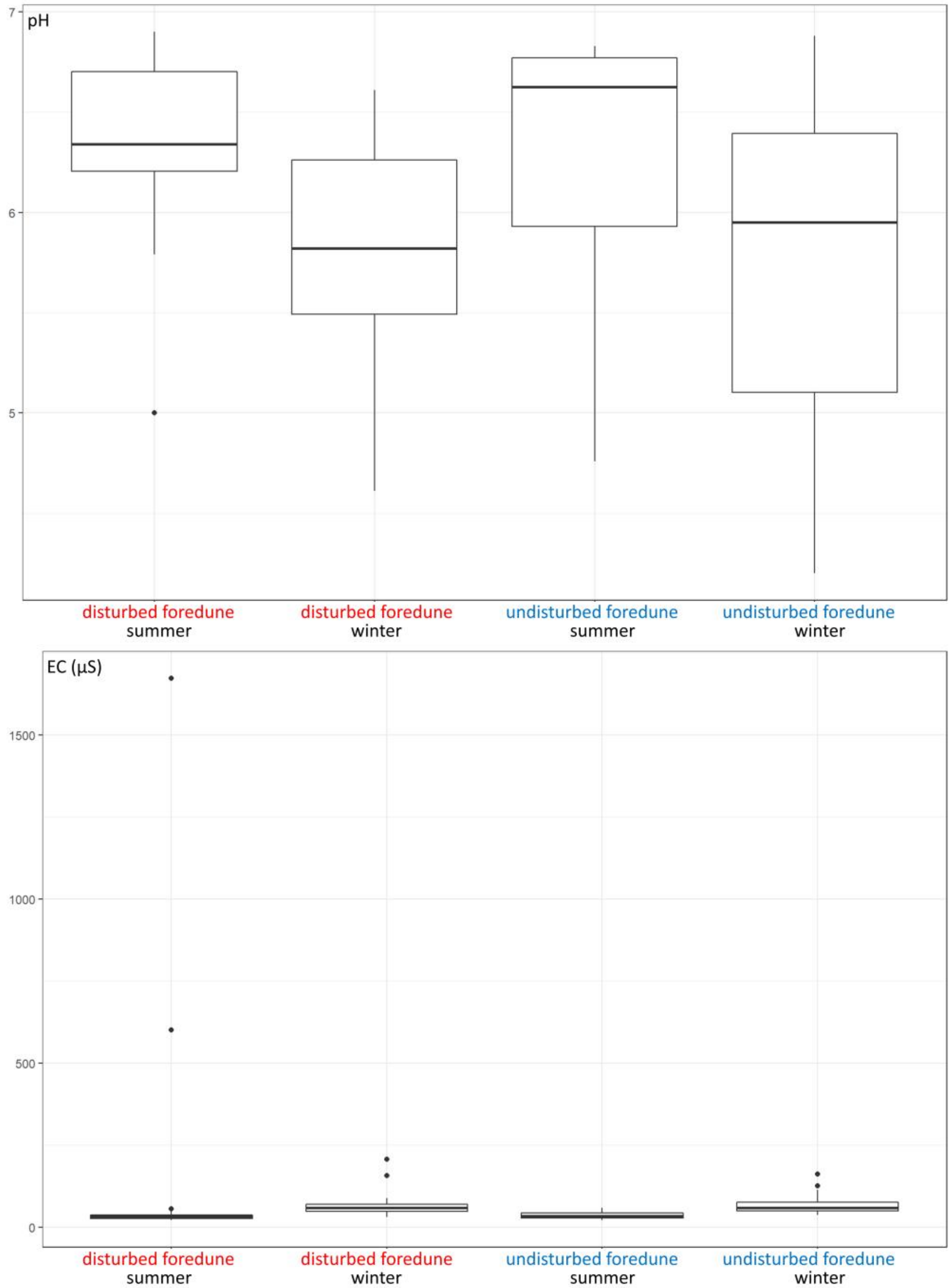
4.1.2. Changes in soil properties – an individualistic approach

With an assumption that the undisturbed foredune is in an edaphic standard state, soil properties change of the disturbed foredune is observed compared with those of the undisturbed foredune. Figure 3 shows the distributions of each soil property, and these graphs demonstrated that soil properties were different depending on the



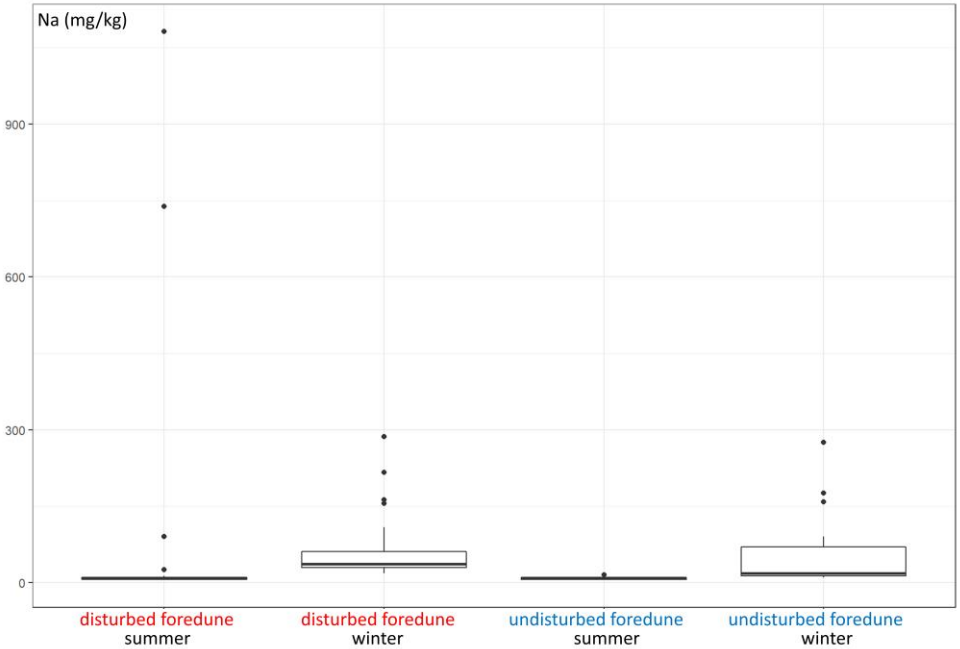
[Figure 3]

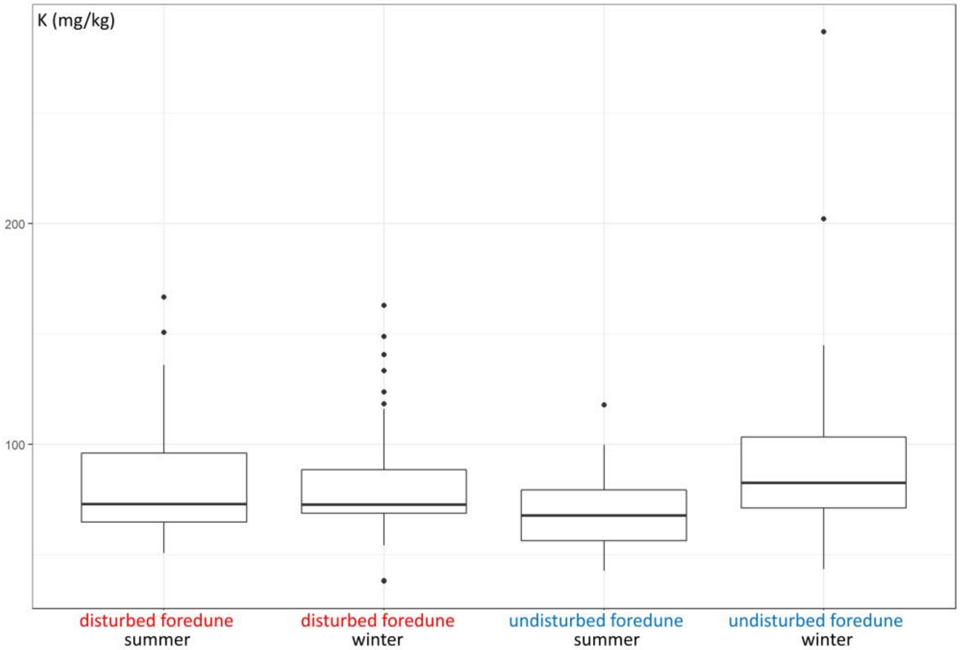
Boxplots of each soil property



[Figure 3] (continued)

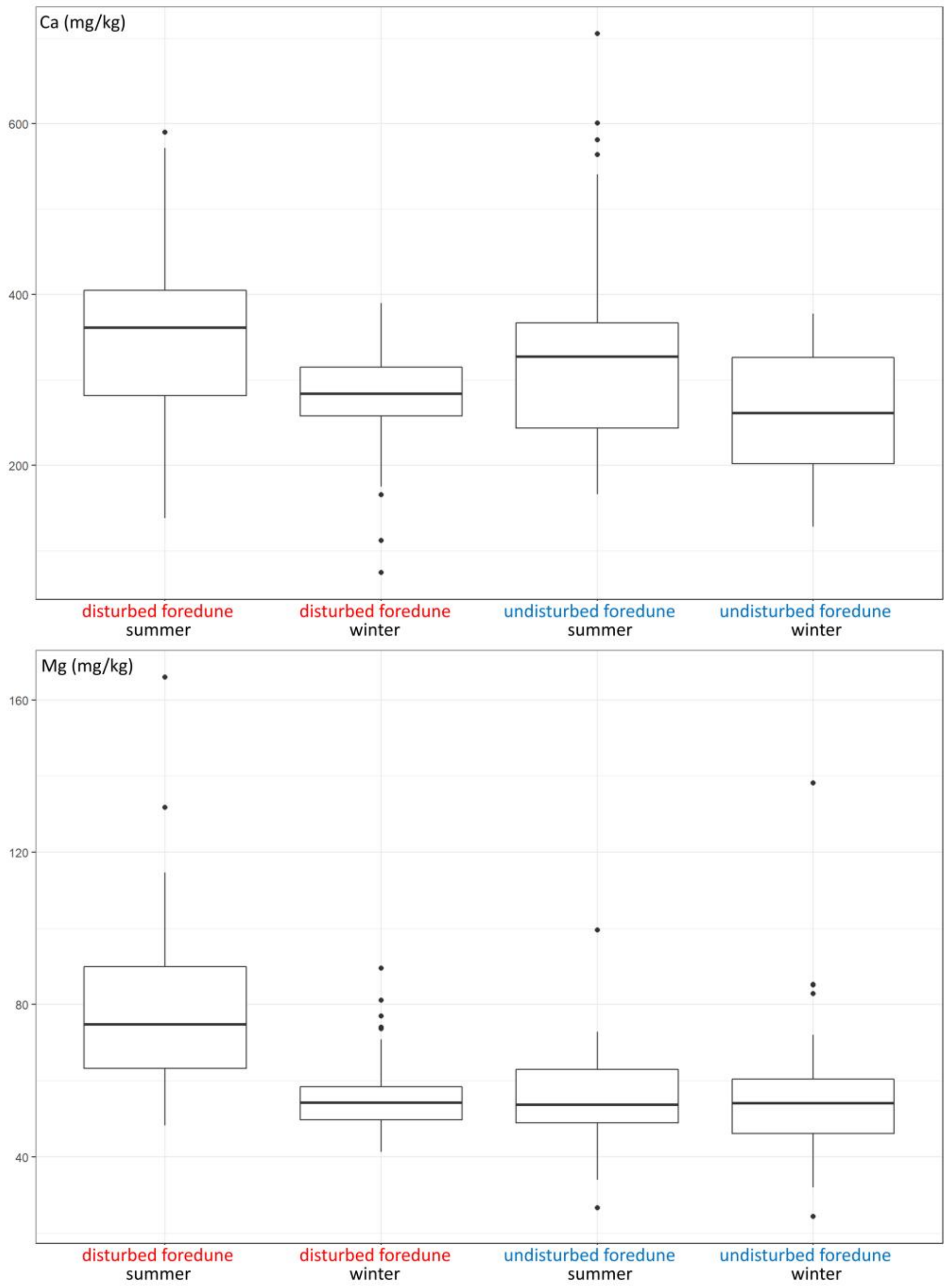
Boxplots of each soil property





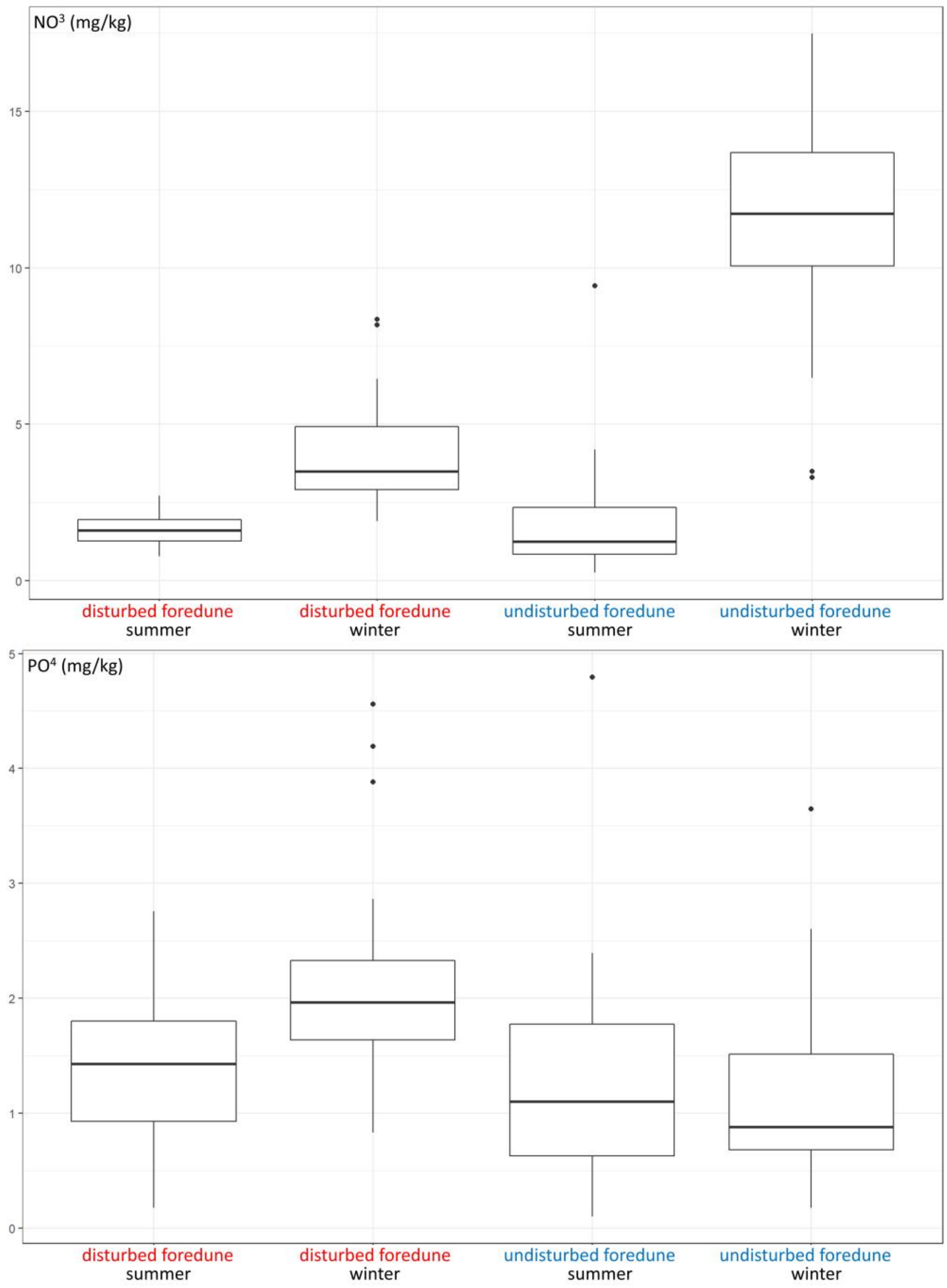
[Figure 3] (continued)

Boxplots of each soil property



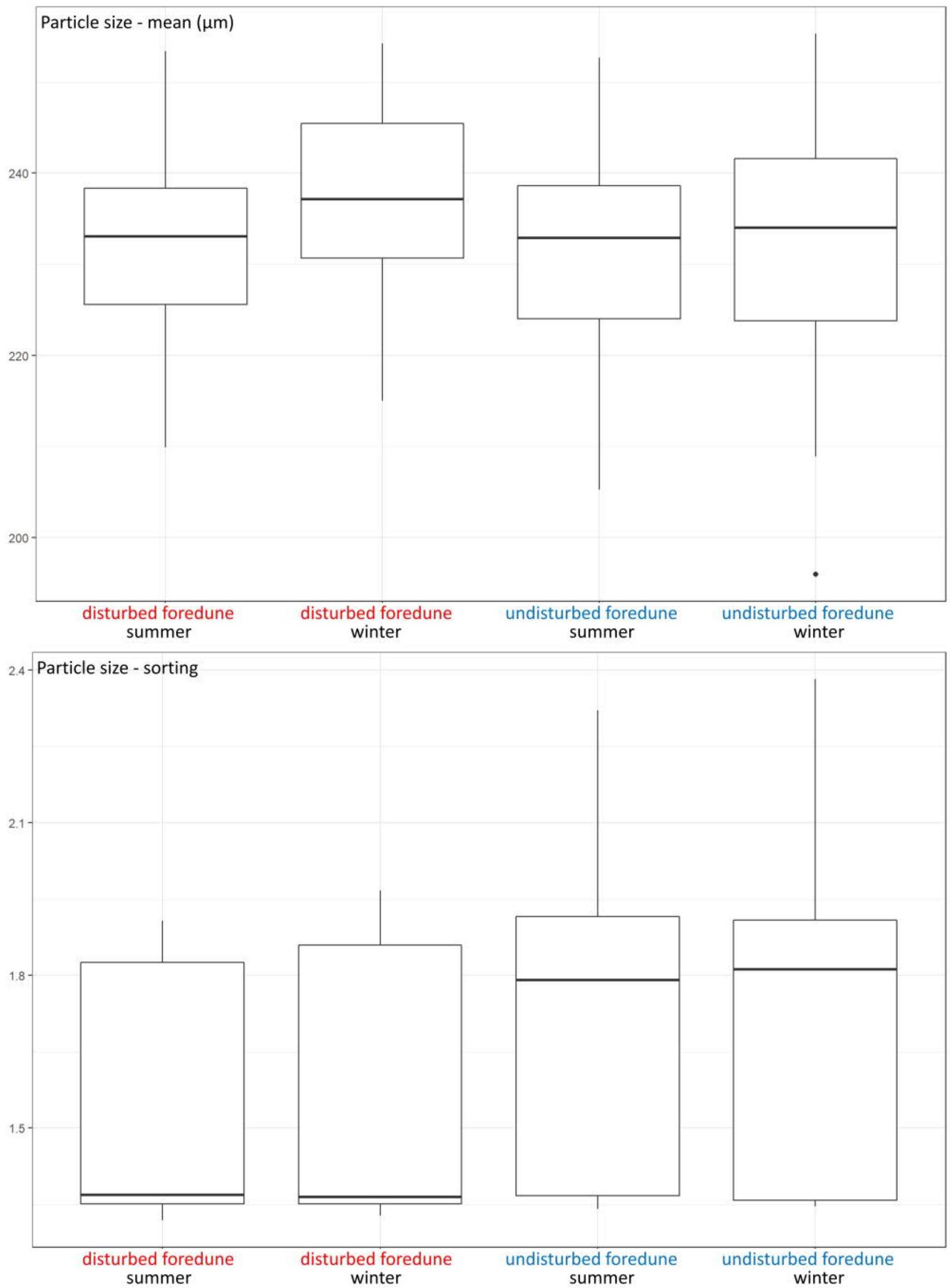
[Figure 3] (continued)

Boxplots of each soil property



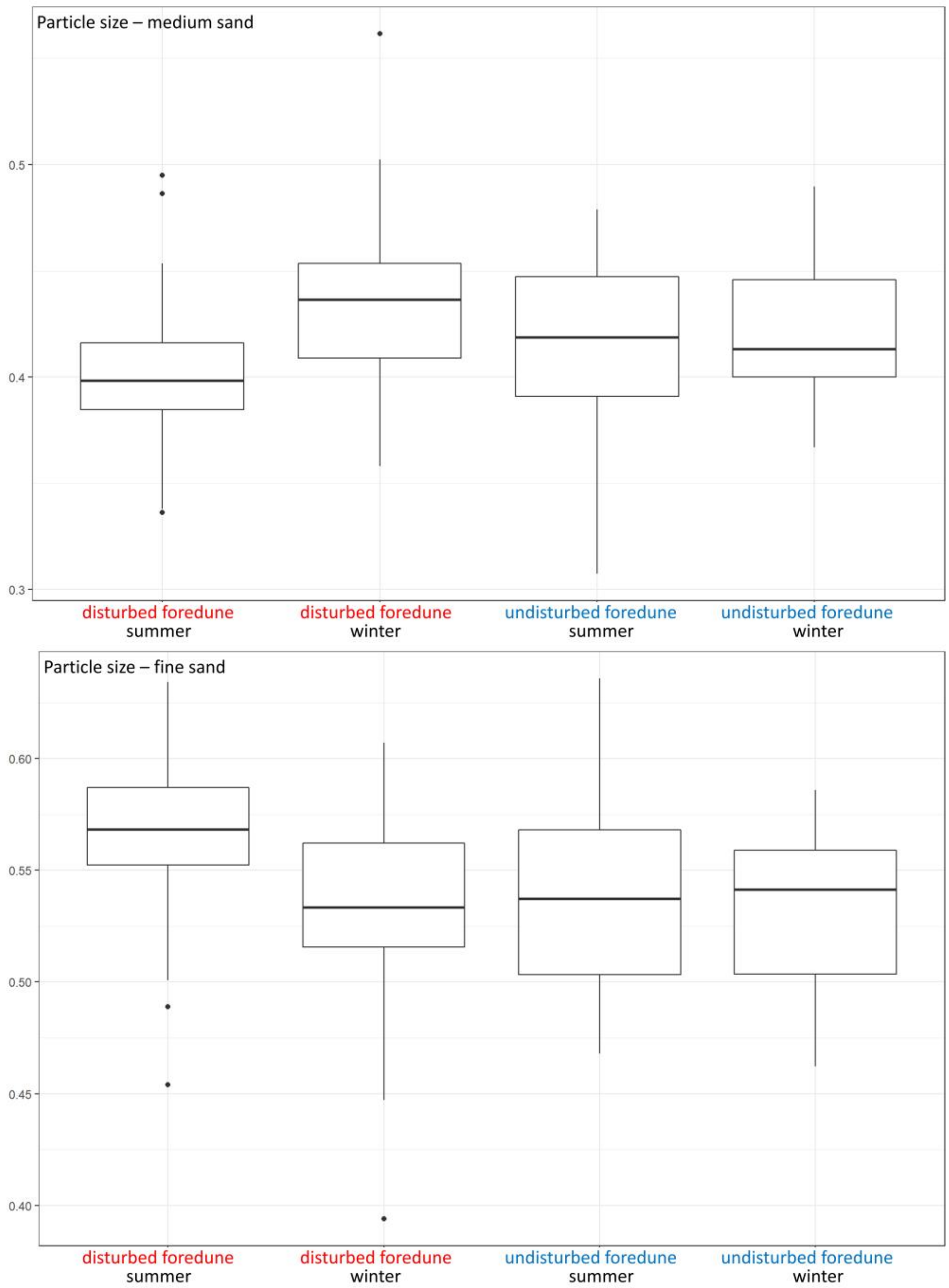
[Figure 3] (continued)

Boxplots of each soil property



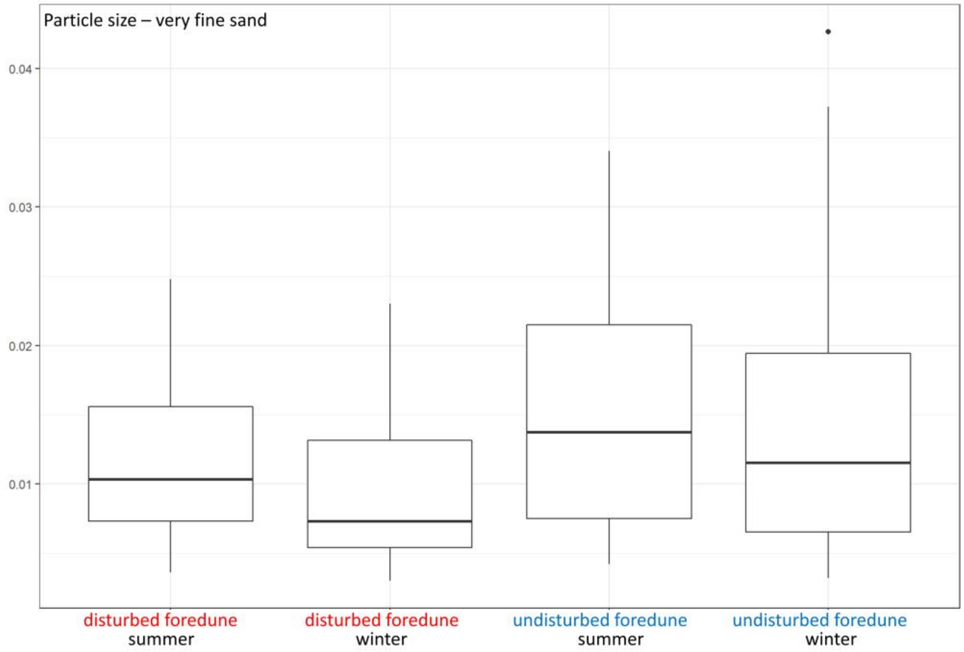
[Figure 3] (continued)

Boxplots of each soil property



[Figure 3] (continued)

Boxplots of each soil property



[Figure 3] (continued)

Boxplots of each soil property

	WINTER	SUMMER	CHANGES
Moist	0.0002	0.5730	sig >> insig
SOM	0.0132	0.3546	sig >> insig
pH	0.6158	0.4029	insig >> insig
EC	0.9714	0.4625	insig >> insig
Na	0.0084	0.6999	sig >> insig
K	0.1615	0.0148	insig >> sig
Ca	0.6737	0.1923	insig >> insig
Mg	0.7175	0.0000	insig >> sig
NO3	0.0000	0.1449	sig >> insig
PO4	0.0000	0.2986	sig >> insig
Particle size – mean	0.1410	0.9953	insig >> insig
Particle size – sorting	0.0843	0.0101	sig >> sig
Particle size – medium sand	0.0740	0.0503	sig >> sig
Particle size – fine sand	0.9858	0.0094	insig >> sig
Particle size – very fine sand	0.0533	0.1476	sig >> insig

[Table 1]

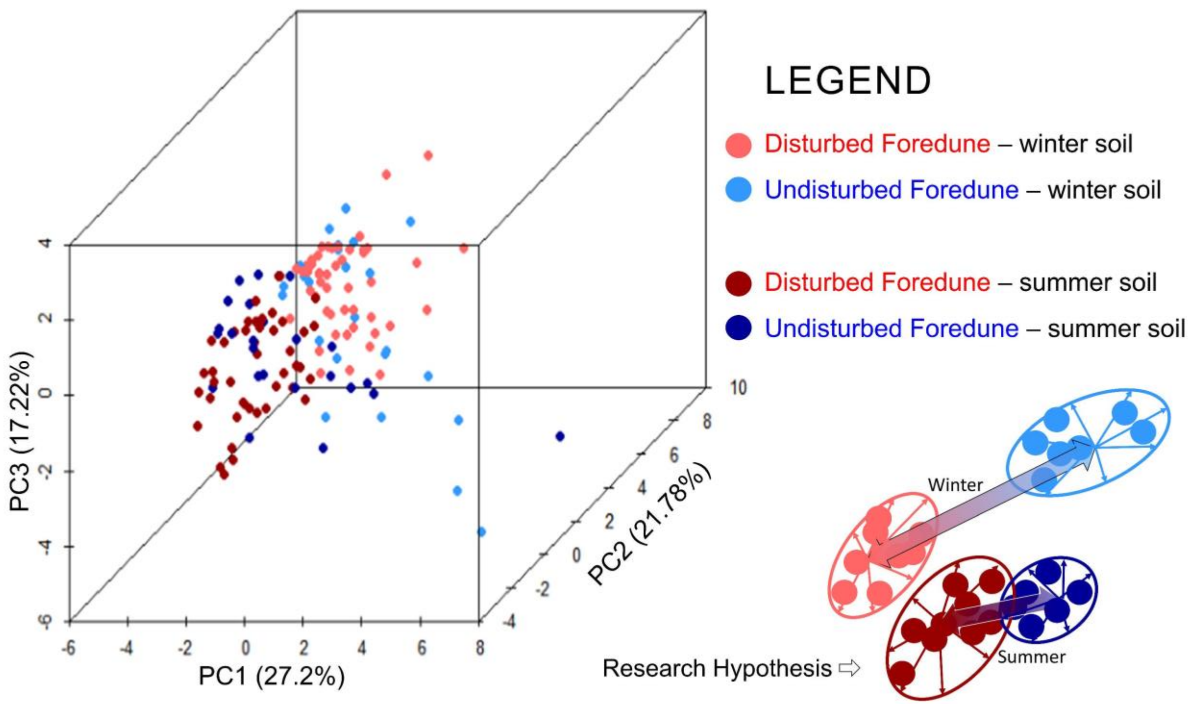
Mann-Whitney tests for soil properties of the disturbed and undisturbed foredunes

<sig> mean values showed statistically significant difference
<insig> mean values showed no significant difference

season and whether they were disturbed or not. The Mann–Whitney test was implemented to show how the disturbed foredune changed compared to the undisturbed foredune (Table 1). The results showed that five soil properties (Moist, SOM, Na^{+}, NO_3^{-}, and PO_4^{3-} in Table 1) of the disturbed foredune became resemble those of the undisturbed foredune. Six properties (pH, EC, Ca^{2+}, and Particle size – mean, medium sand, and very fine sand in Table 1) were thought to become resemble very fast (before the soil survey in winter), not disturbed at all, or determined by external factors. The other five properties (K^{+}, Mg^{+}, and Particle size – sorting and fine sand in Table 1) did not recover or changed in a different direction. More discussions for the results are presented in Chapter 5.1.1.

4.1.3. Changes in soil property – a comprehensive approach

Unlike Chapter 4.1.2, Figure 4 comprehensively showed changes in soil property of the disturbed foredune compared to the undisturbed foredune. Figure 4 visualized the result of principal component analysis with soil property data. The first, second, and third Principal Components (PCs) were selected with appropriate criteria, and their explaining variances were 27.20%, 21.78%, and 17.22% each. The eigenvalues of each PC were 1.95, 1.75, and 1.55 in order. The total explained variance of PC1, PC2, and PC3 was 66.21%.



[Figure 4]

PCA results for the soil data

Selected Principal components and their scores are presented. Closer the site scores (points), the more similar the soil property.

The position of site scores in **Figure 4** showed summarized soil property. Spatial proximity in the 3−D ordination space implies similarity of soil property: the more adjacent to each other, the more similar is the soil property.

Naturally, the soil property of the disturbed foredune in the winter (two months after the disturbance) should be different from the undisturbed foredune one. As a bulldozer disturbed the foredune, strong coupling between vegetation, geomorphology, and soil suddenly broke up, and another transient state might take place, which is entirely new.

The results of ANOSIM showed that the soil property of the disturbed foredune became resembled that of the undisturbed foredune. ANOSIM' s R for winter soil data of disturbed and undisturbed foredune was 0.203, and that for summer soil data of the two areas was 0.129. P−values of each R−value were 0.0012 and 0.0059, respectively, meaning the soil property of disturbed foredune became similar to that of the undisturbed foredune.

The individualistic approach (**Chapter 4.1.2**) is obviously more reasonable and persuasive to measure the changes in soil properties. The comprehensive approach proposed here, however, has its own strength: being able to diagnose and quantify the change in general. With study settings including standard plots and experimental plots, this method will help check the overall soil property difference between two plots of different characteristics or periods.

4.2. Plant species composition

4.2.1. Vegetation of coastal dune system

Dune plants are an essential element in an explanation for a coastal dune system. A strong coupling between vegetation, geomorphology, and soil is the traditional and widely used framework for a coastal sand dune study in Korea (see Kim, Yu, and Park, 2008, Kim and Yu, 2009, and Yu et al., 2012). Particularly, dune plants' sand retention and sand accretion effect play a significant role in hill-like geomorphology formation (Hesp, 1989; Arens, 1996; Hesp, 2002; de Jong et al., 2014). Soil amelioration by vegetation like nitrogen fixation of a leguminous plant is one example of dune plants actively transforming soil property (Kim et al., 2008). Furthermore, the distribution of vascular plants is closely related to the distribution of small animals like insects and amphibians as dense (or sparse) vegetation provides habitat or shelter to them.

The coastal sand dune, by its various definitions, is in a morphologically dynamic state. It is questionable whether a morphological dynamic is a necessary condition for a coastal dune system, but the coastal management authorities of the Sindu dune consider wind-blown sand as a necessary part of a dune. In this sense, complete devegetation and ground flattening, defined as '*disturbance*' in this research, can be '*restoration*.' Martínez et al. (2013) presented devegetation as a method to induce greater

Spp.	May		June		August		September		October	
	group	*p*-value	group	*p*-value	group	*p*-value	group	*p*-value	group	*p*-value
A.sibirica	3	0.0187	1	0.0337	1	0.0000	1	0.0000	1	0.0006
S.collina	1		1		1	0.0010	1	0.0000	1	0.0237
C.soldanella	2	0.0027	2	0.0039	2		1	0.0252	1	
C.pumila	2	0.0000	2	0.0000	2	0.0000	2	0.0000	2	0.0000
A.indica	2	0.0000	2	0.0000	2	0.0001	2	0.0009	2	0.0172
S.carolinense	2	0.0367	2	0.0052	2	0.0038	2	0.0051	NA	
P.australis	2		2	0.0280	2	0.0108	2	0.0125	2	0.0087
D.ciliaris	2	0.0422	2	0.0207	2	0.0081	2		NA	
C.epigejos	2		2		2		2		2	
L.mollis	3	0.0000	3	0.0000	3	0.0000	3	0.0000	3	0.0000
I.cylindrica	3	0.0001	3	0.0000	3	0.0002	3	0.0001	3	0.0001
R.rugosa	3	0.0004	3	0.0009	3	0.0032	3	0.0019	3	0.0015
C.canadensis	3	0.0003	3	0.0001	3	0.0000	NA		NA	

1 = disturbed foredune 2 = undisturbed duneslack 3 = undisturbed foredune NA = no species present (blank = p>0.05)

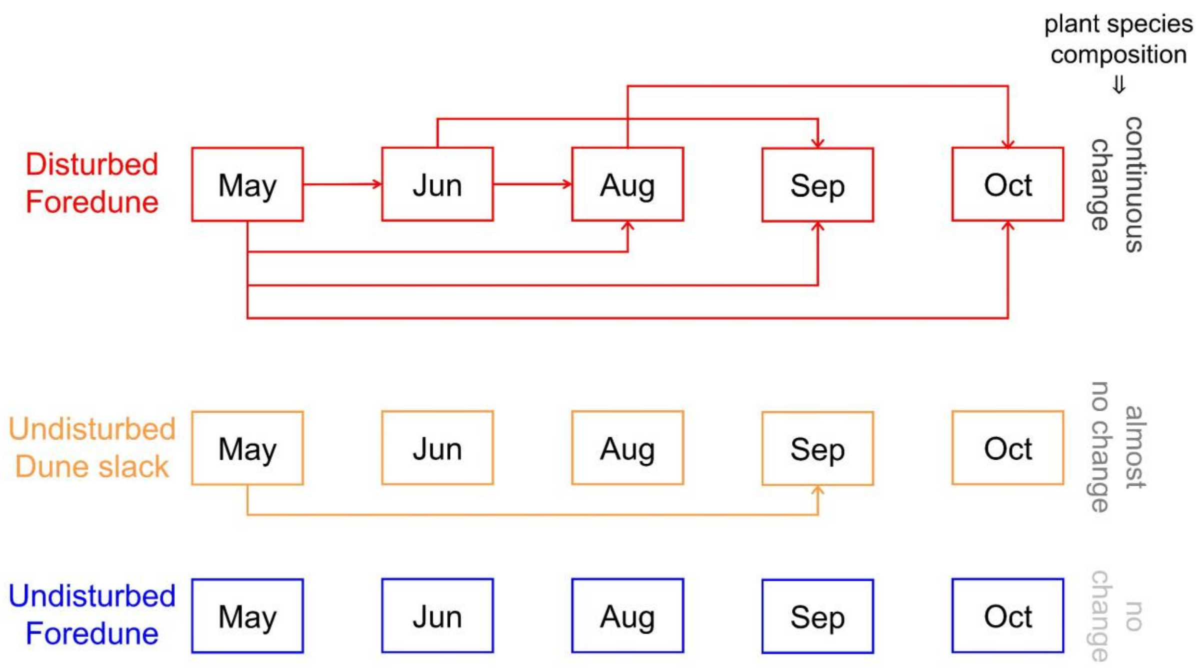
[Table 2] Indicator Species Analysis for the plant species presented aeolian activity. In this research, however, the densely vegetated dune, undisturbed state of the Sindu since the 21st century, was defined as a normal state. Bare ground like the disturbed foredune area was defined as 'disturbed' as the word itself.

4.2.2. Indicator species analysis

Indicator Species Analysis for the data from five times of vegetation survey partly, but specifically show changes in vegetation community of the three research areas (Table 2). In the disturbed foredune, *S. collina* became significant indicator species after August: it showed no significance in May and June though, meaning that the specificity and/or fidelity of the species were not high enough at that time. *A. sibirica*, once an indicator species of the undisturbed foredune in May, became the most significant indicator species of the disturbed foredune. *C. soldanella* was an indicator species of the undisturbed duneslack but became that of the disturbed foredune in September. The significances of indicator values were relatively stable in the undisturbed duneslack and the undisturbed foredune.

4.2.3. Comparing the plant species compositions of multiple groups

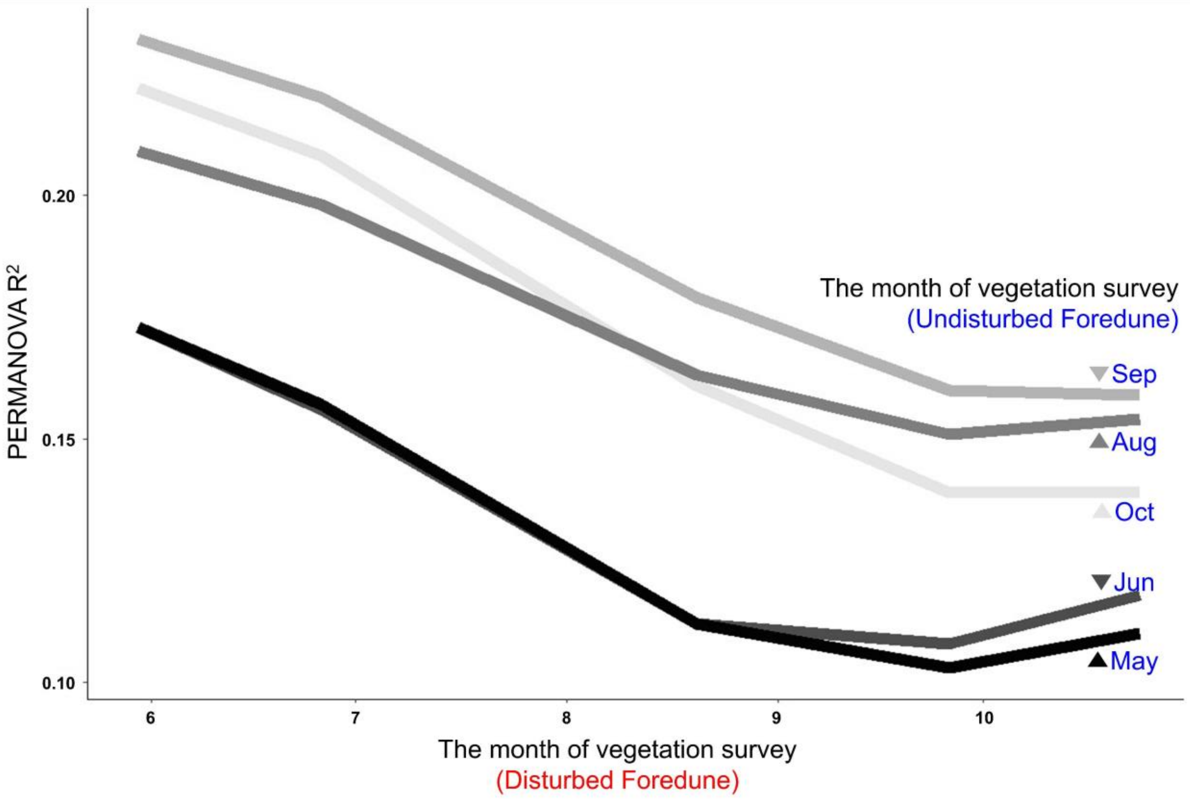
Unlike the indicator species analysis, Permutational Multivariate



[Figure 5]

PERMANOVA *p*-values for the vegetation data

Arrowed relationships show statistically significant plant species composition changes (PERMANOVA p <0.05).



[Figure 6]

PERMANOVA R^2 changes

Lower R^2 indicates higher similarity between two plant species composition

Analysis of Variance (PERMANOVA) was adopted to quantify the overall changes of plant species composition. PERMANOVA' s *p*-values (Figure 5) and R^2s (Figure 6) are presented each. Considering arrowed relationships indicate statistically significant plant species composition change in Figure 5, the undisturbed dune slack and the undisturbed foredune area showed almost no change (e.g., species composition of undisturbed dune slack in May was statistically different to that in September, but no change was captured from June to August). The disturbed foredune, in contrast, showed a quick change of plant species composition. These results imply that undisturbed areas were ecologically stable, unlike disturbed foredune.

To show the sequential change of the compositional difference between the disturbed and undisturbed foredunes, Figure 6 presents gradual changes of PERMANOVA R^2. The higher R^2 value of a PERMANOVA is interpreted as a big difference between two species data. In the same sense, the lower R^2 value indicates a more similar species composition.

The result (Figure 6) showed that species composition of the disturbed foredune (experimental plot) comes to gradually resemble that of the undisturbed foredune (control plot). To strengthen the logic, I analyzed species data of the disturbed foredune with every species data of the undisturbed foredune, surveyed in May, June, August, September, and October. Regardless of the surveyed periods, that is, the species richnesses and the vegetation cover rates of the comparing area (the undisturbed foredune), decreasing trends of PERMANOVA R^2 were observed.

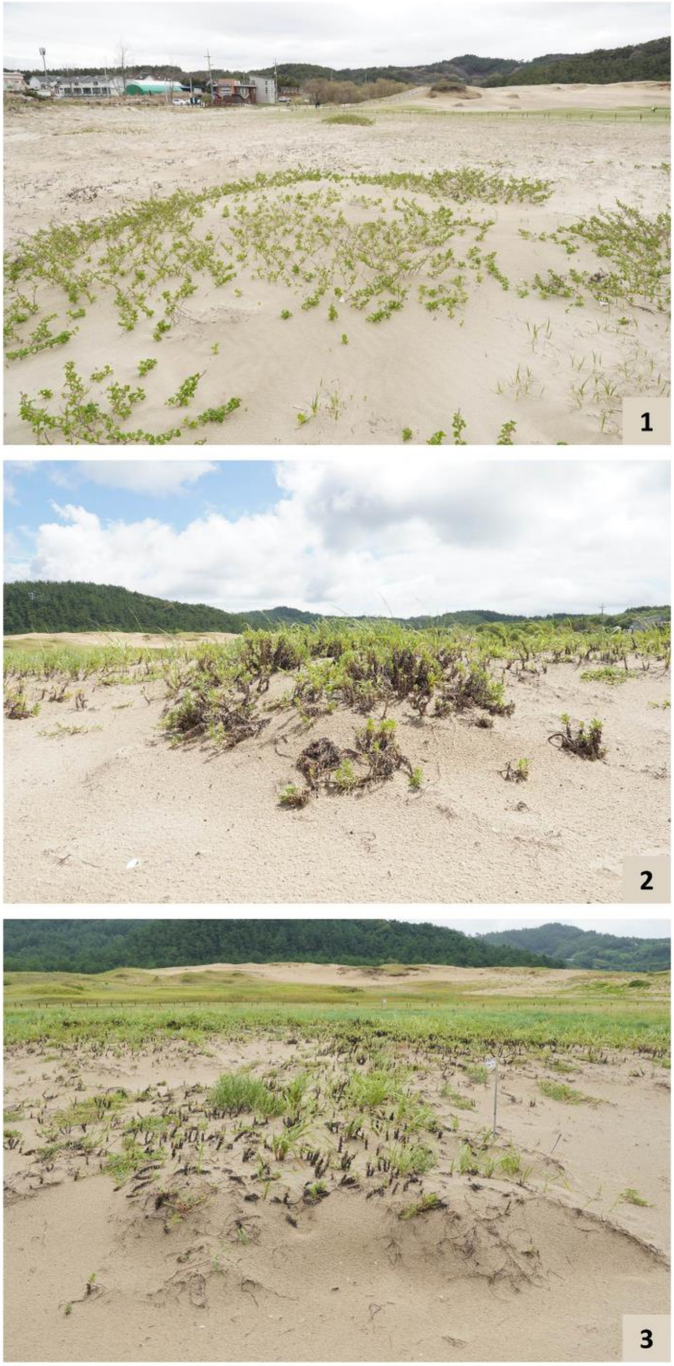
Although the indicator species analysis (Chapter 4.2.2) presented the three species exclusively introduced to the disturbed foredune area, the overall differences between plant communities of the disturbed and undisturbed foredune came to decrease. This statistical method, producing a quantitative index for the difference of two ecological community data, helps check how an experimental plot changes in comparison with a control plot.

4.3. Landforms

The artificial disturbance in October 2019 destroyed the foredune landforms of the disturbed foredune area, and the topography was completely flattened. The mean elevation of the crest at the undisturbed foredune was about 29.60m above sea level, but the mean elevation of the disturbed foredune two months after the disturbance was only 27.03m, similar to the undisturbed dune slack (26.79m).

The absence of vegetation in the "Active moving sand period (winter, *sensu* Yu et al., 2005)" induced a very high rate of erosion in the disturbed foredune area. At the same time, the eroded sands were deposited at the undisturbed duneslack under the influence of the winter northwesterly wind. In the "Inactive moving sand period (spring ~ summer, *sensu* Yu et al., 2005)", the pioneer plants entered the disturbed foredune, and erosion rate decreased, but the overall elevation of the disturbed foredune still gradually decreased through the survey period.

Besides the overall trend of decreasing elevation, some evidence slightly showed the possibility of the foredune landforms regeneration in the disturbed foredune. First, the biogeomorphic process was detected after the introduction of vegetation in the disturbed foredune area. Spearman's rho was used to detect the rank-based correlation between the sand accretion rate and the total vegetation cover. The result indicated that survey points with



[Figure 7]

Photos of the incipient foredunes

higher vegetation cover showed a higher sand accretion rate. This was still significant with partial spearman's correlation analysis controlling the distance to the coastline variable (rho = 0.343, p-value < 0.05). Given the fact that foredune morphology is initially formed with sand deposition induced by dune plants (Hesp, 1989; Hesp, 2002; Hesp, 2013), the presence of the biogeomorphic process implies the possibility of landform regeneration.

The second piece of evidence is not originated from data but from the researcher's knowledge and observation. Figures 7-1, 7-2, and 7-3 are pictures of the incipient foredunes (*sensu* Hesp, 1989) or the shadow dunes (*sensu* Bagnold, 1954). Young rugose rose (*Rosa rugosa*) individuals generated the first one, the second one by siberian sea rosemary (*Argusia sibirica*), and the third one by siberian sea rosemary and sea wheatgrass (*Leymus mollis*). These individuals, inducing sand accretion, are called nucleii (Hesp, 1989) and act as an initial builder of the foredune.

Incipient foredunes, more widely called embryo dunes, were classified into four kinds by Hesp (1989): type 1a, 1b, 2a, and 2b. Type 1a is defined as follows: "... formed by aeolian accretion within discrete annual and perennial plants which have germinated either from wind-dispersed seed or from seed contained within swash aligned drift material." The only difference between type 1a and 1b is that patched plants form the latter. Type 2a is formed by aeolian accretion in alongshore zones colonized by perennial seedlings, and vegetation usually colonizes type 2b with a rhizomestolon. Based on these explanations, Figures 7-1, 7-2, and 7-3 were all considered type 1b incipient foredune as vegetation patch formed semi-circular shaped hummock. Considering the fact that the incipient foredune later becomes fully grown foredune, incipient foredunes can be the beginning of the foredune landform regeneration.

Chapter 5. Discussion

5.1. Changes in soil, vegetation, and landforms

5.1.1. Various directions and speeds of changes in soil properties

Based on the soil survey results (Figure 3 and Table 1), changing mechanisms of each soil property were inferred.

Moist

The distribution of soil moisture in coastal dunes is usually groundwater–dependent. Lower terrain is vertically more adjacent to the water table, therefore wetter (Greaver and Sternberg, 2010). Additionally, strong solar radiation dehydrates surface soil and decreases the soil moisture content.

In these senses, the distribution of winter soil moisture could be explained by the relative elevation of the disturbed and undisturbed foredunes. In winter, as the disturbed area was obviously low, the moist content of the disturbed area was high compared to that of the undisturbed foredune. In summer, soil moisture of both foredune areas was similarly low except for some survey points (represented by outliers in the boxplot). Although the summer of Sindu is known to be the rainy season, clear and hot weather lasted for a long time before the summer soil survey. Thus the surface soil got dried regardless of whether the area was disturbed or not.

SOM

Soil organic matter of coastal dune sediment is supplied mainly by dune plants (Koojiman et al., 2020). The disturbance completely removed the above- and below-ground vegetation, and organic matters were removed hereby. This being so, the SOM of the disturbed foredune in winter was remarkably lower than that of the undisturbed foredune. In summer, however, pioneer plants were entering the disturbed area, and vegetation dynamics during the period could supply organic debris to the disturbed area.

pH

Soil pH of Sindu was irrelevant to the disturbance but showed seasonal difference instead. Many researchers discovered that the soil pH of a coastal dune is deeply related to vegetation (Averiss and Skene, 2001; Isermann, 2005). Fenu et al. (2012) presented an empirical result that the soil of the unvegetated zone was more acid, and the pH of the vegetated zone was higher.

Since the disturbance occurred in early winter, the influence of dune plants on soil pH would be minimal. Therefore, the disturbance could not make a significant difference in the pH of the disturbed foredune. In summer, when dune plants enter both disturbed and undisturbed foredune, the pH increased in both areas.

EC

The electronic conductivity of the foredune areas was seasonally different, but there was no difference between the disturbed and undisturbed areas. EC of a coastal dune usually depends on the salt spray from the ocean (Frederiksen et al., 2006). Since the disturbance occurred in the middle of a strong landward wind season, various ions from the ocean could be accumulated in the disturbed foredune just after the disturbance. In summer, in contrast, the intensity of the wind decreases, and the directions vary, so the EC of summer could be decreasing.

Na^+

Seasonally, the Na^+ content was high in winter and low in summer, and the strong landward wind mentioned earlier would be the reason. What is hard to interpret here was that the disturbed foredune in winter showed significantly higher Na^+ content than the undisturbed foredune. I hypothesize, based on the fact that Na^+ is one of the well-leaching cations in a coastal sand dune (Yu et al., 2005), the vertical disturbance of soil made underground Na^+ accumulations rise to the surface. The empirical work of Van der Valk (1974) advocates the hypothesis, showing that the Na^+ was the only cation whose output (leaching) from foredunes exceeded the input by salt spray.

K^+

The winter K^+ content in the disturbed foredune was statistically similar to that of the undisturbed foredune, but there was a gap in summer. Specifically, the summer K+ content of the undisturbed foredune decreased. Here, I hypothesized that the plant intake made the difference in that K^+ is on of essential ions to the photosynthesis of plants. The body of coastal dune plants consists of many cations (Na^+, Ca^{2+}, K^+, and Mg^+),), and of these, the content of K^+ is the largest (van der Valk, 1974). However, the K^+ amount is one of the smallest in a foredune (van der Valk, 1974; Yu et al., 2012), indicating that plant intake could be a key driver decreasing the K^+ content of dune sediment.

Ca^{2+}

The amount of Ca^{2+} was low in winter and high in summer. At the same time, there was no difference between the disturbed and undisturbed foredune. The results were hard to interpret with the limited data and knowledge since there have been attempts to interpret Ca^{2+} in Sindu with shell fragments in the mudflat across the beach (see Kim, 2004; Yu et al., 2005).

Mg^+

The amount of Mg^+ in the summer disturbed foredune was significantly high, and the rest were similar. Some unknown factors might increase the concentration in the disturbed area, and a follow-up study is needed.

NO_3^-

Due to the disturbance, the NO_3^- content significantly decreased compared with that of the undisturbed foredune. NO_3^- in a coastal dune is supplied by aerial deposition (Plassmann et al., 2008) and produced by mineralization of SOM (Cain et al., 1999). Since the disturbance removed the surface to the subsurface soil layer, deposited and formed NO_3^- would be removed simultaneously.

Seasonally, the NO_3^- content was high in winter and low in summer. This is due to the nitrate intake by dune plants (Lee et al., 1983). Since dune plants of the disturbed and undisturbed foredune intake NO_3^- during the growing season, the summer concentrations largely decreased.

PO_4^{3-}

The disturbance was thought to increase the PO_4^{3-} concentration of the disturbed foredune in winter. The precise reason is unknown, but the underground accumulation of PO_4^{3-} might come up during the vertical soil disturbance by heavy machinery. The distribution of phosphorus in Sindu has not been concretely explained (see Kim et al., 2008), except for the fact that phosphorus is not related to the ocean-derived materials (Yu et al., 2012). Cow's dung was hypothesized to be the driver of phosphorus distribution in this research, but the hypothesis was rejected.

Grain size variables

The mean size and the proportions of the medium-, fine-, and very fine-sized particles were hard to interpret. The ultimate reason for the difficulty was that less than a year was too short for the disturbed sediment size distribution to be recovered. Coastal dune sediment is usually well-sorted (Vincent, 1996; Bertoni et al., 2014) due to the continuous impacts of aeolian processes. In the disturbed foredune, however, the sorting decreased due to the disturbance and could not recover to the level of the undisturbed foredune.

5.1.2. Pioneer species of the disturbed foredune

The artificial disturbance removed all the vegetation and underground rhizome but left the seedbank on/below the ground. This being so, the successional clock of the disturbed foredune area reset, and a secondary succession began to take place. One of the primary concerns of coastal dune ecologists regarding ecological succession is identifying plant species entering the disturbed area, that is, a pioneer species (see Ciccarelli, 2015).

The Indicator Species Analysis (Table 2) identified the three species introduced to the disturbed area after the disturbance:

Argusia sibirica, *Salsola collina*, and *Calystegia soldanella*. Although all of these species were considered pioneer species by their definition (Avis and Lubke, 1996), the sources of each species varied. *A. sibirica* (Siberian sea rosemary) was the indicator species of the undisturbed foredune in May but became that of the disturbed foredune after June. Whether the species was introduced totally from the undisturbed to the disturbed foredune or not is uncertain as the disturbed area has been under the influence of pre-existing seedbank. Nevertheless, the propagules or seeds could partly disperse from the undisturbed foredune in that the northwesterly wind just after the disturbance could transfer them to the disturbed area.

S. collina (Slender Russian thistle) was an indicator species of the disturbed foredune in all months of the study period. Although the p-values went under 0.05 only after August, the specificities of May and June were regarded enough as there was almost no survey point with S. collina present other than the disturbed foredune at those months. Therefore, the existence of the seedbank at the disturbed foredune (see Hayasaka et al., 2012) could be the only reason for the *S. collina* introduction as a pioneer species.

C. soldanella (Beach morning glory) was an indicator species of the undisturbed duneslack first but became that of the disturbed foredune in September when vegetation fully entered the disturbed area. This phenomenon might occur because of the study area's wind direction difference between winter and summer. As explained earlier, the strong northwesterly wind dominates the Sindu in winter, and it is hard for a seed in the undisturbed duneslack to move to the opposite direction at that time, that is, to the disturbed foredune. However, wind regime changes after spring ~ summer, and seed dispersion from the undisturbed duneslack to the disturbed area becomes possible. Indeed, the contribution of the former seedbank should not be excluded.

5.1.3. Regeneration of foredune landforms

Unlike the ecological niche concept of Hutchinson (1957), an organism is able to (actively) modify its habitat (Jones et al., 1994), and this statement is still significant in a coastal dune study (Coreblit et al., 2015; Phillips, 2016). For instance, some dune plant species, so-called 'dune builders' like *Ammophila spp.* (Wiedemann and Pickart, 2008) collect sands delivered by the aeolian processes and provoke sedimentation, making hill-like landforms ultimately (Hesp, 2008; Psuty, 2008). In this regard, characteristics of dune plants such as plant density, plant morphology, plant shape and height, and plant distribution are dominant factors of dune landforms formation (Hesp, 2008).

This research identified three dune builder species of Sindu: rugose rose, siberian sea rosemary, and sea wheatgrass (Figure 7). The rugose rose individuals have dense branches, leaves, and a broad frontal area. The last two species, although they have relatively flexible leaves, show high patch density. These characteristics are advantageous for sand trapping. Furthermore, related quantitative result (Chapter 4.3) is one of the few fieldwork-based empirical research investigating biogeomorphic processes that occurred at coastal dunes (for a numerical model, see Durán and Moore, 2013 and for a conceptual model, see Tobias, 2015).

5.2. Monitoring methods for a disturbed coastal dune system

5.2.1. Three factors of a coastal dune system

As the present paper did, the three factors of a coastal dune system, soil, vegetation, and landforms, should be monitored and analyzed in equal importance. Obviously, vegetation has been considered one of the most critical factors of a coastal dune system. Nonetheless, most previous papers dealing with dune plants focused on one of the environmental factors determining vegetational factors. Landforms (Kahng, 2006; Song and Cho, 2007), aeolian processes (Moreno-Casasola, 1986), disturbances (Partridge, 1992), and edaphic factors (ten Harkel and van der Meulen, 1995; Berendse et al., 1998; Song et al., 2005) are commonly considered as explanatory variables in dune plant research (Bertoni et al., 2014). Despite their huge contribution to understanding a coastal dune plant community, however, these works sometimes get criticism for using only a single factor in explaining dune plants (see Durán and Moore, 2013).

Therefore, so-called multidisciplinary approaches have drawn the attention of dune scientists recently. Studies positing more than two environmental factors explaining dune plants began to appear and got more attention. Usually, edaphic factors such as moisture, SOM, or grain size distribution, and geomorphological factors such as elevation, landforms, or sedimentation characteristics are comprehensively analyzed about dune plants (Kim and Yu, 2009; Fenu et al., 2012; Bertoni et al., 2014; Ruocco et al., 2014; Green and Miller, 2019). This improvement further progressed the knowledge about coastal dune ecology but still has some possibilities for development as vegetation is considered a dependent variable of other environmental variables.

As many other researchers do, I think that plants should be considered both determined and determining factors in coastal dune study. Numerous examples show that soil, vegetation, and landform influence each other. Firstly, many studies indicate that topography is the most crucial factor determining soil properties (Jenny, 1941; Huggett and Cheesman, 2002). At the same time, soil properties such as moisture content affect an aeolian process at a coastal dune (Nolet, 2020). Next, plant species composition varies depending on topographic features (Wiedemann and Pickart, 2008). Simultaneously, the biogeomorphic process by dune plants proposed in Chapter 4.3 forms dune geomorphology (see Chapter 5.1.3). Lastly, edaphic features independently or compositely determine vegetation distribution (Swanson et al., 1988; ten Harkel and van der Meulen, 1996; Brady and Weil, 2002; Kim and Yu, 2009). Concurrently, plant physiology and dead body transform habitat soil properties like SOM or nitrogen (Berendse et al., 1998; Kooijman et al., 2020).

Therefore, any of the three factors of a coastal dune system (soil, vegetation, and landforms) is not the only explaining or explained factor. One can be considered determined, and the other determining factor with a specific study purpose. In a coastal system monitoring work with an integrative approach, however, the three factors should be studied comprehensively.

5.2.2. Suggestions on proper monitoring methods

Proper monitoring of a coastal dune system after a disturbance helps obtain valuable knowledge for coastal management and system recovery in this era of rapid disturbance regime change (Walker and del Moral, 2003; Cooper and Jackson, 2021). However, this study has insufficient data to judge the recovery due to its several limitations. Firstly, the monitoring period was too short. Another artificial disturbance at Sindu stopped the monitoring project by force, so the data were collected only for a year. Next, the soil data should have been collected more often. The soil property of Sindu changed very fast in the first year after the disturbance, and two times of survey was not enough to detect changing trend. Lastly, the monitoring should have started immediately after the disturbance. The 2019 disturbance occurred in winter when sand movement was pervasive; therefore, topography would have been changing rapidly after the disturbance. Furthermore, the soil property change would also have been changing accordingly.

With consideration of these facts, appropriate monitoring methods are proposed as follows.

(1) One of the essential requirements for a successful monitoring project for academic purposes is the proper beginning of the fieldwork. Researchers must visit their site immediately after the disturbance. That is the only way to get robust data regarding the impacts of a disturbance.

(2) For soil property monitoring, the interval between the surveys is important. Since geomorphology (an aeolian process) and vegetation both have an influence on dune sediment, it has to be monitored with consideration of the temporal scale of related factors changes. In a system where strong seasonal wind from the sea supplies ocean-derived materials, soil property varies seasonally. Therefore, a soil property survey should be conducted in a temporally intensive manner, at least for a period before the disturbed system come to stabilize.

(3) Vegetation survey also should be conducted frequently for some years after a disturbance, but the long period is more important. Even though Chapter 4.2.3 showed that the disturbed plant species composition became resemble the undisturbed one as time passes, that does not mean the community converges to the equilibrium deterministically. Long-time monitoring should be carried out to interpret vegetation change in the context of ecological succession.

(4) Many researchers have paid attention to the recovery of disturbed foredune (or barrier island) and published multiple long-time monitoring works worldwide (e.g., Pye and Blott,

2008; Hesp, 2013). For reporting the changing status of a disturbed dune, monitoring needs to be done at least on a decadal scale, considering previous research and the fact that the topographical change of a year at Sindu could not explicitly show the recovering trend. Nevertheless, intensive monitoring for a short period is still scientifically significant if accompanied by a vegetation survey. Although conceptual knowledge and models for foredune formation were widely developed by many scholars, empirical research dealing with the mechanisms of foredune recovery after a disturbance needs more attention (Houser and Hamilton, 2009). As presented in Chapter 4.3, the monthly elevation changing trend, represented by simple regression coefficients, was correlated with vegetation cover rate, and the result would not be found with yearly elevation data.

Chapter 6. Conclusions

Taking advantage of the unusual artificial disturbance at Sindu coastal dune, soil, vegetation, and topography survey were carried out for a year after the disturbance. Based on the data collected, changing factors of the coastal dune system were presented. Furthermore, original statistical methods for the ecological data collected by post–disturbance monitoring and adequate study settings were suggested.

Firstly, soil properties of the disturbed and undisturbed areas were collected two times: winter, two months after the disturbance, and summer, more than half years later from the winter survey. Changing speeds and directions varied depending on soil properties, and some explanations for the changes were given. For a future long–term monitoring study, the suggestion on intervals between each survey was proposed. Since the soil property of the coastal dune system is highly dependent on other factors such as the aeolian process and vegetation, a soil survey should be carried out based on the temporal cycles of related factors. With soil data collected for a long time, one can quantitatively show the soil property difference between two or more (spatially or temporally distinctive) groups with the statistical method presented. This method consists of Principal Component Analysis (for summarizing multiple soil variables to a few vectors) and ANOSIM (to show the difference between groups quantitatively) and can be used to detect the speed and direction of the change.

Next, plant species compositions of the disturbed and undisturbed areas were surveyed five times, one time for a month. Three pioneer species (*A. sibirica*, *S. collina*, and *C. soldanella*) were detected with Indicator Species Analysis, and the sources of each introduction were inferred. For future monitoring, the importance of the longtime study was stressed. The temporal scale of the ecological succession was far more than a year; therefore, a frequent survey is less significant than a long study period. Permutational Multivariate Analysis of Variance, also known as PERMANOVA, helps quantitatively show species compositional differences between multiple groups. With the statistical method presented, the plant species compositions of the experimental plot (the disturbed foredune) were compared with those of the control plot (the undisturbed foredune).

Lastly, the geomorphological survey was carried out once a month. Although one year was too short to show the recovery of foredune landforms clearly, the biogeomorphic process building hill-like topography was detected, and an incipient stage of the foredune formation was observed. The former result could be derived from frequent elevation surveys accompanied by vegetation surveys. Nevertheless, like many other dune monitoring studies, long-term monitoring would reveal a complete landform regeneration.

The three factors, soil, vegetation, and landforms, interact with each other and constitute a coastal dune system. Therefore, categorizing some factors as determining variables and others as determined variables should be avoided, at least in a comprehensive, integrative dune study. With proper study materials, collected by proper monitoring method, and analyzed with appropriate statistical methods, the dune study will provide helpful knowledge for coastal management in this era of rapid disturbance regime change.

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국문초록

천연기념물 제 431호로 지정된 신두리 해안사구에서 지난 2019년 10월, 유례를 찾아볼 수 없는 대규모 인위적 교란이 발생하였다. 전사구 약 1.2ha에 달하는 구역에 대해 완전한 식생 제거 및 지형 평탄화 작업이 진행되었다. 본 연구에서는 해당 사건의 결과가 washover과 같은 자연적 교란의 결과와 유사하다고 판단하였고, 교란 이후 해안사구 시스템이 변화하는 과정을 추적하였다.

교란 이후 교란된 전사구의 생태적·지형적 변화를 연구하기 위해 교란되지 않은 대조군을 설정하였고, 연구지역에서 1년 간 토양·식생·지형 자료를 수집하였다. 해안사구에서의 일반적인 교란 연구는 식생 혹은 지형에만 관심을 두지만, 본 연구에서는 해안사구 시스템을 구성하는 중요한 세 가지 요인들을 모두 고려하였다.

본 연구는 크게 세 가지 내용을 제시한다. 첫 번째로 각 요인들의 변화를 설명하였다. 교란된 전사구의 토양 성질들은 다양한 속력과 방향으로 변화하였다. 식생 자료 분석 결과, 교란 이후 세 개의 초기 천이종이 확인되었다. 연구 기간이 짧아 전사구 지형이 완전히 회복되는 것을 관찰하지는 못했지만, 지형 회복에 필요한 생물지형학적 프로세스와 지형 회복의 초기 단계를 확인하였다. 다음으로 수집된 자료를 분석하는 통계적 방법론을 제시하였다. 여러가지 다변량 분석 기법들을 새롭게 조합하고 해석하여 교란된 해안사구에서 새로운 함의를 도출할 수 있도록 하였다. 마지막으로 본 연구의 한계를 고려한 새로운 장기간의 모니터링 방법론을 제시하였다.

이처럼 적절한 대상(토양·식생·지형)을 적절한 방법으로 모니터링하여 적절하게 분석한다면, 기후변화의 맥락 속에서 교란의 위협을 받는 해안시스템을 보전하고 관리하는 데 도움을 줄 수 있다.