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*Brief Report*

# Spatial Distribution of Sea Salt Deposition in a Coastal *Pinus thunbergii* Forest

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Received: 14 August 2020; Accepted: 22 September 2020; Published: 25 September 2020

**Abstract:** We investigated the sea salt deposition process on the soil in a coastal black pine (*Pinus thunbergii* Parlatore) forest in Japan with reference to sea salt scavenging by the forest canopy and the following washout by precipitation. We collected throughfall and soil-infiltration water along transects crossing the coastal forest and measured the water chemistry—electric conductivity, pH, major cations ($NH_4^+$, $Na^+$, $K^+$, $Mg^{2+}$, and $Ca^{2+}$), major anions ($Cl^-$, $SO_4^{2-}$, $NO_2^-$, $NO_3^-$, and $PO_4^{3-}$), and total organic carbon—at 10-m intervals on the survey transects. Leaching of base cations from surface soil kept lower acidity of soil water in the evergreen broadleaf forest, whereas soil infiltration water was acidified in the soil surface in the *P. thunbergii* forest. Hot spots of sea salt deposition on the soil surface were observed at hollows of the ground surface, slope-facing coastal line, or sites with an abrupt increase in height where the canopy faces the coast. However, the edge effect in sea salt scavenging was not evident in the juvenile stand at the forest edge, which had a height of <5 m. The sea salt deposition was only evident in the coastal black pine forest with canopy height >10 m.

**Keywords:** coastal sand dune; Japanese black pine; evergreen broadleaf forest; sea salt; throughfall; soil infiltration water

## 1. Introduction

Sea salt transport by wind and consequent accumulation in soil form one of the disturbances in coastal ecosystems [1,2]. The impact of sea salt on soils and vegetation in coastal ecosystems has been reported throughout the literature [3–6]. When sea salt was transferred inland, the effect of sea salt on terrestrial ecosystems was evident 20–50 km from the coastline [1,7,8], and sea salt has been detected as much as 230 km from the coastline [9]. Because of the salinization and acidification of soil and the consequent impact on vegetation, protection forests have been established for sea salt scavenging and to prevent sea salt transport to inland ecosystems.

To prevent the harmful effect of sea salt spray accompanied by a strong wind, as well as to prevent sand movement on coastal sand dunes, Japanese black pine (*Pinus thunbergii* Parlatore), one of the common evergreen coniferous species, has been planted to form protection forests [10]. Since ca. 1930, coastal forests in Japan have declined because of harmful nematodes, such as *Bursaphelenchu xylophilus* (Steiner and Buhrer) Nickle, in the host of *Monchamus alternatus* Hope [11]. Forest stands with evergreen broadleaf species have been established within *Pinus* forests, and succession to broadleaf forests is evident. Considering the function of coastal *Pinus* forests to prevent sea salt disturbances, *P. thunbergii* coastal dune forests are considered one of the ecosystems that should be protected. To evaluate the sea salt scavenging function of coastal *Pinus* forest, chemical processes of sea salt transfer from atmosphere to soil should be clarified including the spatial heterogeneity within coastal forests by comparing the different types of forest stands. However, investigation focusing on the spatial heterogeneity of the sea salt deposition process in Japanese coastal forest has not appeared in the literature. Thus, we investigated the chemical processes of sea salt deposition in the Sanri-Matsubara Forest including *Pinus* forest and evergreen broadleaf forest, and establishing on a coastal sand dune with topographic heterogeneity.

Sea salts including aerosols originate from seawater, disperse into the atmosphere by drying, and are transported to terrestrial ecosystems by wind flow. Some aerosol particles are trapped in the foliage or trunks of forests near coastal zones. Deposited sea salts are washed out by precipitation and seeped into the soil. Thus, the soil's chemical environment is affected by sea salt deposition and washout processes of the forest. We determined the sea salt concentration in throughfall and soil water as a function of distance from the coastline, as well as the species composition of stands: *P. thunbergii* stands and evergreen broadleaf forest stands dominated by *Ligustrum japonicum* Thunb, *Cinnamomum tenuifolium* Sugimoto, *Cinnamomum camphore* (L.) J. Presl, and *Celtis sinensis* var. *japonica*. We surveyed on a transect perpendicular to the coastal line and clarified the spatial differences of sea salt deposition in the *P. thunbergii* forest and the evergreen broadleaf forest. The objective of our study was to clarify the spatial difference of the sea salt deposition process on the soil with reference to vegetation and topography by determining the spatial heterogeneity of the sea salt scavenging function by coastal forests.

## 2. Materials and Methods

### 2.1. Study Site

The Sanri-Matsubara Forest is one of the largest coastal *P. thunbergii* forests on the sand dunes of northern Kyushu Island in southwestern Japan (Figure 1). The forested area range 6 km along the coastline and the maximum width is 1.3 km. The total area of the forest is ca. 4.3 km$^2$. The north part of the Sanri-Matsubara Forest faces the Hibikinada Sea. Other than *P. thunbergii*-dominated stands, stands dominated by *L. japonicum*, *C. tenuifolium*, *C. camphore*, and *C. sinensis* var. *japonica* have been established mainly in the inland part of the Sanri-Matsubara Forest.

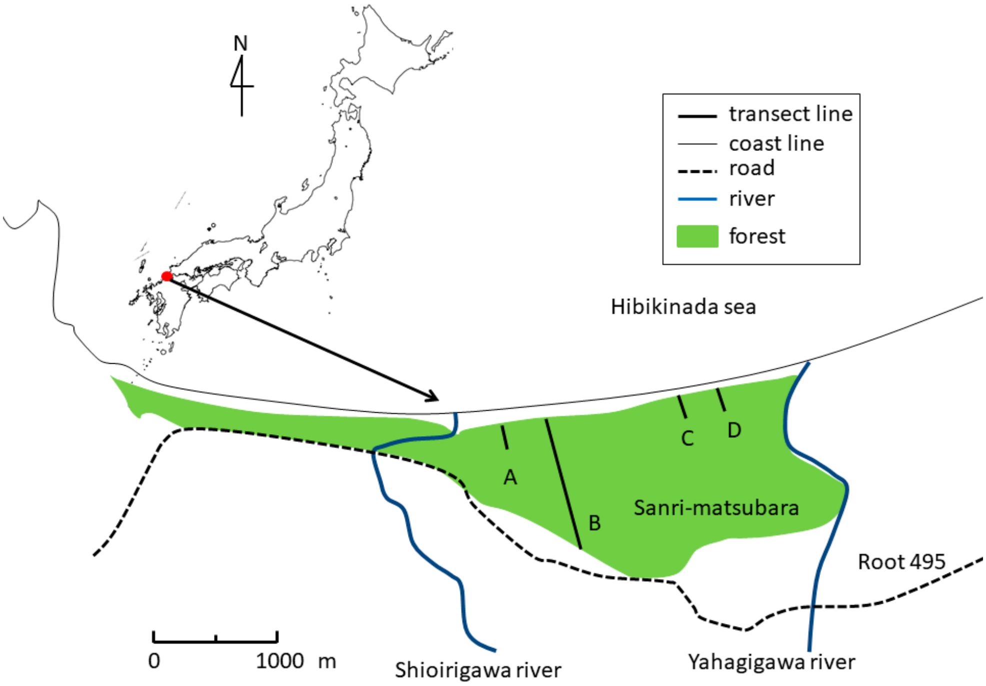

**Figure 1.** Map showing the location of Sanri-Matsubara forest, south-western Japan, and the position of survey transects (**A**: 300 m; **B**: 1040 m; **C**: 340 m; and **D**: 300 m) established in the coastal forest on the Sanri-Matsubara Forest. Survey transects were established on the coastal forest perpendicular to the coastline. Sampling points were located at 10 m intervals on the survey transects.

### *2.2. Field Survey*

#### 2.2.1. Survey in 2010 (Preliminary Survey)

We first established a transect of 1040 m in length (later called as transect B; starting from 33.87882° N, 130.61080° E, 15 m a.s.l.) in July 2010 (Figure 1), which extended across the Sanri-Matsubara Forest from the coastal end to the inland margin. We located 105 sampling points on the transect. and then we started sampling on 03 August 2010 and continued until 02 December 2010.

Throughfall and soil water were collected 10 times from 03 August to 02 December 2010—after every precipitation event. We collected throughfall and soil water samples the day after every precipitation event. Values of pH and electric conductivity (EC) were measured for samples collected after 10 precipitation events. Concentrations of major ions were determined for one precipitation event on 24 September 2010. We surveyed topography and vegetation from November 2010 to February 2011. Measurements (height, diameter at breast height, position, species) were made only of individual trees with foliage over the precipitation collector (height > 0.5 m).

#### 2.2.2. Survey in 2011–2012

We established four transect lines from the coastal edge of the forest in an inland direction almost perpendicular to the coastline (Figure 1). The four lines were located parallel to one another and named transects A, B, C, and D from west to east. We located sampling points at 10-m intervals on each line. Transect A (300 m in length with 31 sampling points; starting from 33.87843° N, 130.60745° E, 12 m a.s.l.) was set up in July 2011 and started collecting samples on 22 July 2011. Transect B (550 m in length with 56 sampling points; starting from 33.87882° N, 130.61080° E, 15 m a.s.l.) was set up in April 2011 and started collecting samples on 28 April 2011. Transect C (340 m length with 35 sampling points; starting from 33.88052° N, 130.62100° E, 14 m a.s.l.) was set up in October 2011 and started collecting samples on 6 October 2011. Transect D (300 m in length with 31 sampling points; starting from 33.88110° N, 130.62417° E, 0 m a.s.l.) was set up in August 2011 and started collecting samples on 5 August 2011. The final sample on the four transects was taken on 17 December 2012.

Throughfall was collected along transects from the first precipitation event after the establishment of each transect until 17 December 2012 at every precipitation event (27 times for transect A, 29 times for transect B, 21 times for transect C, and 25 times for transect D). We collected throughfall samples on the next day after the end of the rain.

Harvest of trees was planned on part of transect A in 2012, and then the measurement of trees with foliage over the precipitation collector was made before the harvest. Every tree (height > 0.5 m) was measured on part of transect A (with a 150- to 230-m range), and the whole range of transects C and D was measured. As for transect B, data of the survey in 2010 were used.

### *2.3. Sampling Methods of Throughfall and Soil-Infiltration Water*

Throughfall and soil-infiltration water was collected by bottles fitted with a plastic funnel (9 cm in diameter). Each collector bottle (250 mL) of throughfall was placed on the forest floor vertical to the soil surface. Each bottle was shielded with a plastic net (1 mm mesh) to exclude debris. Each collector bottle of soil-infiltration water was buried in the soil at a depth that the funnels openings were placed at the mineral soil surface (depth = 0 cm) and a depth of 10 cm. Each funnel was filled with mineral soil at each site carefully keeping horizons. The litter layer was placed over the funnel to keep the original condition. The volume of water in each collector was measured and transferred to the laboratory stored in a cool box.

### *2.4. Topography and Vegetation*

The elevation of each sampling site along the transect relative to the origin of each transect was measured with a digital theodolite (DT-114, Topcon, Tokyo, Japan). Species, height, diameter at breast height (DBH), and coordinates at the base of each tree within a 10-m width along the transects (5 m on both sides from each transect line) were measured. If there was a branching of stems below 1.3 m in height, every stem was measured.

### *2.5. Chemical Analysis*

EC (electric conductivity) and pH were measured in the laboratory within 24 h after sampling with meters for EC (D-54, Horiba, Kyoto, Japan) and pH (D-52, Horiba, Kyoto, Japan). Samples were filtered with a 0.2-µm cellulose acetate membrane filter (Advantec, Tokyo, Japan). The major cations ($NH_4^+$, $Na^+$, $K^+$, $Mg^{2+}$, and $Ca^{2+}$) and major anions ($Cl^-$, $NO_2^-$, $NO_3^-$, $PO_4^{3-}$, and $SO_4^{2-}$) were then analyzed by an ion chromatograph (DX-120, Dionex). The total organic carbon (TOC) concentration was determined for a nonfiltered water sample by a TOC analyzer (TOC-VCSH, Shimadz, Kyoto, Japan).

## **3. Results**

### *3.1. Throughfall and Groundwater Chemistry (Preliminary Survey in 2010)*

The *P. thunbergii*-dominated canopy was established in zones of 0–180, 300–370, and 480–1040 m, whereas the canopy with evergreen broadleaf trees dominated zones of 180–300 and 370–480 m in transect B. A forest stand with 6-year-old (in 2010) *P. thunbergii* juveniles of <10 cm in DBH (<5 m in height) was established within 20 m of the coastal edge of the forests, and DBH increased to 50 cm (23 m in height) 180 m from the coastal edge. Evergreen broadleaf shrubs of <10 cm in DBH (3 to 4 m in canopy height; *Euonymus japonicus* Thunb, *Elaeagnus pungens* Thunb, *L. japonicum*, and *Pittosporum tobira* Thunb) were established under the *P. thunbergii* canopy in a zone of 20–100 m.

Throughfall and soil water pH and EC were determined for samples collected after 10 precipitation events at every site (from 03 August to 02 December 2010). Concentrations of major ions were determined for one precipitation event on 24 September 2010. About 22% of data were missing because of the destruction of the water-sampling apparatus, mainly caused by disturbance by wild animals.

The value of EC showed significant linear regression with $Na^+$ and $Cl^-$ concentrations in both throughfall and soil infiltration water ($p < 0.001$) implying that EC is a measure of sea salt content in precipitation and soil infiltration water in the Sanri-Matsubara Forest (Table 1). Thus hereafter, the EC value of water was used as a proxy of sea salt concentration in precipitation and soil-infiltration water in the Sanri-Matsubara Forest. Regression coefficients were not significantly different between throughfall and soil infiltration water both for $Na^+$ and $Cl^-$, whereas residuals were significantly different between throughfall and soil infiltration water.

**Table 1.** Linear regression of electric conductivity (EC (mS/m); dependent variable: y; log transformed) and $Na^+$ and $Cl^-$ concentrations of throughfall or soil-infiltration water (independent variable: *x*). Data on 24 September 2010 were used.

| Independent Variable | Sample | Regression | n | Significance |
|---|---|---|---|---|
| $Na^+$ (mg/L)<br>(log-transformed) | Throughfall | $y = 0.892^a x + 0.062^A$ | 86 | *** |
| | Soil infiltration water | $y = 0.931^a x + 0.216^B$ | 86 | *** |
| $Cl^-$ (mg/L)<br>(log-transformed) | Throughfall | $y = 0.913^a x - 0.190^A$ | 86 | *** |
| | Soil infiltration water | $y = 0.879^a x + 0.056^B$ | 86 | *** |

The significance level of the regression coefficient: *** $p < 0.001$. Values of the regression coefficient and residual sharing the same letter were not significantly different between throughfall and soil infiltration water.

The value of pH in soil infiltration water was significantly lower than in throughfall both in the *Pinus* stand and in the evergreen broadleaf forest (Table 2). The EC and concentrations of $K^+$, $Mg^{2+}$, $Ca^{2+}$, $NO_3^-$, $SO_4^{2-}$, and TOC of soil water were significantly higher than those of throughfall both in the *Pinus* stand and in the evergreen broadleaf forest. Concentrations of $Na^+$ and $Cl^-$ in soil water were significantly higher than those of throughfall in the evergreen broadleaf forest, whereas those in soil infiltration water and throughfall were not significantly different in the *Pinus* stand. Concentration of $NH_4^+$ in soil infiltration water and in throughfall were not significantly different both in the *Pinus* stand and in the evergreen broadleaf forest.

**Table 2.** Chemical variables of throughfall and soil infiltration water in the Sanri-Matsubara forest.

| | ***Pinus thunbergii* Forest** | | | |
|---|---|---|---|---|
| | **Throughfall** | **Soil Infiltration Water** | **N** | **Significance** |
| pH | 5.18 ± 0.70 | 5.09 ± 0.70 | 491 | ** |
| EC (mS $m^{-1}$) | 11.48 ± 16.48 | 18.00 ± 23.22 | 497 | *** |
| $Na^+$ (mg $L^{-1}$) | 6.01 ± 5.51 | 6.31 ± 6.40 | 59 | NS |
| $K^+$ (mg $L^{-1}$) | 1.81 ± 3.58 | 2.91 ± 1.90 | 59 | *** |
| $Mg^{2+}$ (mg $L^{-1}$) | 0.89 ± 1.60 | 2.11 ± 3.67 | 59 | *** |
| $Ca^{2+}$ (mg $L^{-1}$) | 1.31 ± 1.33 | 4.69 ± 8.43 | 59 | *** |
| $NH_4^+$ (mg $L^{-1}$) | 0.32 ± 0.81 | 0.44 ± 0.66 | 59 | NS |
| $Cl^-$ (mg $L^{-1}$) | 11.01 ± 10.45 | 11.65 ± 14.10 | 59 | NS |
| $NO_3^-$ (mg $L^{-1}$) | 1.76 ± 1.29 | 9.66 ± 23.48 | 59 | *** |
| $SO_4^{2-}$ (mg $L^{-1}$) | 3.58 ± 4.84 | 4.96 ± 3.86 | 59 | *** |
| TOC (mg $L^{-1}$) | 5.76 ± 4.03 | 21.35 ± 8.68 | 59 | *** |
| | **Evergreen Broadleaf Forest** | | | |
| | **Throughfall** | **Soil Infiltration Water** | **N** | **Significance** |
| pH | 5.76 ± 0.62 | 5.58 ± 0.70 | 156 | ** |
| EC (mS $m^{-1}$) | 10.81 ± 11.48 | 23.69 ± 15.76 | 157 | *** |
| $Na^+$ (mg $L^{-1}$) | 5.24 ± 3.78 | 10.76 ± 8.43 | 16 | *** |
| $K^+$ (mg $L^{-1}$) | 3.87 ± 2.21 | 10.08 ± 6.87 | 16 | *** |
| $Mg^{2+}$ (mg $L^{-1}$) | 0.76 ± 0.53 | 5.60 ± 3.28 | 16 | *** |
| $Ca^{2+}$ (mg $L^{-1}$) | 1.96 ± 0.96 | 25.79 ± 16.15 | 16 | *** |
| $NH_4^+$ (mg $L^{-1}$) | 0.17 ± 0.09 | 0.34 ± 0.72 | 16 | NS |
| $Cl^-$ (mg $L^{-1}$) | 10.58 ± 7.46 | 18.70 ± 14.54 | 16 | *** |
| $NO_3^-$ (mg $L^{-1}$) | 2.54 ± 1.50 | 64.23 ± 43.15 | 16 | *** |
| $SO_4^{2-}$ (mg $L^{-1}$) | 3.17 ± 1.56 | 12.79 ± 9.27 | 16 | *** |
| TOC (mg $L^{-1}$) | 6.94 ± 5.34 | 23.74 ± 9.00 | 16 | *** |

EC: electric conductivity Means ± SD were shown. Differences between throughfall and soil infiltration water were tested by Wilcoxon signed-rank test. Data on 24 September 2010 among 8 times of sampling from 31 August to 12 November 2010 were used for ion concentration and TOC. Significance level: *** $p < 0.001$, ** $p < 0.01$, NS, no significance.

### *3.2. Forest Structure and Sea Salt Deposition (Survey in 2011–2012)*

There was a sand dune near the coastline on every transect, and the top of the sand dune corresponded to the forest edge. The elevation was found relative to the origin of each transect (the coastal end of each transect). Transect A had an elevation profile of a steep slope-facing inland ca. 40 m from the coastal end, a flat between 40 and 100 m, and then a gentle slope facing the ocean side from the 100-m point inland (Figure 2a). Transect B had a profile with a sand dune between 40 and 70 m and then a gentle slope facing the ocean side from the 70-m point inland (Figure 2b). Transect C had a profile of a gentle slope facing the ocean side from the 20-m point inland (Figure 2c). Transect D had a profile with the top of a sand dune at 100 m and then flat from the 140-m point inland (Figure 2d).

The forest on the four transects consisted of a *P. thunbergii* stand, an evergreen broadleaf forest, and a mixed forest with *P. thunbergii* and broadleaf trees. A forest stand with 6-year-old (in 2010) *P. thunbergii* juvenile plants of <5 m in height was established within 50 m of the coastal edge of the forests in all four transects (Figure 2a–d). The width of the juvenile *P. thunbergii* forest was 40 m in transects A and D, 20 m in transect B, and 50 m in transect C. A *Pinus*-dominated stand with a 10- to 23-m height was established inland from the juvenile *P. thunbergii* stand to 300 m inland from the coastline except for transect B. Evergreen broadleaf shrubs of 3 to 4 m in canopy height (*E. japonicus*, *E. pungens*, *L. japonicum*, and *P. tobira*) were dominantly established on a zone of the 20- and 50-m section, and the canopy of the 50- to 150-m section was dominated by *P. thunbergii* (Figure 2b). The maximum height of the *Pinus*-dominated stand was 23 m in transects A and B, 14 m in transect C, and 18 m in transect D. A stand of broadleaf forest with 5–15 m in tree height (*C. tenuifolium*, *D. teijsmannii*, and *C. camphore*) was dominantly established on zones between 150 and 260 m, and shrubs of these species continued to the 300-m point (Figure 2b). The vegetation of the forest floor under the canopy of *P. thunbergii* forest with 10–23 m in height was dominated by a broadleaf shrub community of 1–3 m in height (*L. japonicum*, *M. seguinii* Lev, *C. tenuifolium*, and *V. bracteatum*) in all *P. thunbergii* stands in the four transects.

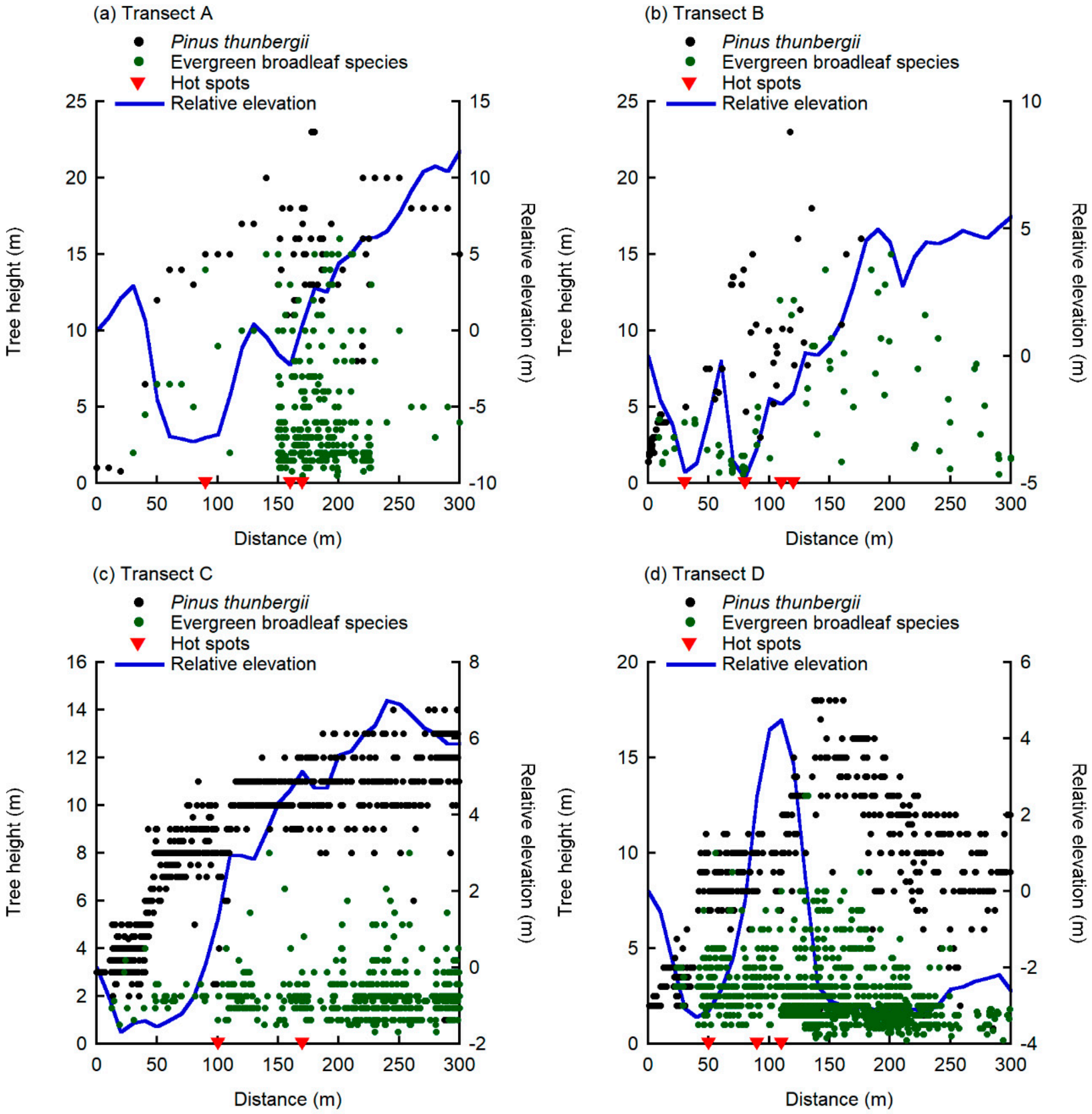

**Figure 2.** Ground surface elevation relative to the original point of each transect line, tree heights of *Pinus thunbergii* (black circles), and broadleaved trees (green circles) in transects A, B, C, and D (width 10 m) in the Sanri-Matsubara Forest, northern Kyushu, Japan. Whole individuals of tree height >0.5 m are shown in 150–230 m section of transect A and 0-300 m section of transect C and D. Trees with canopy over precipitation collector (located 10 m intervals from the original point of each transect) are shown in 0-150 and 230-300 m section of transect A and 0-300 m section of transect B. Hot spots of sea salt deposition (see text) are shown as red inverted triangles.

Several sampling sites with a high sea salt concentration in throughfall were observed in each transect (Figure 3). We defined the hot spots of sea salt deposition as follows. First, we standardized the EC value of throughfall within each transect line (a 0- to 300-m interval from the coastline; n = 31) at each precipitation event. Then, we counted the number of observations (number of precipitation events) that each sampling point showed a throughfall EC value > 3 standard deviations and >2 standard deviations of all the sites at every precipitation event. We found some specific points with a high frequency of observations with extremely high EC value among each transect line (Figure 3). We defined points as hot spots if the frequency of the point showing high EC (> 2 standard deviations) exceeded 50% of the whole number of sampling times. Hot spots were named by combining the name of transect line and distance from the origin of each transect line as A90 (90 m point from the origin of transect A). There were three hot spots (A90, A160 and A170) in transect A, four hotspots (B30, B80, B110, and B120) in transect B, two hotspots (C100 and C170) in transect C, and three hot spots (D50, D90, and D110) in transect D.

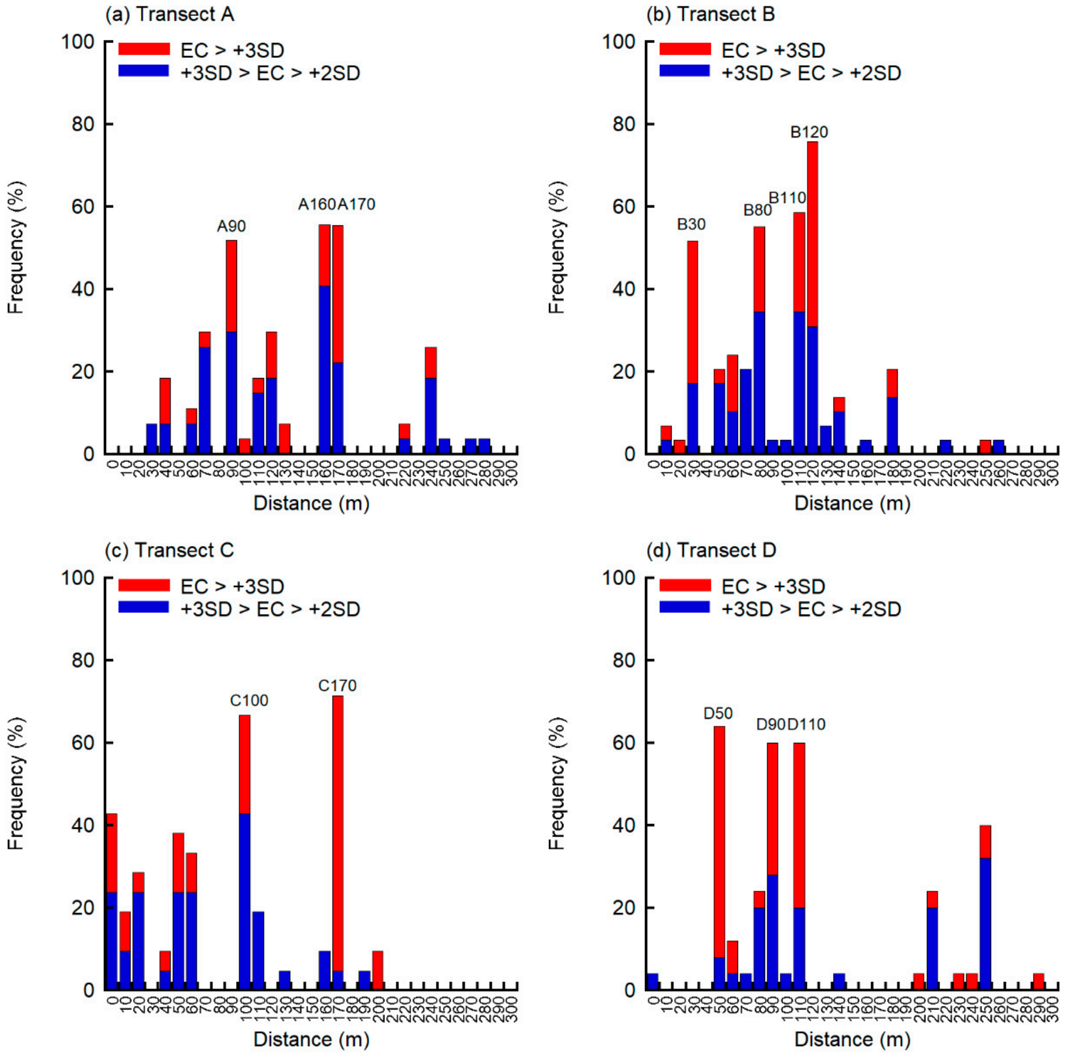

**Figure 3.** Frequency of precipitation events at every sampling point that throughfall showed extremely high value of EC (EC > +3SD; +3SD > EC > +2SD) along transects A, B, C, and D in the Sanri-Matsubara Forest, northern Kyushu, Japan. Hot spots of sea salt deposition (see text) are shown as the code of combination of transect name and distance over the bar. EC: electric conductivity; SD: standard deviation.

## 4. Discussion

### 4.1. Chemical Interaction in Canopy and Soil Surface in the Sea Salt Deposition Process

Comparison between the coniferous forest and the broadleaf deciduous forest on the interaction between atmospheric deposition and forest canopy has been documented by many authors and we showed in the preceding paper [12] that throughfall in the *Pinus*-dominated stand has a higher value of EC compared with the evergreen broadleaf forest stand. The higher EC of throughfall in the *Pinus*-dominated stand implies a higher sea salt scavenging effect of the *Pinus*-dominated forest compared with the evergreen broadleaf stand.

Jung et al. reported on higher leaching of organic acids from a *Pinus banksiana* canopy than from a broadleaf forest that causes acidification of forest soils in *P. banksiana* forests, both on the forest floor and in the mineral soil, than in broadleaf *Populus tremuloides* forests [13]. The value of the pH of soil water was lower than the pH value of throughfall, and elevation of the pH by sea salt deposition was buffered by organic acid that is included in the litter of *Pinus* leaves and branches. Soil infiltration water in both the *P. thunbergii* forest and the evergreen broadleaf forest was significantly acidic compared to throughfall (Table 2). Acidification in the litter layer and A horizon in soil was common in both the *P. thunbergii* forest and the evergreen broadleaf forest. The acidity of throughfall in the *P. thunbergii* forest was higher than the evergreen broadleaf forest, and then the difference of acidity in soil between the forest type was due to the difference of acidification of precipitation in the canopy. Among base cations, $Na^+$, $K^+$, $Mg^{2+}$, and $Ca^{2+}$ were significantly enriched in soil infiltration water in evergreen broadleaf forest, whereas enrichment of $Na^+$ in *P. thunbergii* forest was not significant. Higher leaching of base cations from litter layer or organic materials in surface soil and the consequent enrichment of base cations in soil infiltration water in the evergreen broadleaf forest would keep lower acidity of throughfall and soil infiltration water. Proton leaching by $Na^+$ exchange on the surface soil would be the dominant process of acidification in surface soil in the *P. thunbergii* coastal forest and acidity increased in the surface soil layer.

### 4.2. Sea Salt Scavenging by Coastal Forests

Edge effect and edge-to-interior gradients of chemical deposition to forest soil are commonly observed in the deposition process in the atmosphere over a forest canopy. Neal et al. [14] showed that trees at the forest edge facing prevailing winds in a *Fagus sylvatica* forest with uniform height are particularly efficient at scavenging, especially sea salt. Chloride, magnesium, and sodium fluxes to forest soil were measured from the forest edge to 350 m interior of the forest at 30–100 m intervals and fluxes of these elements decreased along edge-to-interior gradients. Gaps in forests have a greater scavenging effect of some pollutants because of roughness in the forest and the consequent turbulence of aerosol materials in the atmosphere. Vanguelova and Pitman [15] investigated the deposition of atmospheric nitrogen in *Pinus nigra* var. *maritima* forest and *F. sylvatica* forest at 20 m intervals from the forest edge to 200 m interior of the forest and found the strong nitrogen deposition at the forest edge and the nitrogen deposition gradients along edge-to-interior gradients. Beier and Gundersen [16] investigated the deposition of major ions in a *Picea abies* forest at 5–15 m intervals from the forest edge to 50 m interior of the forest and found the clear edge effect of atmospheric deposition and the edge-to-interior gradients of deposition of these chemicals. This literature described the clear edge effect and edge-to-interior gradients of sea salts' or atmospheric pollutants' deposition to forest soil. We found 12 hot spots of sea salt deposition between 30 m and 170 m from the coastal edge of the forest on the investigated transects and no hot spots were found between 0 and 20 m from the edge of the forest (0 m). No hot spots appeared at the forest edge (Figures 2 and 3), although 0–30 m points on transect C showed a relatively high frequency of observations of high EC value. The vegetation of the forest edge is juvenile for the *P. thunbergii* stand, and the sea salt scavenging effect of the canopy of the forest edge is small. The high foliage density of the developed tree and the high surface area of coniferous leaves are necessary factors for effective scavenging of sea salt [13,17].

Haraguchi et al. [18] documented the clear gap of sea salt concentration in soil pore water at the forest edge of the *Picea glehnii* forest on a flat coastal terrace by measuring EC and sea salts in peat pore water at 10 m intervals. The *P. glehnii* forest on the coastal terrace showed no edge effect but higher sea salt deposition within the forest compared to the neighboring non-forested area. The *P. glehnii* forest is established on the flat coastal terrace and the sea salt is transferred by advection fog from the sea. The whole of the needle foliage in the coniferous forest has a scavenging function of fog, then neither the edge effect nor hot spots appeared in the *P. glehnii* forest. The prevailing wind is the main transporter of sea salt containing aerosol particles in the Sanri-Matsubara Forest. The difference in topography, as well as the difference of transporter of sea salt, would cause the appearance of hot spots in the present study site.

Twelve hot spots were recognized on the four transect lines within the range of 300 m from the coastal edge of each transect line. Location of these hot spots were categorized as (1) hollow or bottom of the local topography with lower elevation relative to the neighboring position (A90, A160, A170, B30, B80, and D50), (2) slope facing to the coastal line (north-facing slope) affected directly by prevailing wind from northern direction (C100, D90), and (3) sites with emergent canopy with an abrupt canopy height increase from coastal to inland and the canopy affected directly by prevailing wind (B110, B120, D110). The conditions of the slope facing coastal line (case 2) and emergent canopy (case 3) are located within a similar condition as the canopy surface establishing on slopes those are facing the prevailing wind from the sea. The condition of the hollow of the local topography (case 1) would be similar to gaps with roughness in the forest and the consequent high turbulence of the atmosphere [14].

## 5. Conclusions

We found the different chemical processes in the surface soil between *Pinus thunbergii* forest and evergreen broadleaf forest. The *P. thunbergii* stand acidifies soil as a result of the enrichment of protons in the litter layer or surface mineral soil horizon. The evergreen broadleaf forest supplies base cations by leaching in the litter layer and neutralizes soil. The spatial distribution of sea salt deposition in the coastal pine forest was heterogeneous in 10 m resolution. Hot spots of sea salt deposition depending on micro-topography and forest structure were observed and the deposition of sea salt was not evident at the forest edge consisted of juvenile *P. thunbergii* facing the prevailing wind from the sea. The function of the *P. thunbergii* canopy is only evident in stands with a canopy height > 10 m. As *P. thunbergii* forest can effectively scavenge atmospheric sea salt comparing with the evergreen broadleaf forest, forest regeneration, and afforestation of *P. thunbergii* on the sand dune slope facing the prevailing wind is the effective forest management of the coastal protection forests.

**Author Contributions:** A.H. and M.S. planned the investigation. M.S. mainly collected and analyzed data with support and supervision by A.H., M.S. prepared the first version of the manuscript in Japanese and A.H. completely re-analyzed data and prepared the manuscript. All authors contributed to revisions and completion of the manuscript. All authors have read and agreed to the published version of the manuscript.

**Funding:** This research received no external funding.

**Acknowledgments:** We thank the member of the Faculty of Environmental Engineering, The University of Kitakyushu for supporting the investigation. We also thank two anonymous reviewers for their helpful comments on this paper.

**Conflicts of Interest:** The authors declare no conflict of interest.

## References

1. Farrell, E.P. Atmospheric deposition in maritime environments and its impact on terrestrial ecosystems. *Water Air Soil Pollut.* **1995**, *85*, 123–130. [CrossRef]
2. Pedersen, L.B.; Bille-Hansen, J. Effects of airborne sea salts on soil water acidification and leaching of aluminium in different forest ecosystems in Denmark. *Plant Soil* **1995**, *168–169*, 365–372. [CrossRef]
3. Campbell, D.J. Salt-wind induced wave regeneration in coastal pine forests in New Zealand. *Can. J. For. Res.* **1998**, *28*, 953–960. [CrossRef]

4. Griffiths, M.E.; Orians, C.M. Salt spray differentially affects water status, necrosis, and growth in coastal sandplain heathland species. *Am. J. Bot.* **2003**, *90*, 1188–1196. [CrossRef] [PubMed]
5. Zhang, Z.-H. Impact of seasalt deposition on acid soils in maritime regions. *Pedosphere* **2003**, *13*, 375–380.
6. Marosz, A.; Nowak, J.S. Effect of salinity stress on growth and macroelements uptake of four tree species. *Dendrobiology* **2008**, *59*, 23–29.
7. Gustafsson, M.E.R.; Franzén, L.G. Inland transport of marine aerosols in southern Sweden. *Atmos. Environ.* **2000**, *34*, 313–325. [CrossRef]
8. Silva, B.; Rivas, T.; García-Rodeja, E.; Prieto, B. Distribution of ions of marine origin in Galicia (NW Spain) as a function of distance from the sea. *Atmos. Environ.* **2007**, *41*, 4396–4407. [CrossRef]
9. Kreutzer, K.; Beier, C.; Bredemeier, M.; Blanck, K.; Cummins, T.; Farrell, E.P.; Lammersdorf, N.; Rasmussen, L.; Rothe, A.; De Visser, P.H.B.; et al. Atmospheric deposition and soil acidification in five coniferous forest ecosystems: A comparison of the control plots of the EXMAN sites. *For. Ecol. Manag.* **1998**, *101*, 125–142. [CrossRef]
10. Konta, F. Why is it Japanese black pine? the disaster prevention of the coastal forest in Japan. *J. Jpn. Soc. Coast. For.* **2013**, *12*, 23–28. (In Japanese with English summary)
11. Mukai, Y.; Sugimura, T. Extraction of areas infested by pine bark beetle using Landsat MSS data. *Photogr. Eng. Remote Sens.* **1987**, *53*, 77–81.
12. Haraguchi, A.; Sakaki, M. Formation of soil chemical environment in coastal *Pinus thunbergii* Parlatore forest in southwestern Japan. *Water* **2020**, *12*, 1544. [CrossRef]
13. Jung, K.; Chang, S.X.; Arshad, M.A. Effects of canopy-deposition interaction on $H^+$ supply to soils in *Pinus banksiana* and *Populus tremuloides* ecosystems in the Athabasca oil sands region in Alberta, Canada. *Environ. Pollut.* **2011**, *159*, 1327–1333. [CrossRef] [PubMed]
14. Neal, C.; Ryland, G.P.; Conway, T.; Jeffery, H.A.; Neal, M.; Robson, A.J.; Smith, C.J.; Walls, J.; Bhardwaj, C.L. Interception of chemicals at a forest edge for a rural low-lying site at Black Wood, Hampshire, Southern England. *Sci. Total Environ.* **1994**, *142*, 127–141. [CrossRef]
15. Vanguelova, E.I.; Pitman, R.M. Nutrient and carbon cycling along nitrogen deposition gradients in broadleaf and conifer forest stands in the east of England. *For. Ecol. Manag.* **2019**, *447*, 180–194. [CrossRef]
16. Beier, C.; Gundersen, P. Atmospheric deposition to the edge of a spruce forest in Denmark. *Environ. Pollut.* **1989**, *60*, 257–271. [CrossRef]
17. Cole, D.W.; Rapp, M. Elemental cycling in forest ecosystems. In *Dynamic Properties of Forest Ecosystems*; Reichle, D.E., Ed.; Cambridge University Press: Cambridge, UK, 1981; pp. 341–409.
18. Haraguchi, A.; Iytobe, T.; Nishijima, H.; Tomizawa, H. Acid and sea-salt accumulation in coastal peat mires of a *Picea glehnii* forest in Ochiishi, eastern Hokkaido, Japan. *Wetlands* **2003**, *23*, 229–235. [CrossRef]