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The changes of soil salinity in the *Pinus densiflora* forest after seawater spread using a fire-fight helicopter

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Abstract

The east coast of the Korean Peninsula is susceptible to fires because of the low rainfall in winter and spring, and large forest fires have occurred in this area. Lack of fresh water to combat fires has hampered efforts to prevent widespread forest fires in this region. Seawater has not been used as a suppressant because of possible detrimental effects of salt. We investigated the mobility of saline water in the forest soil and their effect on the microbial activity. Using a fire-fighting helicopter, seawater was sprayed over three plots (50 × 100 m) located on the eastern slope of the Baekdu mountain range in South Korea in April, 2011. We sampled the soil in April 4, May 20, and August 5 to determine the amount of salt that remained in the soil. The electrical conductivity value of the soil decreased to <400 μS/cm over a 1-month period. Approximately, four months after the application of seawater, the electrical conductivity value and Na^+ content in all treatment plots did not significantly differ to those of the control plot, and total microbial activity also recovered to that of the control. Our results indicate that the amount of rainfall, soil physical-chemical properties, and topological factors may be a critical factor determining the mobility of saline water in forest soil.

Key words: fire-fight helicopter, forest fire, microbial activity, saline water, soil properties, soil salinity

INTRODUCTION

The severity and frequency of forest fires have increased globally over the last three decades (Shin et al. 2012, Moody et al. 2013). In some respects, forest fires are considered a part of natural processes rather than an ecological disaster (Pausas et al. 2009). However, forest fires impact many terrestrial and aquatic ecosystem components (Brown et al. 2014). Furthermore, forest fires in populated areas can threaten human life and property.

South Korea experienced its largest recorded forest fires in the springs of 1996 and 2000, which burned about 0.4% of the total forest area in South Korea (Ro et al. 2000). The east coast of the Korean Peninsula is particularly susceptible to fires because of low rainfall and very dry weather in the winter and spring seasons; monthly humidity falls to 30% in the spring (KMA 2013). Furthermore, the high wind speeds that occur during these seasons have been known to accelerate forest fires (Choung et al. 2004).

The limited availability of fresh water for suppressing wildfires on the east coast is one of the main reasons for the large-scale damage caused by forest fires on the Korean Peninsula. While most forest fires have occurred within 10 km from the East Sea, seawater has not been

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used to combat the fires because of possible detrimental effects of salt within the seawater. There is some evidence that soluble salts in soil can damage plant tissues (Munns 2002). Some research indicates that the soluble salts in soil can suppress uptake of water and nutrients by reducing the osmotic potential, which, in turn, causes drought and nutrient stress (Greenway and Munns 1980). High soil salinity can directly affect plant physiology. On the other hand, the Food and Agriculture Organization of the United Nations mentioned the use of seawater for fighting forest fires in Mediterranean forests (Calabri 1983). However, there are no science-based, objective criteria for the application of seawater spray to combat forest fires. This study provides some insights into the mobility of saline water in the forest soil and their effect on the microbial activity when seawater is sprayed using a fire-fighting helicopter.

We investigated the remaining salinity in forest soil (dependent on the length of time after application) in 50 m × 100 m plots after spreading seawater using a fire-fighting helicopter, which is the same method used to combat forest fires. The specific aims of this study were to (1) investigate changes in soil salinity and other soil properties and (2) estimate the effect of seawater spread on the total soil microbial activity.

MATERIALS AND METHODS

Sites description

The study was conducted in Hyeonnam-myeon, Yangyang-gun, Gangwon Province, South Korea, on the eastern slope of the Baekdu mountain range. The Baekdu mountain range includes Seorak Mountain, which is the third highest mountain in South Korea and has many mountains that are >1000 m in height. The bedrock type of our study sites is Jurassic biotite granite (Korea Institute of Geoscience and Mineral Resources 2015). We selected one control plot and three treatment plots (50 m × 100 m) (Fig. 1). The plots were located at an elevation of approximately 300 m, and the distance from the shoreline was about 5.6 km. The dominant high tree species were *Pinus densiflora* and *Quercus mongolica*, and frequently found shrubs included *Rhododendron mucronulatum* and *Lindera obtusiloba*. The large and severe forest fires known to frequently occur in this region are the result of its climatologic characteristics and proximate location to populated areas. The east coast of the Korean Peninsula has low winter and spring precipitation, which is about 20% of the total annual precipitation, and more than half of the annual precipitation falls in the summer (i.e., the monsoon season) (Fig. 2). The monthly mean temperature in the winter is higher than 0°C, which is due to oceanic influences.

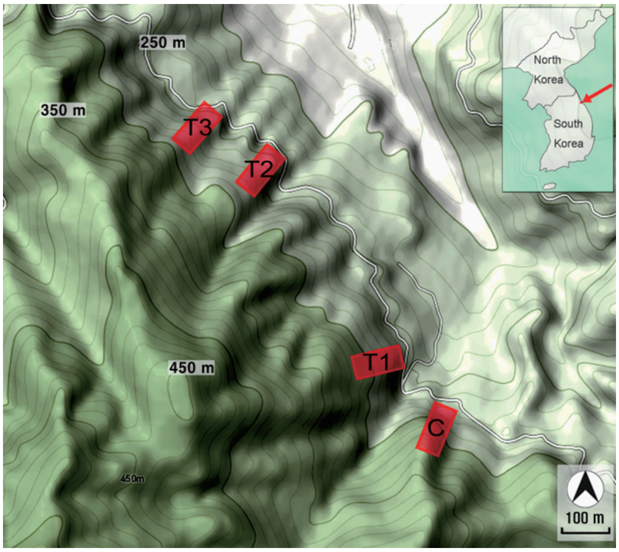

Fig. 1. Topographic map representing the locations of seawater spreading (T1, T2, and T3) and the control area (C).

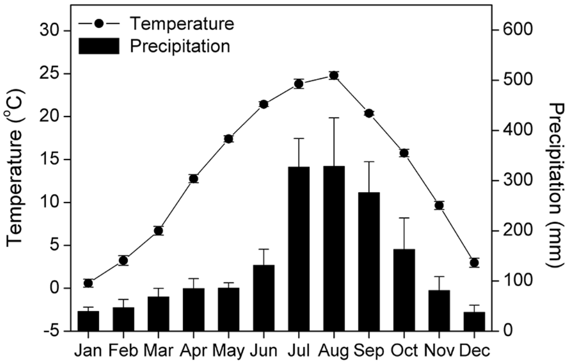

Fig. 2. Monthly mean temperature and precipitation at the Gangneung weather station during 2002–2011 (data from the annual climatological report of the Korea Meteorological Administration). Vertical bars indicate ± SE.

Experimental design and soil sampling

To determine the mobility of seawater applied to suppress forest fires, we selected three treatment plots (i.e., T1, T2, and T3) and a control plot. All plots were 50 m x 100 m and located on a relatively steep slope from 25° to 32° (Fig 1). The control plot had the highest sand content

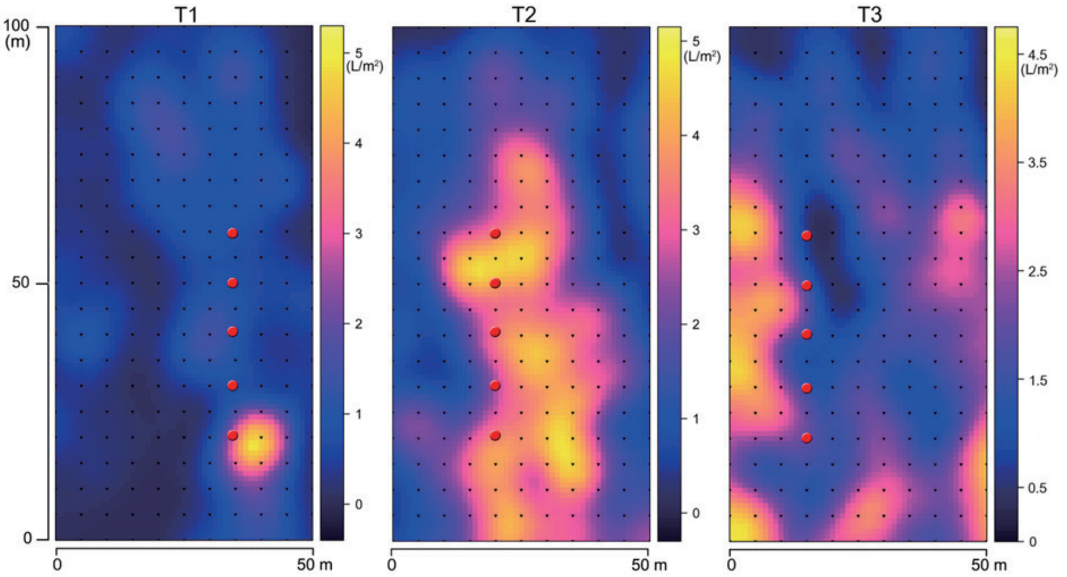

Fig. 3. Interpolation maps showing the amount of seawater that was spread per 1 m^2 soil surface. Red dots represent the spots where soil sampling was conducted.

and the T3 site had the lowest sand content when compared to that of the other plots. Seawater was spread in April 4 (T1), 18 (T2), and 28 (T3), 2011 using fire-fighting helicopter(S-64E, USA) over the canopy (Table 1). Total seawater spread in the each treatment plot was at least 10,000 L, which is enough water to extinguish forest fires (Bae et al. 2013). To estimate the amount of seawater that was spread on the soil surface, we placed 231 plastic containers at the intersections of a 5 m × 5 m grid within the 50 m × 100 m plots before the seawater was sprayed by helicopter, and measured the collected seawater in the plastic containers (12 cm x 8 cm x 6 cm). The ordinary block Kriging interpolation method was used to represent the amount of seawater spread within the three treatment plots using gstat package ver. 1.0-16 under R ver. 3.0.1 (Cousens et al. 2002).

Soil sampling was conducted three times for the control and T1 sites and two times for the T2 and T3 sites. The last soil sampling was conducted in August, after the rainy season in Korea. All superficial organic residues were removed and the soil samples were taken from a depth of 0–10 cm (surface soil) and 20–30 cm (deep soil) at five different spots (*N* = 5) in the each plot (Fig. 3). The collected soils were sealed in plastic bags and stored in 4°C cooled room prior to analysis.

Table 1. Description of seawater spread plots (treatment) and the control plot

Site name	GPS information	Slope	Soil texture			Collected seawater (mL/m^2) (mean ± SE)	Day of sea water spread	Day of soil sampling (Days after seawater spread)
			Sand (%)	Silt (%)	Clay (%)			
Control (C)	N 37°54′21.26″ E 128°44′13.88″	32.8°	S: 63.8 D: 62.5	S: 22.8 D: 21.5	S: 13.5 D: 16	–	–	1) April 4, 2011 2) May 20, 2011 3) August 5, 2011
Treatment 1 (T1)	N 37°54′25.75″ E 128°44′09.63″	28.7°	S: 58.8 D: 57.5	S: 14.8 D: 16	S: 26.5 D: 26.5	632 ± 71	April 4, 2011	1) April 4, 2011 **(0)** 2) May 20, 2011 **(47)** 3) August 5, 2011 **(124)**
Treatment 2 (T2)	N 37°54′39.00″ E 128°43′58.87″	25.1°	S: 58.8 D: 55	S: 17.3 D: 19.8	S: 24 D: 25.3	1924 ± 107	April 18, 2011	1) May 20, 2011 **(33)** 2) August 5, 2011 **(110)**
Treatment 3 (T3)	N 37°54′41.66″ E 128°43′54.24″	26.6°	S: 43.8 D: 40	S: 24.8 D: 27.3	S: 31.5 D: 32.8	1877 ± 87	April 28, 2011	1) May 20, 2011 **(23)** 2) August 5, 2011 **(100)**

S, surface soil (0–10 cm); D, deep soil (20–30 cm).

Fig. 4. Pictures showing spreading seawater using a fire-fighting helicopter over T1 plot (left) and the necrosis of *Quercus mongolica* leaves in T2 plot (right).

Soil analysis

Soil electrical conductivity and pH (soil:distilled water, 1:5) were measured using an electrical conductivity meter (Orion model 150A; USA) and pH meter (Orion model 720A+; USA), respectively. Water content was determined by measuring the amount of weight lost after drying the samples in a 105°C oven for 48 h. Organic matter content was calculated according to weight lost after the samples were maintained in a muffle furnace at 550°C for 4 h (John 2004). The total nitrogen and carbon contents were determined using an elemental analyzer (EA1110; CE Instruments, UK) at the National Center for Inter-University Research Facilities, Seoul National University. Total phosphorus, sulfate, and minerals (Mg^{2+}, K^+, and Na^+) were extracted using a Mehlich-3 extract solution and measured using Inductively Coupled Plasma Optical Emission spectrometer (ICP-730 ES; Varian, Australia) (Cater and Gregorich 2007). The soil texture was determined using the hydrometer analysis method (Day 1965).

Total microbial enzyme activity

The fluorescein diacetate (3′,6′-diacetylfluorescein) (Sigma-Aldrich, USA) hydrolysis assay was used to estimate the total microbial enzyme activity of soil microbial populations (Green et al. 2006). This assay is sensitive to the activity of several enzyme classes, including lipases, esterases, and proteases. The activity of these enzymes results in the hydrolytic cleavage of fluorescein diacetate into fluorescein (fluorescent yellow-green), and the intensity of the fluorescent coloration of each sample (N = 5) was measured using a spectrophotometer (wavelength 490 nm) (Milton Roy Spectronic Genesys 5; Thermo Fisher Scientific Inc., USA).

RESULTS

The concentration of seawater spread on the soil surface differed among three plots due to canopy interaction and wind influence. The largest amount of seawater was spread over the T2 plot. Although the majority of seawater was applied to the left side of the T3 plot, total collected seawater in plot T3 was 3.3% lower than that of T2 plot. However, in case of T1 plot, 67% lower seawater was collected compared to that of T2 plot (Table 1). It was impossible to spread seawater equally because the water spreading using fire-fight helicopter was affected by diverse uncontrolled factors such as wind speed and direction, topography, and the performance of helicopters.

The necrosis of leaves was most frequently found in the T2 plot (Fig. 4). Especially, the broad-leaved trees such as *Q. mongolica* and *R. mucronulatum* were more severely damaged than the species having thicker cuticle layers such as *P. densiflora* and *Sasa borealis*. However, we could not find death trees species in the treatment plots, and the damaged trees recovered from saline water in August.

The mean electrical conductivity (EC) value of the surface soil sampled 3 h after the spreading of seawater (1352 ± 522 μS/cm) was nine times higher than that of the before the seawater spreading (147 ± 11) in the T1 plot. However, the EC value of the deep soil did not significantly differ before and after seawater spreading, and when compared to control plot, only surface soil EC and Na^+ value in T1 plot were significantly higher than those of control plot at

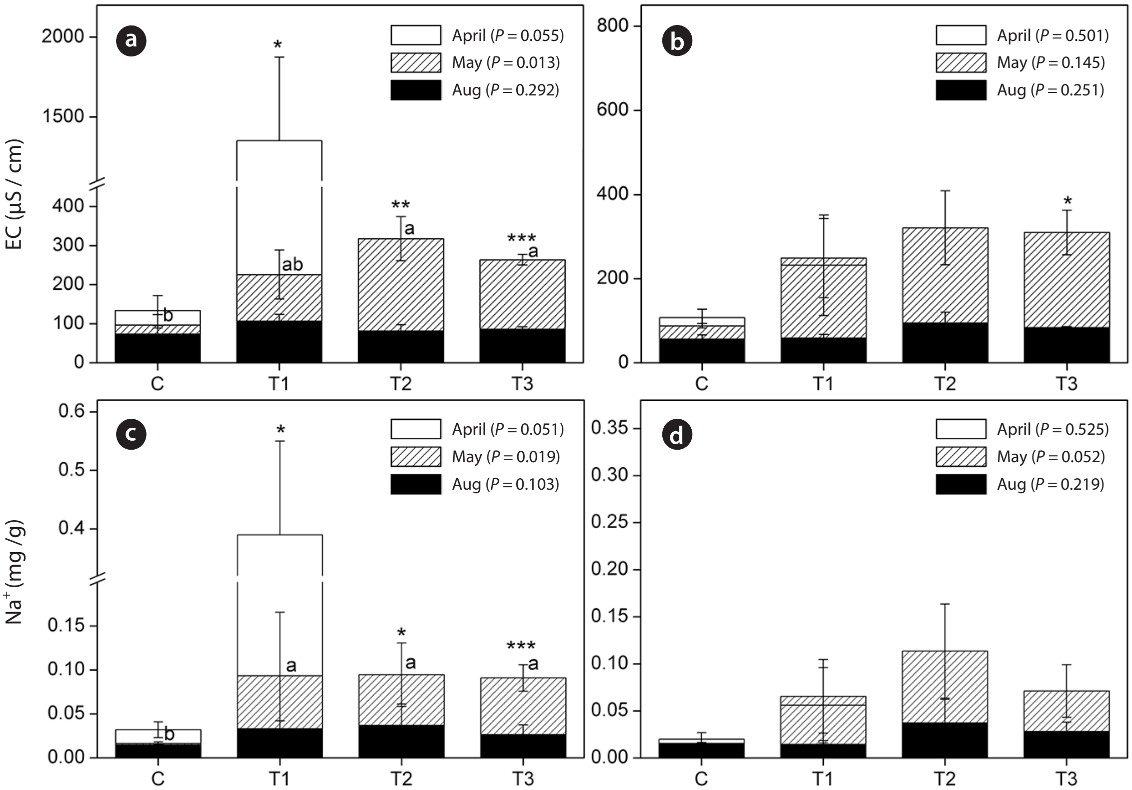

Fig. 5. Changes in soil electrical conductivity (EC) and Na^+ content. (a) EC of the surface soil, (b) EC of the deep soil, (c) Na^+ content of the surface soil, (d) Na^+ content of the deep soil. Letters on the graphs indicate significant differences at the 5% level among seawater treatments based on Tukey's test. The meaningful differences among soil sampling times are marked with *, **, and *** as $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively, based on the results from an analysis of variance (ANOVA). C, control; T1, treatment 1; T2, treatment 2; T3, treatment 3.

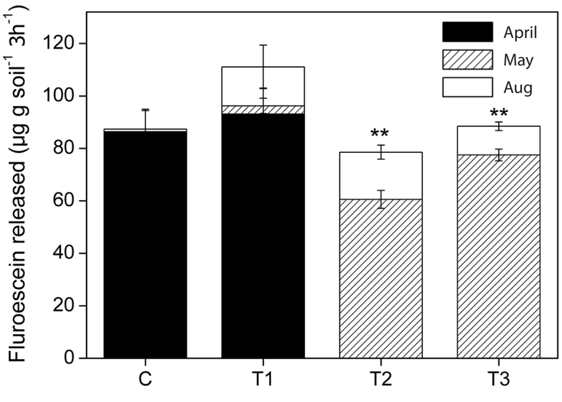

Fig. 6. Changes in total soil microbial activity depending on the soil sampling times. The significant differences among soil sampling times are marked with *, **, and *** as $P < 0.05$, $P < 0.01$, and $P < 0.001$, respectively, based on the results from ANOVA. C, control; T1, treatment 1; T2, treatment 2; T3, treatment 3.

the 10% significant level, suggesting that most of seawater did not penetrate into deep soil over 3 h (Fig. 5). The larger variation of soil salinity in the T1 plot compared to other treatment plots was caused by soil sampling timing after the seawater spread. To determine the remaining salt in the soil (in relation to the length of time after seawater spreading), we also sampled the soil in May and August. The EC and Na^+ contents were shown to steadily decrease. In particular, the surface soil sampled in August had significantly lower EC and Na^+ values than those of the sampled soils in May, and did not statistically differ when compared to those of the control. These results indicate that most salt was drained by rainfall from the soil during the four months. The total amount of rainfall from April to July in 2011 was 882 mm, which is higher than 10 years average 630 ± 76 mm (mean ± SE) (Fig. 2). Although deep soil sampled in May had a relatively higher EC value than that in August, the EC and Na^+ value of the deep soil was not significantly different when compared to the control.

We found significant changes in total soil microbial activity depending on the time span after seawater spreading. Treatment plots T2 and T3, where more seawater had been spread than the T1 plot, showed lower soil microbial activity than that of the control and T1 plot, and microbial activity in August significantly increased compared to that in May (Fig. 6).

Soil physical-chemical properties across the four designed plots are shown in Table 2. Most of the soil properties significantly differed depending on the soil sampling plots and times, except for pH and K^+. The control and T1 plots had higher water and organic matter contents than those of the other plots. Total nitrogen (TN), total carbon (TC), and total phosphorus (TP) contents were also higher for the control and T1 sites. On the other hand, T2 had the lowest values among the four plots, suggesting that the soil nutrients of the T2 plot were comparatively poor when compared to those of the other sites. Seawater spray did not change other soil chemical properties (excluding EC, Na^+, and Mg^{2+}).

DISCUSSION

The east coast forests of Korea have experienced numerous forest fires over the past several decades (Choung 2002), and this region is still susceptible to the dangers of catastrophic forest fires each spring due to climatologic and topographical factors. Furthermore, the shortage of fresh water to combat forest fires has promoted widespread forest fires. While seawater is available to suppress forest fires in this region, most people hesitate to use seawater because scientific research into the mobility of saline water in the forest soil has been limited. It is well known that high Na^+ or Cl^- ions result in a specific type of toxicity or can disturb metabolic pathways as a result of ion imbalances (Allen et al. 1994). When compared the responses of plants to Na^+ and to Cl^- separately, some species was more sensitive to Cl^- than to Na^+, and high Cl^- concentration can damage to the photosynthetic capacity due to chlorophyll degradation (Tavakkoli et al. 2010). Germination can also decrease with the increase of NaCl concentration because of the restriction of water absorption (Khan and Gulzar 2003).

We found that soil salinity decreased rapidly depending on the time span after seawater spreading. It is apparent that many factors interact with soil salinity. Prior work has documented c (Shannon 1979, Pezeshki et al. 1990, Rengel 1992, Maas 1993). Our study also revealed that climate exerts a strong influence on the mobility of saline water in soil after seawater spreading. Salts become concentrated in the dried soil. Thus, the effects of salt can be more severe in hot, arid climates when compared to those in cool, humid climates (Kotuby-Amacher et al. 1997). The Korean Peninsula typically experiences low rainfall and dry conditions in the winter and spring. There is possibility that plants can be damaged in these seasons, when rainfall is limited. However, during the monsoon season in the summer, most of the salt may be drained from all treatment plots. Our results showed that the amount of rainfall can be a critical factor in determining the drainage of saline water from the soil, and the harmful effects of salt on a forest may be insignificant after heavy rainfall. Soil water contents and soil porosity are also important factors to determine the movement of saline solution. Seawater may be diluted with relatively high soil water in our study plot (25.5%), and higher sand ratio in soil can accelerate the movement of saline water after rainfall (Brady and Weil 2010). In addition, the steepness of sites can be

Table 2. Soil physical-chemical properties depending on the soil sampling plots and times

Sampling Month	Treatment	WC (%)	OM (%)	pH	TN (wt %)	TC (wt %)	TP (mg/kg)	K^+ (mg/g)	Mg^{2+} (mg/g)
April	C	23.3 ± 2.68^{ab}	10.3 ± 1.30^{ab}	5.28 ± 0.12	0.26 ± 0.04^{a}	4.57 ± 1.08^{a}	3.53 ± 0.14^{bc}	0.07 ± 0.01	0.03 ± 0.01^{b}
	T1	29.9 ± 3.05^{a}	10.6 ± 0.62^{ab}	5.00 ± 0.05	0.21 ± 0.03^{a}	4.31 ± 0.49^{ab}	4.34 ± 0.52^{ab}	0.10 ± 0.01	0.09 ± 0.02^{a}
May	C	21.9 ± 3.18^{ab}	8.6 ± 1.10^{ab}	5.03 ± 0.08	0.22 ± 0.03^{ab}	3.86 ± 0.50^{ab}	4.00 ± 0.40^{abc}	0.06 ± 0.01	0.02 ± 0.00^{b}
	T1	27.1 ± 2.00^{ab}	8.9 ± 0.98^{ab}	5.12 ± 0.13	0.22 ± 0.03^{ab}	3.80 ± 0.33^{ab}	5.83 ± 0.70^{a}	0.09 ± 0.02	0.06 ± 0.01^{ab}
	T2	19.0 ± 1.33^{b}	6.6 ± 0.46^{b}	5.15 ± 0.13	0.14 ± 0.01^{ab}	2.72 ± 0.26^{ab}	2.75 ± 0.31^{bc}	0.08 ± 0.01	0.04 ± 0.01^{b}
	T3	26.4 ± 1.05^{ab}	9.6 ± 0.32^{ab}	4.99 ± 0.02	0.15 ± 0.02^{ab}	2.55 ± 0.18^{ab}	2.81 ± 0.40^{bc}	0.09 ± 0.01	0.04 ± 0.00^{b}
August	C	27.4 ± 2.63^{ab}	10.7 ± 1.13^{a}	4.82 ± 0.10	0.21 ± 0.02^{ab}	4.11 ± 0.41^{ab}	3.99 ± 0.59^{abc}	0.06 ± 0.01	0.03 ± 0.01^{b}
	T1	31.6 ± 3.27^{a}	10.4 ± 1.24^{ab}	5.05 ± 0.09	0.20 ± 0.02^{ab}	3.48 ± 0.32^{ab}	4.60 ± 0.50^{ab}	0.09 ± 0.01	0.05 ± 0.01^{ab}
	T2	22.1 ± 0.81^{ab}	6.5 ± 0.27^{b}	5.14 ± 0.16	0.11 ± 0.00^{b}	2.16 ± 0.10^{b}	2.21 ± 0.25^{c}	0.09 ± 0.01	0.03 ± 0.01^{b}
	T3	26.1 ± 1.25^{ab}	9.1 ± 0.50^{ab}	4.89 ± 0.14	0.12 ± 0.01^{b}	2.79 ± 0.29^{ab}	2.35 ± 0.14^{bc}	0.06 ± 0.01	0.03 ± 0.01^{b}
P-value		0.011	0.006	0.075	< 0.001	0.017	< 0.001	0.051	< 0.001

Data are presented as the mean ± SE of five independent measurements. The same letters indicate that the values were not significantly different at the 5% level based on Tukey's test. WC, water content; OM, organic matter; TN, total nitrogen; TC, total carbon; TP, total phosphorus.

critical factor for the movement of saline water. We guess that the velocity of saline water fallout from soils may be determined by the amount of rainfall, soil sand content, water content, and steepness in our study plots.

The high content of Na^+ and Cl^- ions in soil commonly induces an increase in the pH of soil. In particular, by increasing soil pH, soil aggregation decreases and soil structure can be poor (Kelsey and Hootman 1990). However, our results showed that soil pH was not changed in the treatment plots, suggesting that the salt in seawater did not severely affect soil structure. We could guess that high organic matter and nutrients in forest soils may result in the stability of the pH in soils by acting as a buffer. Furthermore, the nutrients and organic matter in soil may act as a buffer against the specific toxicity of Na^+ and Cl^-. Salinity has less of an effect on the plants grown in nutrient-rich soil than those of barren soil. The T1 plot had higher organic matter, total nitrogen, and total phosphorus than the other plots. We could speculate that one of the reasons that the T1 plot experienced less salt stress than the other plots was the result of the higher nutrient conditions in that plot.

Several researchers reported that salinity reduced microbial activity and biomass because of the different salinity tolerance among microbial genotypes (Rietz and Haynes 2003, Tripathi et al. 2006, Yuan et al. 2007). Asghar et al. (2012) revealed that microbial communities can adjust to salinity fluctuations and can increase their activity after leaching of salts by heavy rain. Our results also showed that microbial activity reduced by salinity of seawater spray and recovered their activity after heavy rainfall during monsoon season. Previous studies showed that the ability of microbes to tolerate high salinity was increased by adding easily available carbon (Mavi and Marschner 2013) and enzyme activity was stimulated by increasing organic matter contents under saline conditions (Pathak and Rao 1998). There is a fair possibility that reduction of microbial enzyme activity has connection with amount of soil organic matter as well as of seawater spray.

Our study was conducted in the unburned pine forest, hence application of seawater on the burning forest can bring different results. Organic matter and water content may decrease drastically after severe forest fires and salt can condense in soil without dilution or buffer effects. However, the movement of cations including Na^+ can be increased in the burned area during rainy season (Lewis 1974), which can bring positive effects on the fallout of salt from soils.

Lastly, we advise that the decision to spread seawater to combat forest fires should consider several factors to minimize the ecosystem damages including the salinity tolerance of the plant species, climate, soil physical-chemical properties, and topological factors in burning area. Furthermore, in future studies, it is essential to estimate the responses of other organisms living in terrestrial and aquatic ecosystem, and it is need to monitor soil and other ecosystem responses after the application of the seawater in burning areas. Especially, mountain stream ecosystem could experience catastrophic damage because of rapid accumulation of saline water, ashes, and soil inorganic nutrients.

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