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Root growth of *Pinus thunbergii* seedlings related to the restoration of Tohoku region coastal forests after the disastrous tsunami

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Abstract

Due to the disastrous tsunami which occurred along the pacific coastline of eastern Japan, 3660 ha of *Pinus thunbergii* Parlatore (Japanese black pine) coastal forests were heavily damaged. To restore and recover the functions of these coastal forests, artificial growth berms are being constructed to secure enough space for root growth, especially in the vertical direction. However, due to the use of heavy machinery, the surface soil of the growth berm was packed down and significantly compacted. Compacted soil results in hard soil and is often reported to negatively affect root growth of seedlings. Additionally, in some cases, waterlogging after rainfall is not promptly discharged due to low soil permeability and drainage. As oxygen availability becomes severely limited under waterlogging, this can also negatively affect root growth. Considering these problems, studies have been made to elucidate effects of soil compaction and waterlogging on root growth of *P. thunbergii* seedlings and broadleaved species which are new candidates for introduction to coastal forests. Furthermore, at some of the restoration sites, plowing of the surface soil is being experimentally done to soften the surface soil and improve drainage. Here, we review results obtained from several field surveys and pot experiments which suggest important key points to realize the healthy root growth of *P. thunbergii* seedlings at coastal restoration sites.

Key words: Coastal restoration, Japanese black pine (*Pinus thunbergii*), Root growth, Soil compaction, Waterlogging

Introduction

Japanese black pine (*Pinus thunbergii* Parlatore) is an evergreen conifer that naturally distributes from the Honshu islands to the Ryukyu islands (Satake *et al.* 1989). From the mid-17th century, *P. thunbergii* has been widely planted along coastlines from the Hokkaido islands to the Kyusyu islands to prevent blowing of sand and mitigate salt wind, as it has high tolerance against harsh coastal environments such as infertile soil conditions, drought and salt wind (Murai *et al.* 1992; Oota 2012; Konta 2013; Fujita *et al.* 2020b).

P. thunbergii is generally known to be a deep-rooting species (Karizumi 2010), and has been highly expected to mitigate tsunami damage (Konta 2013). Furthermore, it provides recreational spaces and beautiful scenery, giving citizens an environment for relaxation and refreshment (Kasetani *et al.* 2007) and is an important component of the coastal environment.

However, due to the disastrous tsunami which occurred with the Great East Japan earthquake in March 2011, about 3660 ha of *P. thunbergii* coastal forests along the Tohoku pacific coastline were heavily damaged. The tsunami caused *P. thunbergii* trees to tilt, break or up-root, and in some cases broken stems were carried inland by the tsunami, causing further damage (Sakamoto 2012).

To contribute to the restoration of *P. thunbergii* coastal forests of the Tohoku area, we review several field and pot studies elucidating effects of soil compaction, plowing and waterlogging, focusing especially on root growth of *P. thunbergii* seedlings and broadleaved species, which are candidates for new introduction to coastal forests with the aspect of improving biodiversity and tolerance against pine-wilt disease. Focus was made on root growth as they play the vital role of absorbing water and nutrients from the soil and support aboveground activity and growth. Fine roots are also strongly and directly affected by changes in the soil environment, and is an important indicator in plant response (Ostonen *et al.* 2007; Fujita *et al.* 2018).

Currently, great effort is put into the restoration of damaged coastal forests. From surveys of heavily damaged sites, it was found that up-rooted *P. thunbergii* had shallow root systems and the groundwater table was high. Therefore, root growth of *P. thunbergii* may have been limited due to the groundwater table, resulting in up-rooting of trees, and heavy tsunami damage.

Therefore, at the restoration sites, the realization of deep and developed root systems of *P. thunbergii* trees is essential. To achieve this, growth berms (height: 2 m from the original ground surface) are being constructed at the restoration sites (Araki *et al.* 2017). They are aimed to secure enough space for root growth and development, especially in the vertical direction.

However, as the growth berms were constructed by heavy machinery, the surface soil was packed down and significantly compacted (Ono *et al.* 2016). From previous studies, it has been reported that hard soil can negatively affect tree and root growth (Whalley *et al.* 1995; Kozlowski 2008). Furthermore, soil compaction can also lead to prolonged waterlogging. At some of the restoration sites, prolonged waterlogging at the surface

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of the growth berms was observed even after rainfall (Ozawa 2014; Shinomiya *et al.* 2016) (Photo 1 (a), (b)).

The reason for this is reported to be decreased saturated permeability coefficient caused by soil compaction (Shinomiya *et al.* 2016). Under waterlogging, oxygen availability is severely decreased, limiting root respiration (Kozlowski and Pallardy 2002; Ashraf 2012). This can not only decrease root activity and growth but can also result in root death and rot (Dreyer *et al.* 1991; Fujita *et al.* 2020a).

To mitigate soil compaction and to prevent prolonged waterlogging, measures such as plowing of the surface soil before planting and the construction of open ditches (Photo. 2) have been attempted on trial basis (Murakami 2015). Both measures are aimed to improve drainage and permeability of the surface soil so that rainfall does not result in waterlogging (Ono *et al.* 2016; 2018).

Photo.1(b)

Photo 1. Waterlogged restoration site of Tohoku coastal forests
Photos of waterlogged areas of the restoration sites taken at Ara-hama, Sendai City, Miyagi Prefecture (October 2017). Photo from Fujita (2021).

Soil compaction

Field study

Noguchi *et al.* (2021a) conducted a field survey at the restoration sites (Sendai City, Miyagi Prefecture) and evaluated the effect of plowing (1.5-2.0 m depth) on soil hardness and root growth of *P. thunbergii* seedlings for three growing seasons (5-months, 17-months, and 30-months after plantation).

Two-year-old *P. thunbergii* container seedlings were planted eleven days after plowing which was conducted in late May 2017 (four years after the construction of the growth berm). In this experiment, soil softness (S-value, cm drop^{-1}) and root growth were measured at the control plot (no plowing) and plowed plot.

Photo 2. Open ditches at the restoration site
Photo of restoration sites with open ditches (red arrow) to improve drainage, taken at Ara-hama, Sendai City, Miyagi Prefecture (October 2017). Photo from Fujita (2021).

The S-value was measured by an SH-type penetrometer (Daitou Techno Green, Inc.). In this measurement, a 3 kg weight was dropped from 50 cm height, and the penetration depth of the measurement cone per drop was recorded. Here, when the S-value is small, it indicates hard soil and when the value is large it indicates soft soil.

Soil softness of the control plot was smaller than S-value = 0.7 at 10 cm depth to 50 cm depth and or at deeper than 80 cm depth. In contrast, for the plowed plot, at hardly any measurement depth, soil softness smaller than S-value = 0.7 was not observed until approximately 1.5 m depth. However, after 17-months and 30-months a decrease in the S-value was observed near the soil surface (10 cm depth), suggesting that soils especially near the surface hardens with time (Noguchi *et al* 2021a), however effects of hardening at the soil surface were not observed on root growth.

Concerning root growth of *P. thunbergii* seedlings, the maximum root depth was 20 cm throughout the experimental period (30-months) at the control plot. On the other hand, at the plowed plot, maximum root reaching depth was 80 cm at after the first growing season and 110 cm at the second and third growing season, respectively (Noguchi *et al* 2021a). Root growth was relatively small during the second and the third growing season compared to growth during the first and second growing season. The reason for this was that at the plowed plot, roots had reached the hard soil layer (not plowed, S-value < 0.7) and root growth was inhibited.

A clear relationship between the thickness of the rooting depth range and the S value was also reported (Figure 1). Four seedlings in which rooting was observed for S-values smaller 1.2 was analyzed. As a result, it was found that when the S-value becomes smaller the thickness of the rooting depth range also becomes smaller, and the total of the rooting depth differed the most between S-value = 0.7 and S-value = 0.8.

These results matched the “Ground Maintenance Manual in Landscape Planting (2000)” published by the Research Committe of Japanese Institute of Landscape Architecture, where it is reported that it is difficult for most plant roots to penetrate soil with S-value = 0.7.

From these results, it was found that plowing before planting the seedlings not only effectively softens the soil for over three growing seasons, but also had a significant beneficial effect on the root growth, especially in the vertical direction. Additionally, it was found that for *P. thunbergii* seedlings, soil softness of S-value = 0.7 may be a threshold where root penetration is inhibited.

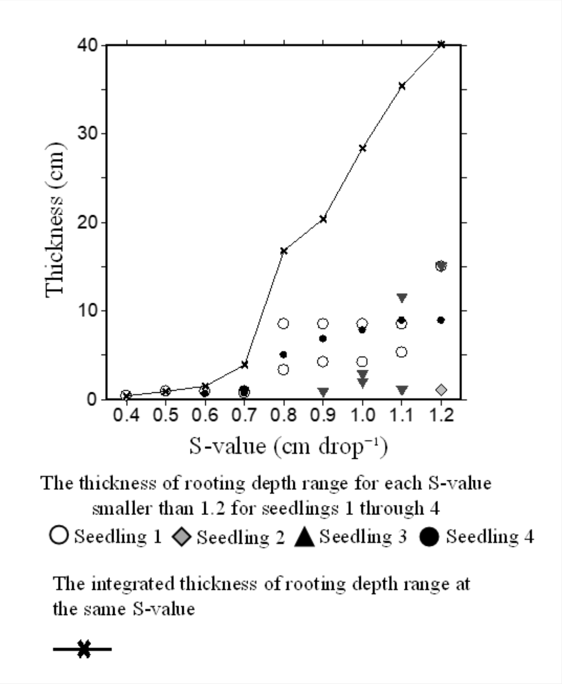

Figure 1. The rooting depth range of roots which penetrated soil with a S-value smaller than 1.2 and its integrated value at the same S-value
Modified from Noguchi *et al.* (2021a)

Pot experiment

Noguchi *et al.* (2021b) conducted a pot experiment using container seedlings to clarify effects of soil softness on root growth of *P. thunbergii* and four broadleaved species (*Zelkova serrata, Quercus dentata, Quercus mongolica* var. *crispula=Q. crispula,* and *Quercus serrata*). In this experiment, seedlings were planted in columns (inner diameter, 15 cm; height, 50 cm) with sand. First, sand was added until 25 cm from the bottom, and at the middle part, 4-8 cm of test soil layer sampled from restoration sites was set to test whether roots could penetrate this test soil layer. The top part of the column was also filled with sand, same as the bottom part.

In Ground Maintenance Manual in Landscape Planting (2000), and also from field survey (Noguchi *et al.* 2021a), the average threshold of plant root penetration is reported to be S-value (cm drop^{-1}) = 0.7. Considering this S-value, the soil softness of the test soil layer in the middle part was set at two levels, S-value = 0.5 (Very hard), and S-value= 0.5-0.7 (hard) along with a control column with a soft soil layer. For *P. thunbergii* seedlings, the thickness of the test soil layer was 4 cm for the very hard (S-value = 0.5) and control (soft) test soil layer, whereas, the thickness was either 4 cm or 8 cm for hard (S-value = 0.7) test soil layer. For the other four broadleaved species, all test soil layers were 4 cm. Root growth and development was evaluated in terms of total root cross-section area at the top and bottom side of the test soil layer. Root growth was measured for one growing season.

From this experiment, it was found that when the S-value of the test soil layer 0.5-0.7 (hard), there was a 99% decrease for *Q. dentata* and average 70% decrease for *P. thunbergii, Z. serrata, Q. crispula* and *Q. serrata* in total root cross section area at the bottom side of the test soil layer compared to the top side, indicating that for all species, it is difficult for most roots to penetrate 4 cm of hard soil (Noguchi *et al.* 2021b).

However, as there was no significant difference between *P. thunbergii* and the broadleaved species, it was suggested that the broadleaved species have a similar root penetration strength as *P. thunbergii* and the use of these species at the restoration sites may be beneficial (Photo 3).

For the very hard test soil layer (S-value = 0.5), only one seedling (out of four seedlings) of *Q. dentata* could reach the bottom of the very hard soil layer. For the *P. thunbergii* seedlings grown in columns with 8 cm hard soil layer, no roots were observed at the bottom side of the hard soil layer (Noguchi *et al.* 2021b).

This result indicated that for *P. thunbergii*, root penetration of hard soil becomes more difficult when the hard soil layer is thicker. Therefore, it is important to consider not only soil softness (S-value) but also the thickness of the hard soil layer.

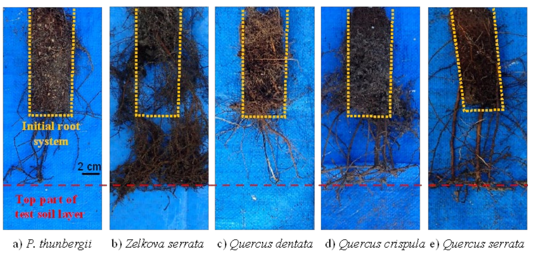

Photo 3. Root system of container seedlings of *P. thunbergii* and four broadleaved species planted with a soil layer of S-value = 0.5
The oragnge-dashed line area is the initial root system of the container seedlings and the red-dashed line is the top side of the test soil layer. Most roots of all five speices could not penetrate past the red-dashed line. Modified from Noguchi *et al.* (2021b). Photo courtesy: Hironori Noguchi.

Waterlogging

Field study

Although not conducted at the restoration site, mature *P. thunbergii* trees were investigated to evaluate the effect of groundwater table depth on root system development, especially in the vertical direction (Hirano *et al.* 2018).

Here, it was reported that root growth in the vertical direction was limited for trees growing at the seaside plot (nearer to the coastline with shallow groundwater table). Penetration of roots in the vertical direction was limited near the ground water table and roots mainly grew in the horizontal direction, resulting in a “plate like" root system. In contrast, for trees at the land side plot (further away from the coastline, deeper groundwater table), roots deeply penetrated the soil (approximately four times compared to seaside plot) and showed a "tap" root system (Hirano *et al.* 2018).

From this study it was found that *P. thunbergii* trees develop different shaped root systems according to the depth of the groundwater table. Under shallow groundwater tables, higher biomass allocation was made to horizontal roots, emphasizing the necessity for management practices and measures which promote the development of tap root systems to enhance the resistance against tsunamis.

Pot Experiment

Concerning effects of waterlogging on root growth of *P. thunbergii* seedlings, it has been elucidated in comparison with four broadleaved species (Fujita *et al.* 2020a) and in terms of waterlogging depth (Fujita *et al.* 2021). In both of these experiments, the ingrowth core (Makkonen and Helmisaari 1999; Andreasson *et al.* 2016) was used to distinctively measure fine root growth under waterlogging. In both studies, the experiment period was for one growing season and measurements were made on seedlings with and without waterlogging.

From Fujita *et al.* (2020a) it was found that for *P. thunbergii*, *Acer mono* and *Quercus serrata* (species which do not naturally inhabit waterlogged environments), fine root growth under waterlogging is severely decreased (Photo 4). For these three species, it is suggested that fine root growth was limited due to an energy crisis caused by the lack of energy production from decreased aerobic respiration under hypoxic conditions (Drew 2002; Sauter 2013). The decrease in fine root growth may also have been caused by root damage due to reduced conditions and toxic substances (e.g., sulfides, soluble Fe and Mn) which inhibited fine root growth (Morard and Sylvestre 1996).

On the other hand, for *Alnus hirsuta* and *Fraxinus mandshurica* var. *japonica* (hereafter, *F. mandshurica*), fine root growth did not differ between seedlings with and without waterlogging. However, fine root growth distribution was slightly different for these two species, where for *A. hirsuta*, fine root growth was mainly observed at the top half of the root system. For *F. mandshurica*, fine root growth was observed throughout the root system (Fujita *et al.* 2020a). The difference in fine root growth distribution may be due to the ability to transport oxygen to roots further away from the soil surface by the production of adventitious roots and aerenchymas (Yamamoto *et al.* 1995).

Concerning the effect of different waterlogging depths on fine root growth, Fujita *et al.* (2021) found that when the root system is only partially exposed to waterlogging (only the bottom half is exposed to waterlogging, Photo 5 (a)), fine root growth is increased at the top part of the root system where it is not waterlogged. At the bottom half of the root system where it was waterlogged, fine root growth was inhibited (Fujita *et al.* (2021), Photo 5 (b)).

For seedlings partially exposed to waterlogging, the vertical distribution of fine root growth was altered, resulting in a similar root system shape as the "plate root system" as reported in Hirano *et al.* (2018). Therefore, the change in root distribution of *P. thunbergii* under waterlogging may not be limited to responses of seedlings but a survival strategy to adapt to waterlogging. Additionally, from this experiment it was found that the construction of open ditches (Fig. 2) may be a beneficial way to not only lower the waterlogging table but also to secure space and enhance growth of roots.

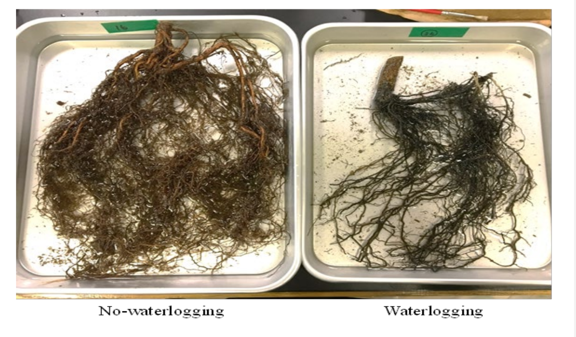

Photo 4. Root system of *P. thunbergii* seedlings without waterlogging (left) and with waterlogging (right).
Photo from Fujita (2021).

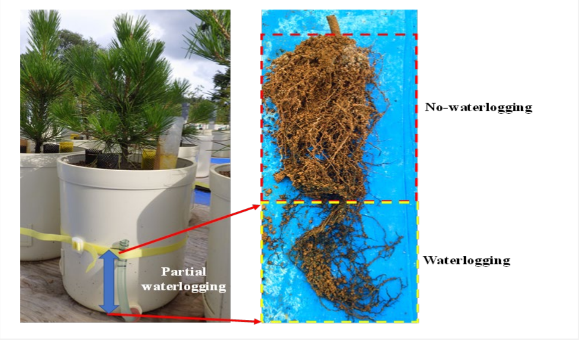

Photo 5. Photo of methodology on partial waterlogging treatment (left) and root system of *P. thunbergii* seedling exposed to partial waterlogging (right)
Left: A tube was set to maintain the waterlogging depth 15 cm from the bottom of the pot for the partial waterlogging treatment (Modified from Fujita *et al.* 2021). Right: At the top part of the root system (inside dashed-red box), roots were brown and root growth was not observed, however, at the bottom half (inside dashed-yellow box), where it was exposed to waterlogging, roots were black and new roots were not observed. Photo from Fujita (2021).

Conclusion

The growth and development of seedlings is one of the most important goals in the restoration of the damaged coastal forests. Some of the obstacles in achieving this goal are the negative effects of soil compaction and waterlogging. However, from results from field surveys and pot experiments, methodology on ways to mitigate or improve growth conditions of roots have been intensively explored.

From both field survey and pot experiments, it was confirmed that the S-value= 0.7 is about the threshold of root penetration for *P. thunbergii* and the other four broadleaved species, which match previous reports on the relationship between soil hardness and plant root growth. An important result that was found was that if the soil hardness is decreased by measures such as plowing, it has a significant and long-lasting effect of softening the soil and can greatly benefit root growth. However, as the experimental period was limited, root growth may be continued by the increasing power of root penetration enabled by the thickening of roots (radial growth), and further investigations must be made on this point.

Furthermore, although waterlogging severely decreases root growth of both mature trees and seedlings, at both life stages, *P. thunbergii* can plastically change its root system. However, as a shallow groundwater table leads to a shallow root system, decreasing the waterlogging depth is vital. Additionally, more information, especially on long-term effects should be obtained at the restoration sites as results from pot experiments are limited to one growing season.

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