論文の内容の要旨

森林科学専攻
平成 30 年度博士課程入学
氏名　藤田　早紀
指導教員名　丹下　健

研究題目　Responses of *Pinus thunbergii* seedlings to waterlogging
（クロマツ苗の滞水応答に関する研究）

Knowledge of the waterlogging responses of *Pinus thunbergii* is of urgent need, especially related to the restoration of the Tohoku region's coastal forests after the disastrous tsunami that occurred in March 2011. With the construction of growth bases, coastal forest restoration is ongoing. Growth bases are being constructed to secure space for vertical root growth, as root depth is reportedly strongly related to tsunami tolerance. However, in some cases, prolonged waterlogging occurs at the surface of the growth bases after rainfall due to poor permeability and drainage caused by heavy machinery compaction.

Discoloration in needles, decreases in shoot growth, and inhibition of vertical root growth have been reported as waterlogging responses of *P. thunbergii* from previous field observations and surveys. Waterlogging is a condition where the soil is saturated with water. Prolonged periods of waterlogging reduce the oxygen availability to roots. These conditions limit root respiration and can cause a decline in root function, root death, and rot. Therefore, waterlogging may be a critical concern in coastal forest restoration.

To prevent the occurrence of waterlogging, measures, such as plowing or construction of open ditches on the top of the growth bases, have recently been attempted on a trial basis. These measures are aimed to improve drainage and permeability of the surface soil of the growth bases so that heavy rainfall does not result in long-term waterlogging. It has been reported that plowing improves soil hardness to about 1.5 m depth, and effects are maintained. Hence, plowing before planting may be a beneficial way to improve soil hardness and waterlogging. However, knowledge of

the responses of *P. thunbergii* seedlings to various waterlogging conditions, in terms of depth and duration, is still lacking.

This study focuses on fine roots (diameter < 2 mm) as they play a vital role in absorbing nutrients and water from the soil and are critical for the growth and survival of seedlings after planting. Fine roots can plastically change their growth pattern and morphology according to environmental conditions. The effects on not only mass but elucidations on morphological characteristics and spatial distribution must also be made to understand waterlogging responses of *P. thunbergii* seedlings better.

The research objective of this study is to obtain knowledge on the waterlogging responses of *P. thunbergii* and contribute to achieving restoration of the Tohoku region's *P. thunbergii* coastal forests. Especially responses regarding waterlogging depth and duration were elucidated to reveal conditions in which *P. thunbergii* seedlings can recover or maintain growth after the release from waterlogging. This dissertation consists of 5 chapters. Chapter 1 describes the general background and objective of this study. Chapter 2 elucidated the waterlogging responses of *P. thunbergii* and four broadleaved species and compared the waterlogging tolerance of *P. thunbergii* relative to the other four broadleaved species. The four broadleaved species were selected from different natural habitats related to waterlogged environments. Chapters 3 and 4 elucidated the responses of *P. thunbergii* to different waterlogging depths and durations. Chapter 5 is the overall discussion and conclusion. In the following paragraphs, Chapters 2 through 4 are briefly summarized.

In Chapter 2, *P. thunbergii*, *Acer mono*, *Quercus serrata*, *Alnus hirsuta*, *Fraxinus mandshurica* seedlings were exposed to ten weeks of waterlogging, where the water table was set at the soil surface. By comparing the waterlogging responses of *P. thunbergii* and four broadleaved species, it was clarified that *P. thunbergii* was most negatively affected by waterlogging, and this was attributed to 1) the death of pre-existing fine roots (grown before waterlogging), 2) the significant inhibition of fine root growth under waterlogging and 3) the death of seedlings the following year. For pre-existing fine roots, root color turned from brown to black under waterlogging, and this change in root color was most evident for *P. thunbergii*. Root tissue density (RTD) was also significantly decreased. These results suggested root tissue death and waterlogging caused root damage.

Moreover, *P. thunbergii* seedlings that were subjected to waterlogging died the following growing season, indicating that roots were dead and did not recover or grow new roots after the waterlogging treatment ended. Fine root growth inhibition was also observed for *A. mono* and *Q. serrata*, species that do not naturally inhabit waterlogged environments. On the other hand, fine root growth continued under waterlogging for *A. hirsuta* and *F. mandshurica*, species that naturally inhibit waterlogged environments.

Chapter 3 suggested that *P. thunbergii* can adapt to partial waterlogging and maintain aboveground activity by changing its fine root growth distribution, especially in the vertical direction. In this chapter, responses of seedlings under 1) no waterlogging (Control), 2) partial waterlogging

(Partial-WL, waterlogging depth=15 cm from the bottom), 3) full waterlogging (Full-WL, waterlogging depth= from the bottom to the soil surface, 26 cm) were evaluated. Focus was made on fine root growth distribution, fine root morphology, and transpiration, which was measured to evaluate fine root water absorption. The waterlogging duration was eight weeks during the growing season. Fine roots that grew 1) during the whole experiment period and 2) during the waterlogging period were distinctively measured using the in-growth core method. Fine roots were evaluated on growth and morphological characteristics for the root system's top (11 cm) and the bottom part (15 cm), respectively.

As a result, fine root growth and transpiration were significantly decreased at full-WL. Furthermore, pre-existing fine roots of Full-WL (top and bottom part) and Partial-WL (bottom part) showed symptoms of damage (darkening in root color and decrease in RTD), as observed in Chapter 2. As transpiration was also decreased, it was suggested that fine root water absorption function was also negatively affected. Fine root growth was significantly increased for Partial-WL compared to Control and Full-WL at non-waterlogged top part. Additionally, transpiration of Partial-WL, which had decreased after four weeks of waterlogging, showed no significant difference compared to Control after eight weeks. This recovery in transpiration is likely to be attributed to the increase in fine root growth at the non-waterlogged top part, which compensated for damaged roots at the waterlogged bottom part. From these results, it was shown that although *P. thunbergii* cannot adapt to waterlogging when the whole root system is exposed to waterlogging, it can adapt to partial waterlogging by plastically changing the vertical distribution of fine root growth and increasing fine root growth at the top part.

Chapter 4 elucidated the effects of three different waterlogging durations on *P. thunbergii* seedlings. Focus was especially made on responses of fine root growth and transpiration during and after the release of waterlogging. In this chapter, four treatments were set: 1) no waterlogging (Control), 2) short-term waterlogging (Short-WL, seven days), 3) medium-term waterlogging (Mid-WL, 17 days), 4) long-term waterlogging (Long-WL, 32 days). The waterlogging treatment was carried out by maintaining the water table at the soil surface. Fine roots that grew 1) before and during waterlogging treatment and 2) after being released from the waterlogging treatment were distinctively sampled using the in-growth core method. Fine roots were measured for growth and morphological characteristics. A portable photosynthesis measurement system measured transpiration rates throughout the experimental period to evaluate the effects of waterlogging on fine root water absorption function.

As a result, for Long-WL and Mid-WL, pre-existing fine roots showed a darkening in root color and a decreasing trend in RTD. Transpiration rates were also decreased by waterlogging compared to Control. On the other hand, for Short-WL, although transpiration rates showed a decreasing trend after waterlogging, hardly any changes in fine root color and morphological traits were observed. Transpiration rates after the release from waterlogging recovered to a value that did not differ from Control within a week for Short-WL and Mid-WL, suggesting that the effect of waterlogging on water absorption function was reversible and could recover after the release from waterlogging. Furthermore, fine root growth after the release from waterlogging increased compared to Control.

For Long-WL, responses after the release from waterlogging largely varied within the group. Some seedlings could recover transpiration rates quickly, as observed in Mid-WL. On the other hand, two seedlings could recover transpiration rates to values that did not differ from Control approximately two weeks after release from waterlogging. For these two seedlings, fine root growth was observed after the release from waterlogging, suggesting that these seedlings could slowly recover water absorption function by replacing severely damaged roots with new roots. Hence, when waterlogging is short, the fine root water absorption function damage is reversible. On the other hand, when the waterlogging duration is longer than 17 days, the effect of waterlogging on fine root water absorption function is irreversible, and recovery requires new fine roots.

This study elucidated valuable knowledge on the waterlogging responses of *P. thunbergii*, allowing a better understanding of its adaption strategy to waterlogging. Mainly, this study suggests the following: First, the potential use of broadleaved species such as *Alnus hirsuta* and *Fraxinus mandshurica* instead of *P. thunbergii* at sites where the waterlogging frequently occurs up to the ground surface. Planting species other than *P. thunbergii* is suggested for sites where the groundwater is consistently high due to geographical factors and sites where prolonged waterlogging due to rainfall is difficult to improve with time due to the microtopography of the growth bases, such as hollows. For sites where prolonged waterlogging due to rainfall is expected to improve with the improvement of the growth base's soil physical properties with tree growth, *P. thunbergii* seedlings should be planted after soil permeability and drainage have improved by planting waterlogging tolerant species. However, at places especially near the coastline (the front line of coastal forests), considerations of salt wind stress should also be made other than waterlogging when selecting species other than *P. thunbergii*. Second, if waterlogging is maintained "partial" (topsoil not waterlogged), *P. thunbergii* seedlings can change their fine root growth distribution and maintain aboveground activity. Third, if the waterlogging duration is relatively short, such as several weeks, the water absorption function of roots can rapidly recover after the release from waterlogging.

Although limited to the experiment conditions of this study, knowledge was obtained of conditions in which *P. thunbergii* seedlings can maintain growth and survive, which is expected to benefit the restoration of the Tohoku region's coastal forests.