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Complex environmental factors affecting the decline of *Pinus densiflora* in the Seto Inland Sea area of western Japan

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Abstract

This study reconsidered the cause of forest decline of Japanese red pine (*Pinus densiflora* Sieb. et Zucc.) in the Seto Inland Sea area, western Japan. Although the decline in pine forests was attributed to pine-wood nematode infection, the stress of air pollution was also shown to have negative physiological effects on pine needles. Secondary pollutants related to NOx accumulate in the morning dew then liquid-phase free radicals (•OH) form by photochemical reactions on the needle surface. The stress of polluted dew induces faster needle senescence and defective needle gas exchange. The influence of atmospheric O_3 and SO_2 was not significant.

Understory vegetation also had negative physiological effects on the overstory pine needles through competition of roots for water and nutrients. Abandonment of management accelerates growth of understory vegetation causing decline of *P. densiflora* plantations. Each of these stresses was shown to independently and significantly reduce needle photosynthesis, which consequently seemed to reduce pine resistance to pathogens.

In many cases, air pollution and progressing succession have not been considered as important causes of *P. densiflora* decline. Careful on-site atmospheric chemical and eco-physiological measurements are therefore important for accurate evaluations of the conditions of pine growth and the causes of decline.

Key words: Dew, Hydroxyl radical, Photosynthesis, *Pinus densiflora*, Succession

1. Introduction

Japanese red pine (*Pinus densiflora* Sieb. et Zucc.) is an evergreen coniferous tree that has been planted widely throughout Japan for several hundreds of years; pure *P. densiflora* forests in western Japan are mostly secondary (Miyawaki, 1984). However, today, almost none of these forests are being used or managed, and most are in decline. Although this decline is usually attributed to pine wood nematode infection (*e.g.*, Kishi, 1995), many anthropogenic factors are also thought to be important. For example, the physiological deterioration of needle leaves as a result of air pollution is one such factor. From the 1960's to 1970's, the high concentration of SOx discharged from industrial areas has accelerated forest decline around the Seto Inland Sea area, western Japan (Tsuno & Sato, 1976a; b). However, the emission of SOx drastically decreased after the 1970s and, in recent years, atmospheric SO_2 concentrations have fallen within acceptable levels. On the other hand, levels of atmospheric NO_2 and suspended particulate matter, which are indexes of auto exhaust pollution, have been increasing, particularly in urban areas (Environmental Agency, 1998). Furthermore, pollution has expanded into rural areas because of the opening of new express highways and increased total NOx emissions from vehicles, especially those with diesel engines.

2. Effects of radicals generated in polluted dew

To evaluate the effects of air pollution on the decline of *P. densiflora* forests, various research has been conducted around Mt. Gokurakuji (34° 23′N, 132° 19′E, 693 m a.s.l.), north of the Seto Inland Sea. A few kilometers south, on the seaward side, the polluting effects of industrial areas and heavy traffic (mainly associated with the Sanyo-Express Highway) can be observed; obvious damage to the pine forests is visible.

Significant correlations have been observed between atmospheric NOx concentrations, which are on average lower than 30 nl l^{-1}, and tree mortality and shedding of needles (Naemura *et al.*, 1997). Atmospheric NO_2 concentrations are negatively correlated with needle longevity and positively with needle ethylene emission (Kume *et al.*, 2000a). The net photosynthesis (*Pn*), stomatal conductance (*gl*) and intercellular CO_2 concentration (*Ci*) near saturating irradiance in declining forest stands were shown to be lower than those in non-declining stands (about 30, 50 and 20 % lower, respectively). Moreover, the emission of stress ethylene from needles increased significantly even at quite low atmospheric NO_2 concentrations (8 nl l^{-1} year^{-1}), increasing with increasing concentrations, suggesting that atmospheric NOx or related substances

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induce higher ethylene emission in declining stands (Kume *et al.*, 2001a). However, when various plants were directly exposed to NO_2 over a short period, at least 100 nl l^{-1} NO_2 was needed to cause detectable effects (*e.g.*, Natori & Totsuka, 1984). Although the indirect toxic effect of NO_2 via O_3 formation is much more damaging than the direct effect of atmospheric NO_2 (Heber *et al.*, 1995), the causes of physiological needle disorders are thought to be NOx-related substances rather than O_3 (Kume *et al.*, 2000a; 2001a). In addition, examination of wet deposition in declining stands at Mt. Gokurakuji revealed that neither the rain nor dew was severely acidic (pH 4 - 5). Soil characteristics (pH, nitrogen content and C/N ratio) and altitude had no significant correlation with *P. densiflora* decline (Kume *et al.* 2000a; 2001a).

On clear days there is a large diurnal air temperature range in the Seto Inland Sea area. On such days, throughout the year, dew often forms during the night; the frequency of natural dew formation is about 30 % in the summer (Chiwa *et al.*, 2003). Under these conditions, secondary pollutants related to NOx accumulate in the morning dew (Nakatani *et al.*, 2001) and/or fog (Kobayashi *et al.*, 2001). The accumulation of dry deposition on needle surfaces and concentrations of NO_3^- and SO_4^{2-} in the dew were found to be clearly different between declining and non-declining forest areas (Chiwa *et al.*, 2003). Higher dry deposition rates in declining areas enhance concentrations of NO_3^- and SO_4^{2-} in the dew; these pollutants generate hydroxyl radicals (•OH) on needle surfaces (Arakaki *et al.,* 1998; Nakatani *et al.,* 2001). NO_3^-, and especially NO_2^-, are sources of •OH generation during photochemical processes associated with wet deposition (Arakaki *et al.*, 1999a, b; Nakatani *et al.*, 2001). In addition, hydrogen peroxide, iron and oxalate, which are present in wet deposition (Yamashita *et al.* 1994), promote photo-formation of •OH (Zepp *et al.*, 1992; Zuo & Hoigné, 1992; Arakaki & Faust, 1998; Arakaki *et al.*, 1998; 1999a). The concentrations of these •OH sources tend to be much greater in dew than rain (Arakaki *et al.*, 1998, 1999a); and •OH photo-formation rate in dew was several times greater than that in rain (Arakaki *et al.*, 1999b).

In the declining stands of Mt. Gokurakuji, •OH formation rates in dew on needle surfaces were found to be about twice as large as those in the non-declining stands (Nakatani *et al.*, 2001). Under experimental conditions, the generation of free radicals in polluted dew water decreased *gl* or caused abnormal stomatal opening in *P. densiflora*, decreasing *Pn* and increasing ethylene emission from needles (Kume *et al.*, 2001b; Kobayashi *et al.*, 2002). Therefore, •OH formation on the needle surface is thought to play an important role in the physiological decline of needles.

In remote forests, O_3 might act as the sole harmful air pollutant (Gregg *et al.*, 2003), because O_3 is relatively stable in the air and can be transported a long distance (Akimoto *et al.*, 1996). On the other hand, atmospheric NO_2, together with other pollutants, always acts near the pollution source. NO_2 is assimilated from plant surfaces and utilized for nitrogen resources (Morikawa *et al.*, 1998). Because NOx therefore has both positive and negative effects on plant growth, determination of the cause-and-effect relationship between forest decline and NOx-related air pollution is likely to be complex (*e.g.*, Gregg *et al.*, 2003). The effect of interactions between plant species with different NOx sensitivities will also influence the process of decline.

3. Effects of secondary succession

Pinus densiflora is a common pioneer tree species that naturally occurs in the early stage of succession when soil nutrient conditions and the water retention capacity are poor, and competition is not so severe. These characteristics make *P. densiflora* a suitable tree for repeated coppicing, especially in western Japan where the substratum is low-nutrient granite. In this region, *P. densiflora* was planted in a broad area originally not a natural habitat of this species, but repeated coppicing has kept these areas as pine forests for several hundreds of years. However, the use and management of these forests has been declining since the early 1960's, and today almost all *P. densiflora* forests have been abandoned. Abandonment of plantation management accelerates the growth of understory vegetation and promotes secondary succession (Da & Ohsawa, 1992; Fujihara *et al.*, 1992).

The understory vegetation that invades during secondary succession has a negative physiological effect on overstory pine needles through competition of roots for water and nutrients (Kume *et al.*, 2003). Iida (2003) also showed significant changes in hydrological processes of *P. densiflora* forests during secondary succession and concluded that the sharp decline in *P. densiflora* was caused by increased evapotranspiration from understory vegetation because of cessation of mowing of the lower vegetation layer. In addition, seedlings of *P. densiflora* were shown to be more susceptible to pine wilt disease when grown with competitors than when alone (Nakamura *et al.*, 1995).

In the Seto Inland Sea area, significantly lower mortality of *P. densiflora* has been observed on ridges and peaks (the natural habitat of this species) where the development of understory vegetation is restricted (Fujihara *et al.*, 2000; Miki *et al.*, 2001). Miki *et al.* (2003) suggested that drought resistance and pine wilt disease resistance are correlated. Further study is needed to understand the interactions between the growing conditions and physiological characteristics of *P. densiflora*.

3. Conclusion

Pinus densiflora is sensitive to various air pollution stresses. Proper evaluation of liquid phase pollutants is therefore needed for elucidation of the effect of air pollution on the physiological decline of *P. densiflora* in Japan. *Pinus densiflora* is also sensitive to growth of understory vegetation. Each stressor was previously shown to independently reduce needle photosynthesis by 20 - 40 % in comparison with control trees, lowering the matter production efficiency of individual trees (Kume *et al.*, 2000a; 2003). Changes in matter economy decrease the size of new shoots and change the allometry of shoots (Kume *et al.*, 2000b). The resulting decrease in photosynthesis seems to consequently reduce the resistance of these pines to pathogens (Fukuda, 1997). Damage to pine forests as a result of pine wilt disease was shown to be significantly correlated with succession (Fujihara *et al.*, 1992; Shiratsuki *et al.*, 1999). Although pine wilt disease epidemics accelerate the decline of pine forests, abandonment of plantation management seems to be the most important factor affecting sustainability of *P. densiflora* forests in the long term. In later stages of physiological decline, it might be difficult to distinguish between physiological decline and direct damage by biotic agents (Bell *et al.*, 1993). Moreover, synergetic effects are thought to have an effect on pine decline. This study clearly shows that various anthropogenic factors affect the decline of *P. densiflora* forests in Japan. In many cases, air pollution stress and succession have not been considered as causal factors. This study shows that careful on-site atmospheric chemical and eco-physiological measurements are very important for accurate evaluations of the conditions necessary for pine growth and the cause of decline.

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