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A Trial for Reforestation After Forest Fires with Sakhalin Spruce in the Northern Most Japan

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Abstract

Sakhalin spruce (*Picea glehnii* Masters) is a common species native to Hokkaido Island in northern Japan. This tree species can grow in infertile regions, such as serpentine, swamp, volcanic ash soils, etc. In comparison to other spruces, Sakhalin spruce classified as slow growing spruce species. The growth, photosynthetic rate, and concentration of nitrogen in needles were relatively lower for Sakhalin spruce compared to other spruce species. However, Sakhalin spruce had greater needle longevity, and required lower nutrients for growth than other spruce species planted in Japan. These distinct ecophysiological traits observed for Sakhalin spruce were advantageous for growth on serpentine soils, which are low in nutrients. Serpentine soil contains high concentrations of magnesium and heavy metals, such as chromium and nickel. Sakhalin spruce grown on serpentine soil had shown a high capability for excluding these elements. The Teshio Experimental Forest undertook a reforestation project, in which about half a million Sakhalin spruce seedlings were planted on a serpentine barren area that had been disturbed by four times of forest fires during these 10 decades. The climatic conditions of this area were severe, especially in winter months. Sakhalin spruce planted on serpentine barren area endured these stresses and survived in winter seasons. Based on this reforestation trial, Sakhalin spruce is a suitable tree species for this disturbed site with a high capacity of adapting severe climatic and edaphic conditions.

Key words: *Picea*, serpentine soil, forest rehabilitation, disturbance, nutrient physiology

Introduction

Hokkaido Island, in northern Japan, was known as “Forest Island” because it was entirely covered by various species of tree. However, since 1875, farming has developed and the area of forested lands has decreased. There are now 12,000 km^2 of farmland on Hokkaido Island (15% of the total land area). Intensive development of industry and farming in recent years has also caused increased encroachment on the land surface, increased flooding, and degradation of the soil (Ishigaki and Fukuda 1994).

Reforestation effort has recently been undertaken, to prevent disasters and conserve the forest environments. For example, in the Shiretoko National Park, which is located in northeast Hokkaido and was named a World Heritage in 2005, there were the lands where farming gave up because of harsh natural environment. In 1977, the National Trust movement began to operate in this area (Kikuchi 2005). The contributors of the National Trust purchased former farmland to prevent tourist development and started preserve the natural environment. After the purchase, reforestation work began; and thousands of trees have been planted since 1997 (Kikuchi 2005). The most suitable species for reforestation of this area is the Sakhalin spruce (*Picea glehnii* Masters) (Kayama *et al*. 2007). The edaphic condition of the Shiretoko is characterized by acidic soil, which prevents the growth of many crops (Kikuchi 2005). However, Sakhalin spruce flourishes even in acidic soil (Shiretoko Natural Foundation 2002). The species can also grow well on various types of infertile habitat (Tatewaki 1958) and has a high tolerance of toxic soil (Kayama 2004, Kayama *et al*. 2005, 2006). Therefore, these positive growth characteristics of Sakhalin spruce make an excellent candidate species of tree for reforestation in various edaphic conditions.

For the pioneer of reforestation, Hokkaido University Forests started a project to restore the original vegetation of the barren mountainous slope in the Teshio Experimental Forest (TEF) from 1983 to 1997 (Komiya 1996). In the eastern part of TEF, Hokkaido University, serpentinite distributes on the whole mountainous slope of the barrens where forest fires had occurred four times during 70years in 1900’s (Takaoka and Sasa 1996). Original forest vegetation in these barrens was Sakhalin spruce (Kayama *et al*. 2002, Kayama *et al*. 2005),

In the initial reforestation program between 1983 and 1997, Hokkaido University Forests undertook the restoration of the original vegetation of the barren mountainous slopes of the Teshio Experimental Forest (TEF) (Komiya 1996). In the eastern part of TEF,

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serpentinite is found on all the barren mountainous slopes, where in the 20th century, forest fires occurred four times within 70 years. The Sakhalin spruce was the original forest vegetation in these areas (Kayama *et al*. 2002, Kayama *et al*. 2005).

We present the trial for reforestation effort of the serpentine barrens using with the Sakhalin spruce, and discuss important issues related to the study of reforestation of Sakhalin spruce after forest fires under four categories: (1) the growth characteristics of Sakhalin spruce, (2) the characteristics of serpentine soil, (3) the environmental conditions of the reforestation site, and (4) case studies of the revegetation methods used in the serpentine area.

Growth characteristics of Sakhalin spruce

The distribution area of Sakhalin spruce is Hokkaido, Honshu, Sakhalin, and the Kuril Islands (Tatewaki 1958). The population of Sakhalin spruce in Honshu, Sakhalin and Kuril Islands is sparse, and a major distribution area of this species is Hokkaido Island. Habitats of Sakhalin spruce that is a main component species of vegetation are severe environment compared with those of other species. Sakhalin spruce is distributed in serpentine regions (Photo 1), swamp (Photo 2), volcanic ash soil (Photo 3), sand hills, sites composed of rock and gravel, and sites that have experienced forest fire in the past (Tatewaki 1958, Matsuda 1989). This spruce has a high acclimation capacity in soil environments: e.g., the range of soil pH for its habitats is 3.6 to 7.4 (Nakata and Kojima 1987, Kayama 2004). However, Sakhalin spruce does not compete strongly with other species of tree, so that it is rarely found in fertile soil regions, where other species are dominant (Miyawaki 1977). In view of the peculiarity of the Sakhalin spruce's distribution, Miyawaki (1977) called it the "pitiable Sakhalin spruce."

We firstly examined the growth characteristics of Sakhalin spruce. We compared the growth characteristics of 29-year-old trees of eight spruce taxa on the plantation in the Tomakomai Experimental Forest, Hokkaido University (Kayama *et al.* 2007). Normally, two general categories in plant growth are related to environmental conditions (Chapin *et al.* 1993, Lambers *et al.* 1998): fast-growing and slow-growing species. We found that annual shoot growth of Ezo spruce (*Picea jezoensis* Carr.), which is distributed on fertile habitats in Hokkaido (Miyawaki 1988), was 14.3 cm $year^{-1}$ whereas that of Sakhalin spruce was 9.3 cm $year^{-1}$. Moreover, tree height and DBH were larger for Ezo spruce than those for the Sakhalin spruce. We defined that Ezo and Sakhalin spruces were classified as fast-growing and slow-growing spruce species, respectively.

Ezo spruce had high photosynthetic capacity in younger needles, and a high concentration of nitrogen in needles, which was closely related to its photosynthetic capacity (Lambers *et al.* 1998). By contrast, photosynthetic capacity in younger needles and concentration of nitrogen in needles were lower for Sakhalin spruce than those for Ezo spruce. However, Sakhalin spruce had long needle longevity, and maximal needle age was about ten years. The photosynthetic capacity and photosynthetic nitrogen use efficiency (PNUE), which is an indicator of the allocation of leaf nitrogen to the photosynthetic apparatus (Field and Mooney 1986), remained high with Sakhalin spruce until the needles were six years old. Sakhalin spruce also had low demand for nutrients, and the concentration of nitrogen in needles was lower than other spruce species grown in the same nursery (Kayama *et al.* 2005, 2006). These characteristics may facilitate its early acclimation to infertile habitats.

Sakhalin spruce also had low tolerance of shade (Kayama 2004). When Sakhalin spruce grown in an understory conditions at low photosynthetic photon flux (PPF), the photosynthetic capacity of this species was relatively low, and its photosynthetic rate was not saturated until 1500 μmol $m^{-2}s^{-1}$ PPF (Kayama 2004). However, Sakhalin spruce was able to survive in the understory, by extending its needle longevity (Kayama 2004).

Characteristics of serpentine soil and plant tolerance against its soil

In many parts of the world, a serpentinite is outcropped, and particular floras are found (Brooks 1987). In Hokkaido, the Kamui-kotan metamorphic belt runs from north to south, and serpentinite is distributed along it (Mizuno and Nosaka 1992). The serpentinite region in the Teshio Experimental Forest (45°N, 142°E) is located in the most northerly part of the metamorphic belt (Photo 4), where the forest consists entirely of Sakhalin spruce (Photo 1, Nakata and Kojima 1987, Matsuda 1989). Serpentine soil, which is created by the weathering of serpentinite, is characterized by an excess of elements such as Ni, Cr, and Mg, a low Ca/Mg ratio, and low levels of several essential nutrients for plant growth (Proctor 1971, Brooks 1987).

In the presence of these negative edaphic factors, toxicity of Ni is the most serious problem for plant growth on serpentine soil, when soil pH is below 7.0 (Mizuno and Nosaka 1992). Excess Ni has a negative effect on various physiological activities, and inhibits root growth and the photosynthetic capacity of plants (Jones and Hutchinson 1988a, Jones *et al.* 1988, Miller and Cumming 2000, Kayama *et al.* 2006). Serpentine soil also has minimal silt and clay content, and is typically shallow soil (Brady *et al.* 2005). The water-holding capacity of serpentine is therefore low, and water deficiency occurs frequently (Freitas and Mooney 1996, Curtis and Claassen 2005). All these characteristics make serpentine soil a harsh environment for plant growth.

To survive and grow in serpentine soil, plants require a high tolerance of negative edaphic factors, especially the toxic metals in this soil (Brooks 1987). The tolerance mechanisms of plants that can handle high concentrations of toxic metals in soils generally either restrict the uptake and translocation of metals (exclusion), or accumulate the metal in a non-toxic form (accumulation) (Baker 1987). The concentration of Ni in needles of Sakhalin spruce grown on serpentine

Photo 1. Pure forest of Sakhalin spruce on serpentine region in the Teshio Experimental Forest.

Photo 2. Dwarf shrub of Sakhalin spruce in swamp in the Teshio Experimental Forest.

Photo 3. Forests of Sakhalin spruce on volcanic ash soil in Akan National Park, eastern Hokkaido.

Photo 4. Outcropped serpentine substance in the Teshio Experimental Forest.

Photo 5. Serpentine barren area in the Teshio Experimental Forest.

Photo 6. Aerial photograph of the reforestation site in the serpentine barren, Teshio Experimental Forest (the Nakanomine Research Site)

S slope **NW slope**

Photo 7. Sakhalin spruce planted S and NW slopes in the serpentine barren (upper part: S slope, lower part: NW slope) in the Nakanomine Research Site, Teshio Experimental Forest.

Photo 8. Sakhalin spruce planted S slope in serpentine barren in winter exposed above the snow cover.

Photo 9. Snow fence established in reforestation site for accumulation of snow as shelter against winter desiccation.

soil is lower than in other species of spruce (Blandon *et al*. 1994, Kayama *et al*. 2005).

Sakhalin spruce is therefore a Ni excluder (Kayama *et al.* 2005, 2006). For tree species, symbiosis with ectomycorrhizae is important in excluding toxic metals, and ectomycorrhizal species in serpentine soil provide protection against toxic metals (Panaccione *et al*. 2001, Kayama *et al*. 2005, Kayama 2006). When ectomycorrhizae are inoculated into the roots of tree species, the concentration of Ni in the leaves decreases and root growth accelerates, despite the high concentration of Ni (Dixon and Buschena 1988, Jones and Hutchinson 1988a, b, Jones *et al.* 1988, Wilkins 1991).

We planted seedlings of three spruce species (Sakhalin, Ezo and Norway) in serpentine soil, to examine their tolerance to harsh soil conditions (Kayama *et al.* 2005). The growth of the Sakhalin spruce on serpentine soil was almost same as on non-serpentine (i.e., brown forest) soil. In contrast, growth of the other two spruces on serpentine soil was significantly less than on brown forest soil. Moreover, the roots of the Sakhalin spruce seedlings on serpentine soil were infected at a high percentage with ectomycorrhizae, and the concentration of Ni in their needles and roots was found the lowest of the three spruce species examined. On the contrary, the percentage of ectomycorrhizal infection was over 20% lower for Ezo spruce seedlings on serpentine soil than that for Sakhalin spruce. Concentration of Ni in needles and roots was higher for Ezo spruce seedlings on serpentine soil than that for Sakhalin spruce; therefore, the roots of Ezo spruce with no ectomycorrhizal infection may have absorbed Ni. Based on these findings, we conclude that ectomycorrhizal infection provides Sakhalin spruce a high capacity to exclude Ni. The capacity of ectomycorrhizal infection to exclude toxic heavy metals in serpentine soil improves the growth of spruce seedlings and saplings.

We also compared the growth characteristics of 60-year-old trees of three spruce species (Sakhalin, Ezo and Norway) planted on serpentine and non-serpentine (i.e., brown forest) soils (Kayama *et al.* 2002). There was no significant difference in the shoot growth of Sakhalin spruce on serpentine and non-serpentine soil, whereas on serpentine soil the growth of the other two spruces was reduced. Needle longevity of Sakhalin spruce on serpentine soil was about ten years, the longest of the three spruces. On serpentine soil, Sakhalin spruce maintained high photosynthetic capacity in its needles until it was eight years old. The concentration of nickel in Sakhalin spruce needles on serpentine soil was relatively low. These results indicate that Sakhalin spruce was better able to acclimate to serpentine soil than Ezo and Norway spruces.

Environments of serpentine barren

Serpentine regions have peculiar flora with their own species distribution (Brooks 1987). When disturbed, the vegetation of the serpentine region is relatively fragile (Curtis and Claassen 2005, O'Dell and Claassen 2006a). If the vegetation of a serpentine region has declined, it recovers only too slowly (Curtis and Claassen 2005). For example, when forest fire occurred in the serpentine region, the speed of regeneration was relatively slow (Millar 1981, Arabas 2000). The serpentine region also contains metal and asbestos mines, and these areas have remained as barrens nearly a bare ground for decades (Moore and Zimmermann 1977, Smith and Kay 1986, Hoover *et al.* 1999). The barren areas of the serpentine region are also susceptible to erosion and landslides, which occur frequently (Lee *et al.* 2004, O'Dell and Claassen 2006a). Fibres from the asbestos mines are spread by wind, creating a health hazard for humans (Moore and Zimmermann 1977). The original vegetation of the serpentine barren area should therefore be restored, to prevent disasters and conserve the environment.

In the eastern part of TEF, there is a serpentine barren area (Photo 5). This barren area suffered from forest fires for four times in the 20th century (Takaoka and Sasa 1996); only dwarf bamboos (*Sasa senanensis* and *S. kurilensis*) regenerated (Kayama *et al*. 2000, Kayama 2006). Landslides occurred in this serpentine barren area (Photo 5). Fortunately, *S. senanensis* was able to survive, even when its aboveground organ was destroyed by fire (Sasa *et al.* 1992). It regenerated successfully after being burnt, and serpentine barren area in TEF was escaped from the exposure of its substrate. However, with the exception of the dwarf bamboo, the plant species making up the original vegetation were unable to regenerate. This was because of the dwarf bamboo's extremely high reproductive capacity.

In addition, the climatic conditions in this barren area are relatively severe. Northernmost Hokkaido is a region of strong winds, especially in winter (Takaoka 1993, Kayama *et al.* 2000). The regeneration of plants in the serpentine barren area in TEF was therefore hampered by edaphic and climatic factors, and by the dominance of the dwarf bamboo.

To analyze the environmental conditions for reforestation, we examined the climatic conditions, the soil properties, and the growth characteristics of the dwarf bamboo in the serpentine barren area in TEF (Kayama *et al.* 2000, Kayama 2006). The minimum temperature of this region in winter was –18.9°C. The wind direction in winter was mostly southwest. The daily average winter wind speed was 5.1 m sec^{-1} (until early March). In latter March, it reached a maximum value of 7.5 m sec^{-1}.

We analyzed the south-facing slope (S slope) and the northwest-facing slope (NW slope) of the serpentine barren area in TEF. The micro-topography of the two slopes differs. The S-slope was a ridge slope, whereas the NW slope was a valley slope. The average depth of snowfall in winter was deeper for the NW slope (160 cm) than for the S slope (80 cm). Snow accumulation was affected by micro-topography, and the NW slope might be favorable of snow accumulation. Moreover, the concentrations of nutrients in the soil and its available depth were higher for the NW slope than those for the S slope. It is likely that the pattern of

accumulation of organic matter was similar to that of snow, favoring the NW slopes. The height of the dwarf bamboo, its photosynthetic rate, and its concentration of nutrients were higher on the NW slope than that of the S slope. Dwarf bamboo cannot survive exposure above the snow depth (Sasa *et al.* 1994). The growth of dwarf bamboo on the S slope was limited by the shallow accumulation of snow and the poor nutrient conditions.

Case studies of revegetation on the serpentine barren

Despite the harsh environmental conditions in the serpentine barren area, there have been many attempts to restore its original vegetation (Moore and Zimmermann 1977, Smith and Kay 1986, Koide and Mooney 1987, Hoover *et al*. 1999, Curtis and Claassen 2005, O'Dell and Claassen 2006a, b). Most revegetation studies have used endemic herbaceous species distributed in serpentine soil (Smith and Kay 1986, Koide and Mooney 1987, Curtis and Claassen 2005, O'Dell and Claassen 2006a, b). However, experiments showed that some herbaceous species could not survive and/or grow without fertilization (Smith and Kay 1986, O'Dell and Claassen 2006a, b). In contrast, over 90% of Jeffrey pine (*Pinus jeffreyi*) grown on the serpentine region survived, even without fertilization (Hoover *et al.* 1999). This led Hoover *et al.* (1999) to suggest that mycorrhizal inoculation can be used to increase revegetation on serpentine soil. Indeed, even without any special inoculation of ectomycorrhizae, the growth of Sakhalin spruce planted on serpentine soil was enhanced by its natural symbiosis with ectomycorrhizae (Kayama *et al.* 2005). Sakhalin spruce is consequently a useful tree species for the revegetation of serpentine soil.

To restore the original vegetation of the serpentine barren, TEF began a reforestation project in 1983 (Komiya 1996). At the serpentine barren had disturbed by forest fires, more than 530,000 seedlings of Sakhalin spruce were planted as a reforestation experiment from 1983 to 1997 (Komiya 1996). However, dwarf bamboo coverage restricts the growth of Sakhalin spruce. To secure space to plant the Sakhalin spruce seedlings, a strip cutting of dwarf bamboo was mown at intervals of two meters along the contour of the slope, and the roots of dwarf bamboo were dug out to prevent regeneration. Seedlings of Sakhalin spruce were planted on the mown areas at intervals of 2 m. After planting, the dwarf bamboo was mown for seven years, because the regenerated bamboo had the effect of shading the Sakhalin spruce seedlings. Sakhalin spruce had the lowest shade tolerance of the three conifers (*Picea glehnii*, *P. jezoensis*, *Abies sachlinensis*) native to Hokkaido (Kayama 2004), and it is therefore likely that shading by dwarf bamboo would suppress its growth. As a result of the continuous tending practices, the landscape of the reforestation site shows the view of like a tea plantation (Photo 6).

From 1999 when reforestation project was finished, we performed follow-up survey about growth characteristics of Sakhalin spruce (Kayama *et al.* 2000, Kayama 2006). The tree height of the Sakhalin spruce was 110 cm on the south-facing slope (S slope), and 232 cm on the northwest-facing slope (NW slope) (Photo 7). The tree height of Sakhalin spruce on the two

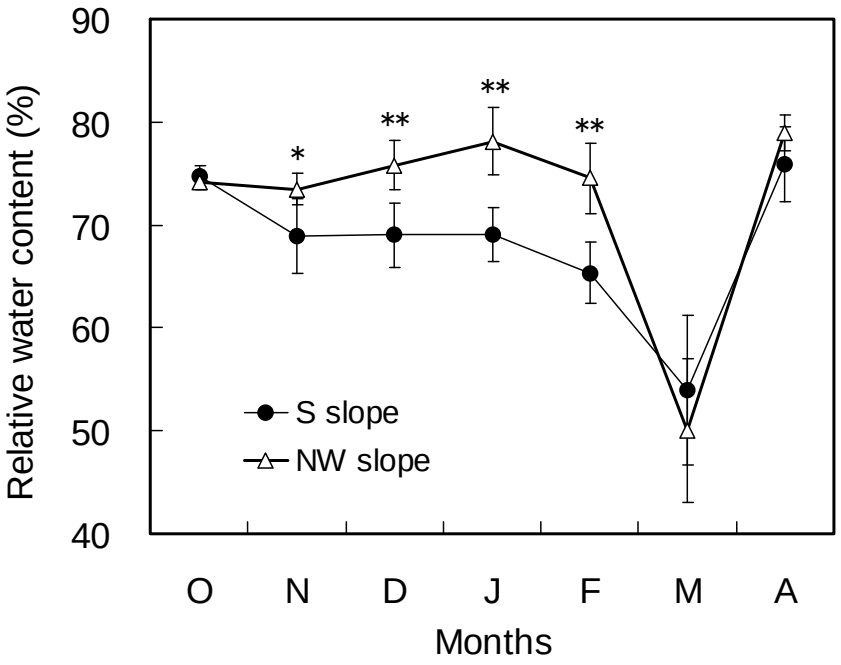

Fig. 1. Relative water content for 2-year-old needles of Sakhalin spruce exposed above the snow planted on the S and the NW slopes (From October 2003 to April 2004, 12:00-14:00, n=12). Asterisk shows significant difference (* $P<0.05$, ** $P<0.01$) based on t-test between values of S and NW slopes.

types of slope was less than the height of the dwarf bamboo from 1996 onwards, and the shoot growth of Sakhalin spruce on the S slope was reduced from the same year. The dwarf bamboo usually acts as a shelter against strong wind, but it was fallen down in the snow when snowfall increased above 80 cm (Sasa *et al.* 1994). As a result, the dwarf bamboo did not act as a "shelter" plant in winter. The shoots of Sakhalin spruce exposed above the snow usually suffered from stress, and over half the needles were shed during winter (Fig. 1, Photo 8). We measured the relative water content (RWC, Marchand and Chabot 1978) in the needles of Sakhalin spruce exposed above the snow, in order to examine desiccation stress in winter.

The RWC of needles decreased from November for the S slope, and in March for the NW slope (Fig. 2). The RWC reached a minimum value in March 2004 for both slopes, and recovered in April 2004. The RWC of shoots of the Sakhalin spruce exposed above the snow on the S slope may have suffered from desiccation stresses for a longer period than those on the NW-slope.

The RWC of needles at the low position of Sakhalin spruce canopy protected by snow cover was 75% in March, with no effects of desiccation stresses (Kayama 2006). Two-year-old needles showed high photosynthetic rates for both slopes (Fig. 3). In contrast, the photosynthetic rate at light saturation (P_{sat}) in August 2003 was reduced in two-year-old needles at the high position of the canopy on both slopes (Fig. 3). The stomatal conductance (gs) of the high-position needles was lower than for the low-position needles (Fig. 3). The high-position needles may also have suffered from drought stress in the growth period; as a result, P_{sat} and gs may have been reduced. The low-position needles of the Sakhalin spruce had a shorter life on the S slope (Fig. 2). From three years of age onwards, the photosynthetic rate of the needles and their concentrations of nitrogen were significantly lower for the S slope than for the NW slope (Kayama 2006). Soil nutrients were poor for the S slope, which suggests that needles on the S slope translocate nutrients from old needles to young needles prior to needle shedding. These characteristics may enable the Sakhalin spruce to grow in infertile soil conditions.

Many snow fences were built at different points on the reforestation site where the growth of Sakhalin

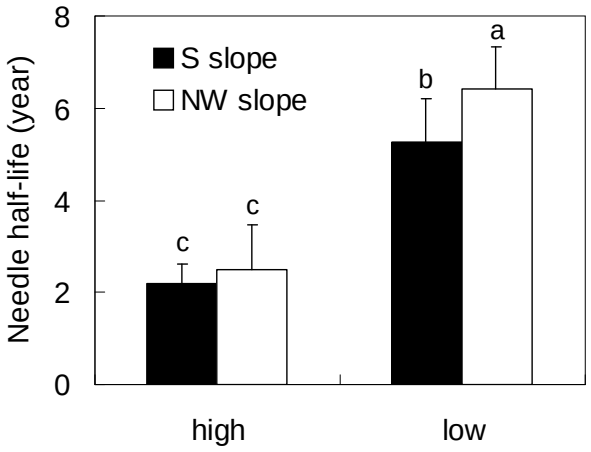

Fig. 2. The year of needle half-life estimated needle longevity of Sakhalin spruce planted on the S and the NW slopes (October 2003, n=12). "High" position is located above the snow cover (S slope: 90cm, NW slope: 180 cm). "Low" position is located in the snow cover (S slope: 50cm, NW slope: 130 cm). The values between different alphabets show significant difference (P<0.05) based on Tukey test.

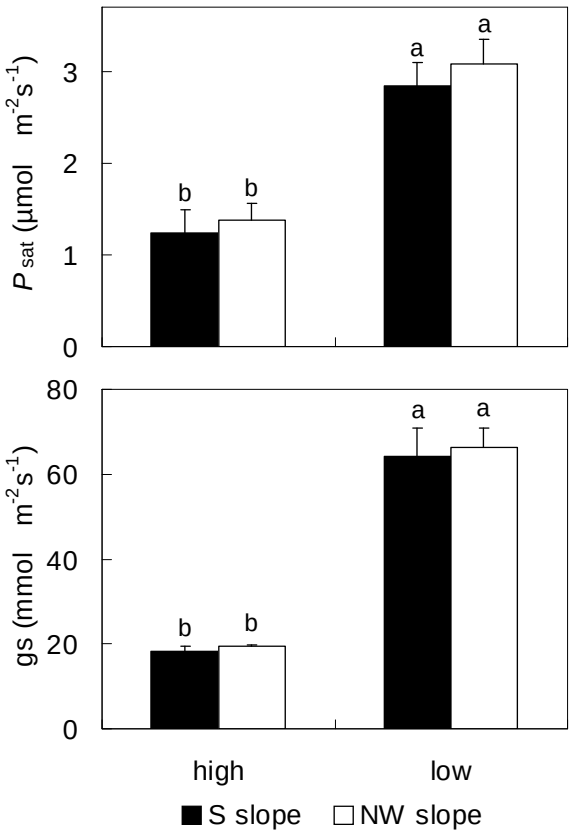

Fig. 3. The net photosynthetic rate at light saturation (P_{sat}) and stomatal conductance (gs) for two positions of two-year-old needles of Sakhalin spruce planted on the S and the NW slopes (August 2003, n=8). Values of P_{sat} and gs are expressed as area base. The values between different alphabets show significant difference (P<0.05) based on Tukey test.

spruce was poor, to accumulate and retain snow that would then protect the seedlings from winter desiccation damage (Photo 9). However, there was no noticeable improvement in the growth of Sakhalin spruce (Kayama 2006), possibly because the accumulated snow had little effect because the wind direction in winter had not been taken into account. Moreover, the structure of the fence required improvement, to increase the amount of snow cover. When the depth of snow increases, the Sakhalin spruce and the dwarf bamboo will be protected against stresses in winter.

Conclusion

The growth characteristics of Sakhalin spruce demonstrate that the species is a slow-growing spruce, with long needle life and lower nutrient demand for growth and development. The species also has high capacity to exclude toxic elements in serpentine soil, especially nickel. Ectomycorrhizal association with this species probably plays an important role in excluding toxic elements in serpentine soil. Sustaining symbiosis with ectomycorrhizae, Sakhalin spruce can survive and grow in serpentine barren areas, so that the Sakhalin spruce is a suitable species for revegetation. If tending management for Sakhalin spruce will continue to eliminate the dwarf bamboo, the spruce may be able to grow favorably without effects of shading by bamboo. Sakhalin spruce could prove a suitable tree species for reforestation in cold and windy conditions, since it can endure and survive stresses during winter months. It has also been used to create windbreaks alongside roads (Civil Engineering Research Institute for Cold Region 2003, Torita *et al.* 2004).

Growth of Sakhalin spruce was not uniform throughout the reforestation areas in serpentine soil in TEF. In particular, the climatic conditions of the S slope were relatively severe, and the soil of this slope was very shallow and infertile. The Sakhalin spruce planted on the S slope survived by the efficient transfer of nutrients from old needles to new ones. With the use of a snow-retaining fence, Sakhalin spruce seedlings may be able to survive and grow, even in the severe conditions of the S slope.

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