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The effects of intensive forest fire on forest revegetation patterns in interior Alaska (mid-term report, February 2007)

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Abstract: To detect the revegetation patterns of *Picea mariana* forests after large-scale fire occurred in the summer of 2004, we monitored 96 1 m × 1 m quadrats within 16 10 m × 10 m plots at Poker Flat, interior Alaska, USA, from the spring of 2005 to the summer of 2006. To detect relationships between fire intensity and revegetation, variously-burned sites were selected, i.e., the ground cover mostly consisting of *Sphagnum* remained patchily. In six 1 m × 1 m quadrats on each plot, we recorded plant cover on each species and marked all tree seedlings. Vegetatively-recovered shrubs and sedges were dominant on the unburned ground surface, while *Epilobium angustifolium* was common on burned surface. Of bryophytes, survived *Sphagnum* spp. were dominant on the unburned surface, but did not change in cover from 2005 to 2006. While, *Ceratodon purpureus* increased in cover on the burned surface. Therefore, the plant community structures differed greatly between unburned and burned sites. Furthermore, the safe sites for seedling emergence varied greatly between tree species, i.e., *Picea mariana* germinated more on *Sphagnum* mat and *Betula neoalaskana* and *Populus tremuloides* emerged only on the burned surface. The survival of *P. mariana* did not differ between the burned and unburned surfaces, while the growth was slower on the mat of *Sphagnum*. Broad-leaved trees grew faster than *P. mariana*. The recovery of *P. mariana* is not plausible in the present state, and the re-establishment of *Sphagnum* must be a key to promote the regeneration to *P. mariana* forest. The surveys on the relationships between revegetation patterns and its related environmental factors will be continued in 2007.

Key words: forest fire; *Picea mariana*; plant cover; seedling emergence, growth and survival; permanent plot; *Sphagnum*

Introduction

Wildfires with different intervals, intensities and scales operate plant community structures and functions in regions where fires occur frequently, since fires alter the above-and below-ground environments, i.e., light and nutrient (Johnson 1992; Keane et al. 2004). Wildfires often take place in taigas, e.g., Siberia and Alaska, due to lightning (van Cleve et al. 1986; Engelmark 1999).

Picea mariana is adapted to establish wet and nutrient-poor habitats that are distributed more in north slopes of mountains (van Cleve et al. 1986). On forest regeneration, the initial stages are particularly important to determine the patterns and dynamics. In Alaska, ordinary forest fire is so-called crown fire (Bonan & Shugart 1989). 'Crown fire' is that the ground- surface cover is incompletely burned. *P. mariana*, that is semi-serotinous tree, disperses seeds after fire after the crown fire more than unburned periods (Bonan & Shugart 1989). In discontinuous permafrost regions, the scenarios of succession differ between north and south slopes, due mostly to the presence of permafrost on the north slopes and the absence on the south slopes (van Cleve et al. 1986). Soil properties are also different between south and north slopes in interior Alaska (Ping et al. 2005). In general, *Picea mariana* forest develops more on the north slopes, while mixed white spruce forest establishes on the south slopes.

Since the frequency, intensity and scale of fire will be altered by global warming (Dale et al. 2001; Hinzman et al. 2005), fire may become larger and more intense. Also, fire frequency is related to seasonal-moisture variability in atmosphere (Lynch et al. 2004). As well, permafrost thaw accelerates in boreal peatlands in the last century (Camill 2005). Therefore, we have mentioned the effects of large-scale fire on the regeneration of *Picea mariana* forest on a north-faced slope in interior Alaska. To predict the regeneration patterns, we focus on the regeneration patterns of trees and vegetation changes in this progressive report. The major objectives are: 1) Detecting differences in plant community recovery patterns between burned and unburned grounds, 2) Characterizing regeneration dynamics after wildfire in a discontinuous permafrost zone, and 3) Generalizing the revegetation patterns.

This mid-term report is situated in a comprehensive research on forest community dynamics after large-scale fire (Team Leader, M. Fukuda, ILTS, HU). The summary of researches in 2005 has been previously reported (Tsuyuzaki & Narita 2005). Firstly, we briefly summarize the results surveyed in 2005 in the next section. Then, we report our finding on researches in 2005 and 2006, although we have to say every study has been ongoing.

Study area and methods

Study area

Poker Flat, approximately 50 km north of Fairbanks, interior Alaska, USA, was selected for monitoring revegetation, because of large-scaled and intensive fire, north slope, and high accessibility and convenience. On climate data at Fairbanks during 1971 and 2000, annual precipitation averages 297.4 mm, maximum monthly mean air temperature is 23.0°C in June, and the minimum is -25.0°C in January (ACRC, 2007). The forest fire was recorded in the summer of 2004. Based on tree-ring analysis, we confirmed that the relationship between height and age on *P. mariana* was positively and linearly correlated (Tsuyuzaki & Narita 2005).

In the region, there are three types of upland taiga forests: *Picea mariana*, *Picea glauca*, and *Betula-Populus* (Kielland et al. 1998). Of these forest types, *Picea mariana* forest is characterized by the predominance of *Picea mariana* on nutrient-poor habitats (Bonan & Shugart 1989). Vegetation on Poker Flat is typically categorized into the *P. mariana* forest that is situated in the northern part of Alaskan boreal forest above the boundary between continuous and discontinuous permafrost zones.

Field methods

On a slope at Poker Flat, 16 10 m × 10 m plots were

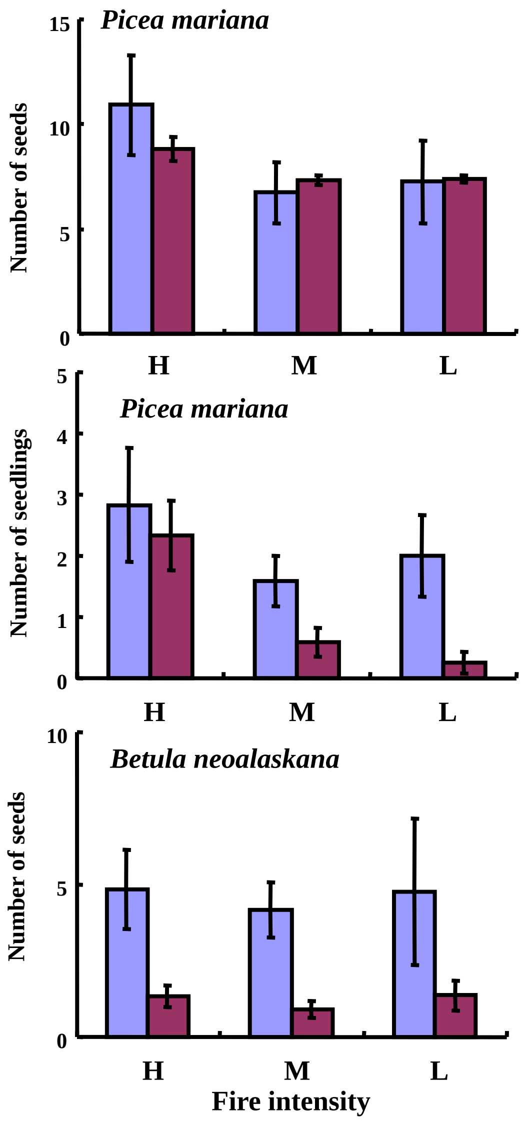

Fig. 1. Number of seeds captured by seed traps with reference to three burned intensities, and number of seeds germinated by the seed germination experiments. Blue columns show the results in spring, and purple columns show the results in summer. Mean number of seeds per trap is shown with standard error. H = heavily-burned, M: moderate, and L = less. On *P. mariana*, number of seeds captured by traps is not different between three fire intensities and between spring and summer (Tukey's test with ANOVA). The number of germinated seeds is different between the two seasons, and is not significantly different between habitats. On *B. neoalaskana,* number of captured seeds is different between the two seasons.

established in the spring of 2005. The burned area on the ground surface was visually estimated in each plot. In each plot, we measured tree height and diameter at breast height (DBH = 1.3 m) for stems ≥ 1.3 m in height. DBH was measured by a tape or a pair of calipers. All dead and alive stems were measured to reconstruct forest structure before the fire. The fallen trees with ≥ 1.3 m in height were included in the measurement. Stem volume was calculated by DBH and height under the assumption of conical-shaped stem.

In each plot, six 1 m × 1 m quadrats were randomly set up. At every census, vegetated area was measured on each quadrat. Then, cover on each species was recorded separately between burned and unburned areas on each quadrat. The voucher specimens will be kept in the Hokkaido University Museum (SAP). Photos were taken on each quadrat at 1.3 m above the ground surface by a fish-eye lens in the summer of 2005, and canopy openness was measured by the photos, using a freeware Gap Light Analyzer ver. 2.0 (Frazer et al. 1999). Albedo was measured ca 1 m above the ground surface on each quadrat in spring and summer, 2005, by a radiometer (MR-22, Eko Instruments, Co. Ltd., Tokyo) that measured wavelength between 0.3 μm and 3 μm. On each point, albedo was measured twice and averaged. Duff (or moss-organic layer) thickness was measured by a steel stake.

Two plastic seed traps were set up on each plot in the summer of 2005. The design of trap is illustrated by Terry’s Lab. In early May and late July 2006, seeds were collected from the seed traps. Then, sampled seeds were performed to seed germination test in an incubator. The conditions of seed germination were 15°C/25°C (12 hr/12 hr) with discontinuous light (12 hr/12 hr) in spring and with continuous light in summer.

When annual tree seedling was observed in any quadrats, each seedling was marked by a numbered flag and was recorded on height, crown diameter and location. The long and short axes of crown were measured, and the crown area was calculated as an oval shape.

For the further studies, we classified into three intensities of forest damages by the fire, i.e., less-, moderately-, and heavily-burned areas, based on burned area and the ratio of alive trees. Less-burned plot (hereafter, i.e., L) is characterized by high *Sphagnum* cover retaining on the ground surface and higher survival rate on trees. Moderately-burned plot (M) is situated between less-disturbed and heavily-disturbed areas, i.e., most trees were dead, but plant cover remained somehow on the ground surface. The variance of mean on burned area in quadrats fluctuated greatly, in particular, in moderately burned plots. Heavily-burned plot (H) is completely burned by the fire, i.e., all stems were killed and more than 80% ground surface was burned out. Based on those investigations, four, six and six plots were grouped into categories L, M and H, respectively.

Table 1. Number of seedlings emerged in 2005 and 2006, with reference to burnt and un-burnt sites. The density (/m^2) is shown in parentheses.

		Habitat	
	Year	Burned	Unburned
Picea mariana	2005	364 (11.2)	95 (1.5)
	2006	200 (6.2)	63 (1.0)
Betula neoalaskana	2005	-	20 (0.3)
	2006	2 (0.0)	17 (0.3)
Populus tremuloides	2005	-	93 (1.5)
	2006	-	169 (2.7)
Salix spp.	2005	-	4 (0.1)
	2006	-	34 (0.5)
Unidentified	2005	-	-
	2006	-	11 (0.2)
Total	2005	364 (11.2)	212 (3.3)
	2006	202 (6.2)	294 (4.6)

*: The burnt area is based on the area determined in 2005. The values in 2005 are corrected from the research in 2006.

Statistical analysis

Linear regressions were applied to observe relationships between dependent variables (e.g., stem height) and independent variables (e.g., DBH). The differences in stem height and crown area were examined between habitat on *P. mariana*, and between *P. mariana* and broad-leaved tree taxa on the burned surface by ANOVA (Zar 1999). The number of seeds captured by seed traps and the number of germinated seeds were compared between L, M and H and between spring and summer by Tukey’s test after ANOVA.

The determinants on albedo were examined by a multiple regression analysis with a backward procedure. At the first step, all examined environmental factors, incident radiation, canopy openness, burned area and plant cover on each quadrat were input to the regression.

Brief summary and additional remarks on surveys in 2005

Fires in 2004 and older

In every plot, 5-54 *Picea mariana* stems ≥ 1.3 m established with a 13.0 m in maximum height. Three other tree taxa, *Alnus crispa*, *Betula neoalaskana* and *Salix* spp., were recorded with extremely-low frequency. In the 16 plots, 97% of tree stems was likely to consist of *Picea mariana* before the fire. Owing to the 2004 fire, 81% of *Picea mariana* stems were burned and dead, and the total stem volume declined about 78%. The unburned ground surface was covered mostly by *Sphagnum* spp. After the fire, the unburned plant cover ranged from 0% to 100% on the ground surface, indicating that the forest floor was patchily burned with various scales and thus was suitable for this study.

Sampled tree cores showed that the maximum age was 174. Relationship between tree height (m, independent variable x) and age (yr, dependent variable y) was explained by a linear regression (y = +0.05x + 0.05, r^2 = 0.78, P < 0.01). The stem-diameter growth has a peak at 40-60 years (and probably 130-140 years) before 2005 on a few stems, suggesting that drastic events, such as fire, occurred around 60 years before the present date. Therefore, the forest regeneration before the 2004 fire was not simultaneously, and the previous forest fires, that were presumably categorized into 'crown fire', incompletely killed the established stems.

Environments and fire intensities

The altitudes on the plots ranged from 244 m to 437 m. The slopes on all the plots faced 7.0°-43.5° from north to west. The slope gradient ranged from 4.8° to 19.0°.

Duff thickness ranged from 3 cm to 73 cm, and was negatively correlated to burned area. The albedo ranged from 0.7% to 19.6% in spring and from 3.9% to 23.7% in summer on the quadrats. The fittest models on the multiple regression analysis were explained by the following equations:

$$y_{sp} = +0.065x_{sp} + 2.542, \ (r^2 = 0.762, n = 80)$$

$$y_{su} = +0.066x_{su} - 0.119x_{co} + 17.252, \ (r^2 = 0.757, n = 80),$$

where y_{sp} and y_{su} are albedo on each plot measured in spring and summer, respectively. x_{sp} and x_{su} are total plant cover on each plot in spring and summer, respectively. x_{co} is canopy openness. r^2 is adjusted correlation coefficients. The other variables were not adopted in any cases. These results implied that albedo is determined mostly by total plant cover, and the albedo can not return to the pre-fire conditions until vegetation cover becomes higher enough to reflect radiation.

Frozen soil layer probably developed in unburned sites, but was not detected in burned sites (Sawada, et al. 2007). The canopy openness ranged from 57% to 95% on the 80 quadrats. A forest unburned by the 2004 fire, of which height was comparable with the examined burned area, showed the canopy openness was less than 54%. Even on L plots, therefore, plant cover on forest floor decreased down to 40% by the fire. Those results indicated that the surveyed area received fire damage even on less-disturbed area.

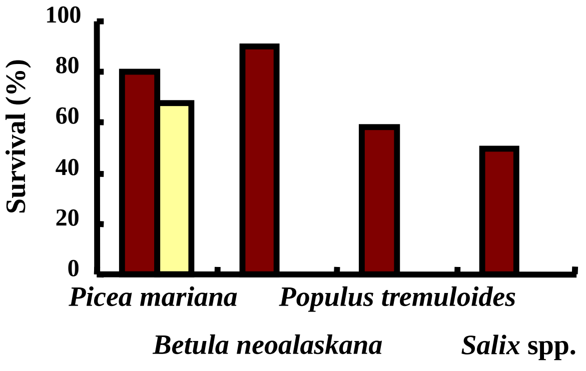

Fig. 2. Survival rates on the four tree taxa on the burned (brown column) and unburned (yellow column) surface.

Results surveyed in 2005 and 2006

Seed immigration on tree species

In total, seed traps captured 838 and 335 seeds in spring and summer 2006, respectively. Of those seeds, 318 and 253 seeds were from *P. mariana in* spring and summer, respectively. The other species were *Betula neoalaskana*, *Polygonum alaskanum*, *Calamagrostis canadensis* and *Epilobium angustifolium*.

Even though two years have passed for the last fire, 5-10 seeds per trap were still supplied on *Picea mariana* (Fig. 1). In spring, seed traps frequently caught *Betula neoalaskana* seeds, although the seed density declined greatly to summer. The seed germination on *P. mariana* averaged 25.6% in spring and 14.6% in summer, while *B. neoalaskana* germinated few seeds. Although the annual seedlings of *Salix* spp. were recorded from the field, the seed traps captured only one seed on *Salix*, probably because the layout was inadequate for willow seeds having light pappus. Based on the results combined with seed dispersal and seedling emergence, the tree species producing long-distance wind-dispersed seeds could immigrate steadily even soon after the fire. In particular, *P. mariana* could immigrate seeds even to heavily-burned plots, showing that seed limitation did not restrict its regeneration. Interestingly, the seed germination percentage declined from H to L via M.

Seedling emergence, survival, and growth

In 2005 and 2006, respectively, 576 and 496 seedlings were marked (Table 1). *Picea mariana* was the most common tree seedlings for the two years, and about 3/4 *P. mariana* seedlings emerged on the unburned surface. The density was significantly higher on the unburned surface.

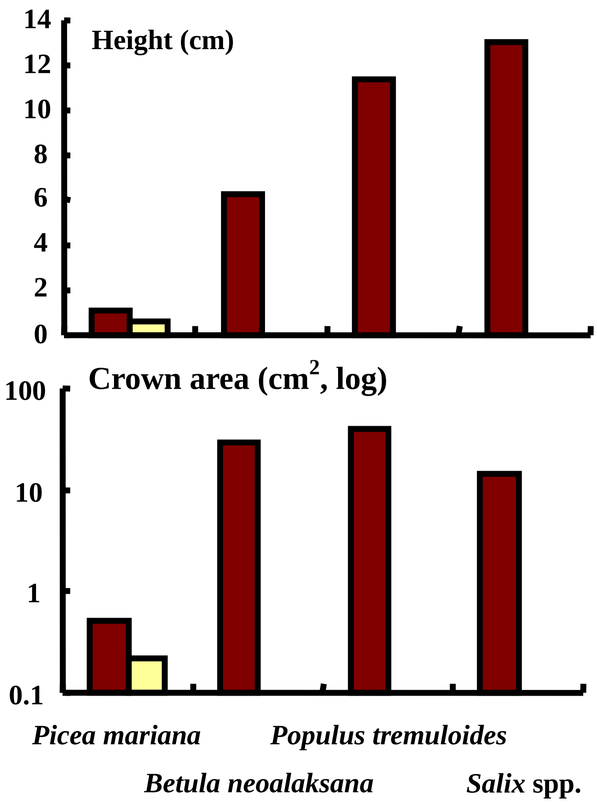

Fig. 3. Seedling growth of tree species from the summer of 2005 to the summer of 2006. Brown and yellow columns indicate the growth on the burned and unburned ground surface, respectively. The height and crown area of *P. mariana* are significantly different between the burned and unburned surface at $P < 0.01$ (ANOVA). The height and crown area are significantly different between P. mariana and broad-leaved trees (*Betula*, *Populus* and *Salix*) on the burned surface.

In contrast, on broad-leaved tree species, i.e., *Populus tremuloides* and *Betula neoalaskana* and *Salix* spp., all seedlings established on the burned ground surface in 2005, and most seedlings were on the burned surface in 2006. However, there was only 1 stem ≥ DBH on *B. neoalaskana* and no stems ≥ DBH on *P. tremuloides* in the 16 10 m × 10 m plots surveyed. This also meant that most seeds on broad-leaved trees came from the external environments.

On *P. mariana*, seedling survival rate averaged 80% on the burned ground and 68% on the unburned ground (Fig. 2), indicating that the survival did not differ greatly between the burned and unburned surface. Since there were no seedlings for broad-leaved tree species on the unburned surface in 2005, seedling survival on the unburned surface was not evaluated. On the burned surface, the survival rates of broad-leaved trees were 50-90%. In particular, the most common broad-leaved tree, *B. neoalaskana*, showed 90% on survival.

Stem growth, evaluated by height and crown area, was significantly higher on the three broad-leaved tree taxa than *P. mariana* (Fig. 3). On *P. mariana*, stem growth was significantly slower on the unburned surface than on the burned surface. Furthermore, stem growth was slower on *P. mariana* than on any other tree species even on the burned ground. Those indicated that the establishment of broad-leaved trees proceeded if the ground was burned completely.

Plant communities in herb layer

For two years, i.e., 2005 and 2006, 42 plant taxa were recorded from 96 quadrats. Of those, 30 taxa were vascular plants, consisting of 4 trees, 13 shrubs, 11 herbs, and 2 ferns (*Equisetum sylvaticum* and *Lycopodium annotinum*).

On trees, annual changes in cover were synchronized with the changes in seedling density (Table 2), viz. broad-leaves trees, *B. neoalaskana* and *P. tremuloides*, increased in cover on the burned surface, and *P. mariana* established on both the grounds. The high cover on P. mariana was from juveniles survived through the 2004 fire.

The dominant shrubs increased in cover on both the habitats from 2005 to 2006. By the field observations and measurements, we confirmed that most shrubs, e.g., *Ledum groenlandicum* and *Vaccinium* *vitis-idaea*, came from legacies (vegetative reproduction) through the latest fire even on the burned surface. Since there were few seedlings on shrubs in the quadrats, vegetative reproduction was the most important for the regeneration of shrubs.

Herbs fluctuated in cover less than trees and shrubs on the unburned surface, and increased on the burned surface. In particular, a remarkable increase in cover was observed for *Epilobium angustifolium* and *Calamagrostis canadensis* on the burned ground.

Mosses and lichens were also common. As expected, *Sphagnum* spp. were predominant on the unburned surface, while *Ceratodon purpureus* increased greatly in cover on the burned surface.

Discussion

Seed immigration and seedling establishment

For tree regeneration on Poker Flat, seed immigration is unlikely to be prohibited by the fire. *Picea mariana* and all the broad-leaved trees recorded in this study usually produce a great amount of long-distance, wind-dispersed seeds. Furthermore, *P. mariana* can provide viable seeds for several years, by producing (semi-) serotinous cones (Bonan & Shugart 1989). The different seed germination rates between the three fire intensities seem to be reflected to the ratio of seeds from internal habitats (by serotinous cones) and external ones.

The intensive forest fire, that removed duff layer, promoted the immigration of broad-leaved trees for the two years surveyed. Between Yukon and British Columbia, seedling recruitment on *Picea mariana* is highest in the first five years after fires, while additional establishment is not observed after 10 years (Johnstone et al. 2004). Seed immigration from serotinous cones must decrease over time, while long-distance seed dispersal could persist on broad-leaved trees. Therefore, tree regeneration patterns, in particular, on *P. mariana*, should be determined for the first several years after fire. Furthermore, the seedling survival did not differ between *P. mariana* and broad-leaved trees, and the growth was extremely higher on broad-leaved trees than on *P. mariana*. Our findings may support that fire severity may change the successional sere of P. mariana forests towards mixed conifer and broad-leaved forests (Johnstone & Kasichke 2005).

Table 2. Yearly changes in plant cover (/m^2) on the three leading species in each life form category (tree, shrub, herb, and moss) on the burned and unburned grounds from the summer of 2005 to the summer of 2006. On each life form, three most frequent species are shown. +: less than 0.1%. -: no individuals observed.

Species	Habitat			
	Unburned		Burned	
	2005	2006	2005	2006
Tree				
Pieca mariana	1.6	1.6	0.1	0.1
Betula neoalaskana	-	+	+	0.8
Populus tremuloides	-	+	+	0.3
Shrub				
Ledum groenlandicum	8.6	11.6	1.9	2.6
Vaccinium vitis-idaea	3.9	5.4	0.3	0.5
Vaccinium uliginosum	3.9	4.6	1.4	1.8
Herb				
Carex bigelowii	4.0	4.1	0.7	0.9
Calamagrostis canadensis	1.1	1.2	1.8	3.8
Epilobium angustifolium	+	+	2.8	4.7
Moss				
Sphagnum spp.	79.7	79.1	0.6	1.1
Polytrichum strictum	2.7	2.5	0.7	0.9
Ceratodon purpureus	+	+	2.5	7.3

*: *Sphagnum* spp. contained a few species.

Environmental changes

When moss mat remains on the ground surface after fire, soil temperature keeps low. However, the complete removal of moss mat should promote soil temperature increase and/or melting permafrost (Yoshikawa et al. 2002). In fact, permafrost was not detected in a heavily-burned site on Poker Flat (Sawada et al. 2007). Albedo is also changed by fire, and is mostly determined by total plant cover on Poker Flat. By MODIS satellite observation in Queensland, Australia, changes in albedo on visible light differs between ecosystems, such as grasslands and savannas, before and after fire (Jin & Roy 2005). Therefore, fire severity, in particular, on the forest floor rather than on forest crown, must be mentioned to predict regeneration. Albedo change also derives changes in temperature and radiation on the ground surface. For example in *P. mariana* forest, surface temperature increases after, due to increase in canopy openness and decrease in albedo (Chambers et al. 2005). Those environmental factors, such as direct solar radiation, albedo and snow-cover period, interact with the plant communities (Liu et al. 2005). We have to clarify the relationships between those environmental factors and the prime determinants on the environmental changes.

Prediction of regeneration patterns

Mean annual biomass increment is higher in dry sites than in wet sites along a chronosequence on *Picea mariana* forests in Manitoba, Canada, but carbon pools in bryophyte, understory and forest floor are less for the dry sites (Wang et al. 2003). In *Picea mariana* forest, the ground surface is mostly covered by mosses, represented by *Sphagnum* spp., that may explain 80-90% of the aboveground biomass (Bonan & Shugart 1989). Forest fire, in particular, on north slopes in interior Alaska, usually occurs as crown fire and thus moss mat is removed incompletely (Bonan & Shugart 1989). In permafrost-free areas, surface soils become dry because infiltration is not restricted (Hinzman et al. 2005). Those suggest that the patterns of removal and recovery of plant cover on the ground surface are prerequisite to predict the fates of tree seedling emergence and growth after fire.

On Poker Flat, removal of plant cover on the ground surface by fire determines immigration patterns on tree species. The recovery of a few shrubs and herbs were also determined by presence/absence of *Sphagnum* mat. Canopy openness influences the distribution pattern and productivity of herbaceous plants on the forest floor (Reich et al. 2001; Whigham 2004). However, initial tree composition after fire had little effects on understory composition in the coniferous forests of eastern Canada, while soil burn severity significantly affected temporal changes in understory species (Lecomte et al. 2005). Those suggest that forest regeneration after large-scaled fire differs from fires that have usually occurred so far.

Based on the changes in vegetation patterns from 2005 to 2006, we concluded that the regeneration of *P. mariana* is not possible if the ground surface completely lost *Sphagnum* layer. Instead of *P. mariana*, the immigration and establishment of broad-leaved trees, that occur usually in the intermediate stages of succession on south slope, were faster. The keystone species on the north slope of interior Alaska must be *Sphagnum* spp.

Future plan (in 2007)

To clarify determinants on forest development, we have a plan to monitor the following five subjects in 2007. 1) Changes in plant community structures will be monitored in the plots and quadrats. 2) Safe sites for seedling survival and growth will be determined with reference to the effects of *Sphagnum* cover. 3) Relationship between seed immigration and seedling establishment will be clarified. 4) Temporal changes in canopy openness will be measured, 5) Net primary production, mostly derived from *Sphagnum* spp., will be estimated. The other measurements not described above will be conducted, *pro re nata*. We expect that those investigations clarify plant community-climate interactions with micro-and macro-scaled, spatio-temporal changes not only in boreal forests after disturbances.

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