



Effects of Water Level via Controlling Water Chemistry on Revegetation Patterns After Peat Mining

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Abstract The recovery of plant communities is related to various environmental factors, in particular, waterlevel and chemistry, after peat mining. The changes over time after peat-mining were annually monitored from 2002 to 2007 in Sarobetsu peatland mined during 1970 and 2003, northern Japan, by using permanent plots setting up in various ages after mining. *Rhynchospora alba* was the earliest colonizer in the post-mined peatland, and three grasses followed. The recovery was slow when waterlevel was low, while *Sphagnum papillosum*, being predominant in pre-mined peatland, established well in post-mined sites with high waterlevel of which values were equivalent to post-mined site. Water chemistry was variable according to the effect of waterlevel in the post-mined peatland, while they were relatively stable in pre-mined peatland. Therefore, with large scale, merged with post-and pre-mined peatlands, water chemistry became the first determinants manipulated by waterlevel. In conclusion, high waterlevel that decreases nutrients in groundwater is a prerequisite to promote *Sphagnum* recovery in a post-mined peatland. Also, low pH was related to nutrient uptake by vascular plants and dilution by groundwater, and was advantageous for *Sphagnum* establishment. Re-establishment of vascular plants may promote the stabilization of water chemistries and facilitate revegetation towards the original *Sphagnum* peatland.

Keywords Direct and indirect effects · Permanent plot · Chronosequence · pH in groundwater · *Sphagnum papillosum* · Water level

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Introduction

After *Sphagnum* peatlands (bogs) are mined for agricultural and industrial use, the mined peatlands have been attempted to be restored to the original bogs (Lavoie et al. 2003). When the success of restoration is evaluated by recovering ecosystem function in mined peatlands, the recovery of *Sphagnum* mosses is the assessment criterion. Because *Sphagnum* mosses make their habitat environment by their morphological, physiological and chemical properties, they are key species in the ecology and development of most peatlands (Rocheftort 2000). Spontaneous revegetation towards the original ecosystem is unexpected on most mined peatlands, owing to drastic changes in environments after mining (Nishimura et al. 2009). There are various obstacles for revegetation in mined peatlands; supplying excess nutrient, altering water level, increasing ground surface instability, increasing drought, etc. (Campbell et al. 2002; Lamers et al. 2002). *Sphagnum* peatland is characterized by acidity and poor nutrient with the stable of seasonal and low water levels, e.g., 37 cm of depth in west-central Canada (Vitt and Chee 1990; Zoltai and Vitt 1995), while mined peatland is covered with nutrient-rich peat with fluctuating water level due to the agitation of peat and/or drainage construction (Wind-Mulder et al. 1996; Price and Whitehead 2001). To detect the determinants on successional changes in wetlands, therefore, water level and chemistry should be monitored (Benscoter and Vitt 2008; Graf et al. 2008). Water level and chemistry are seasonally fluctuated, and the variance is often related more to species composition than the mean (Proctor 1994; Hajek and Hekera 2004), showing that the mean and variance of environmental factors work differently to the revegetation. Therefore, the mean and variance of environmental factors were analyzed separately in this study.

Here, we reported the promoters on *Sphagnum* wetland revegetation clarified by monitoring for 6 years. On Sarobetsu mire in the northern Hokkaido of Japan, peat mining had been undertaken annually from 1970 to 2003. Inter-specific

relationships, i.e., competition and facilitation, often determine more to revegetation patterns than environmental limitations (Tilman and Wedin 1991; Mahaney et al. 2004; Koyama and Tsuyuzaki 2010). Because individual species differ in their nutrient-use properties, species composition influences nutrient retention of ecosystem (Tilman et al. 1997). In undisturbed peatlands, the balance *Sphagnum* mosses and vascular plants is maintained by their use of different sources of nutrient (Malmer et al. 1994). Some fertilization experiments showed that increasing nutrients availability in the rhizosphere, i.e., nitrogen, phosphorus or both, involved the growth of vascular plants by drawdown of *Sphagnum* mosses (Gusewell et al. 2002; Heijmans et al. 2002; Limpens et al. 2003). More increasing nutrients than those of natural habitat have the positive effects for the growth of vascular plants and *Sphagnum* mosses, respectively. But, the decreasing through the use of nutrients in the rhizosphere have the negative effects for only vascular plants (Malmer et al. 2003), because *Sphagnum* mosses can use nutrients derived from rainwater on the surface. The exposure of peat by the excavation has resulted in higher nutrient concentrations for water and peat chemistry than those of original peatland. Therefore, the competitive balance may shift toward *Sphagnum* mosses or vascular plants depending on amount of nutrient concentration, then the revegetation patterns of *Sphagnum* mosses may be altered. The hydrological or hydro-chemical conditions directly influence nutrient availability in wetlands, and indirectly influence plant growth through root completion to nutrients in water (Kotowski, et al. 2001). The temporal changes in environmental conditions, such as hydrological and hydro-chemical conditions, generate the spatial heterogeneity due to topography or geomorphology variation (Abreu et al. 2009). These spatial heterogeneity are linked with trends in vegetation structure over time, thus the variability of the successional vegetation in disturbed peatland is expected that follow multiple trajectories. Hydrological conditions would have mainly the effects on their threshold when divergence occurs. In particular, the high and stable conditions in water level promote the restoration toward the original *Sphagnum*-dominated vegetation that could be expected to occur. Forecasting trajectories and identifying factors that regulate their development is crucial to understanding community mechanisms. Additionally, these spatial heterogeneity complicate the interpretation of successional trends with the application of a synchronic approach. Therefore, the major objectives of this study is to combine chronological and synchronic analysis to detect 1) revegetation patterns, in particular, for *Sphagnum*, by monitoring chronologically-established permanent plots, 2) relationships between *Sphagnum* colonization and the environmental factors and between *Sphagnum* and vascular plants, and 3) the effects of water level and chemistry and their fluctuation patterns on revegetation patterns. Based on these results, the keys for restoration were discussed.

Materials and Methods

Study Area

Sarobetsu mire, consisting of 2,773 ha, is situated on the downstream of the Teshio River Basin, 5 km east of Japan Sea, northern Hokkaido, Japan (45°06'N, 141°42'E, 7 m a.s.l.) (Hotes et al. 2004). The original mire is classified into raised-ombrotrophic bog with peat about 6 m deep. Climate is warm-cool temperate. Mean annual temperature is 6.6 °C during 2002 and 2007 with a maximum of 25.4 °C in August 2006, and a minimum of −13.7 °C in January 2003. Annual precipitation averages 996 mm. Snow-free period is usually from May to November. The maximum snow depth was recorded at 135 cm in 2004 at Toyotomi Town 6 km far from the mire (Japan Meteorological Agency 2008).

In the un-cut original mire, the ground surface is covered with *Sphagnum* spp. with low vascular plant cover by *Carex middendorffii*, *Hosta rectifolia* and *Hemerocallis middendorffii* (Nishimura et al. 2009). *Sphagnum* peat was mined at 3–22 ha down to more than 3 m every year from 1970 to 2003, by a large suction-type peat-rig. After the extraction of high quality peat, the remainder was returned to the original location. The remainder floated up to the water surface, and then created the compact ground surface where plants grew. However, the creation of the ground surface required about 10 years.

Field Measurements

In 2002, a total of 192 1×1 m plots were set up in eight differently-aged sites mined between 1970 and 1994. The sites were more than 50 m apart to each other within ca. 370 ha. In an unmined area adjacent to the mined area, 9 plots were set up in 2002 and additional 9 plots were set up in 2003 for control. More explanations about the location of surveyed sites and the setup method of plots have been described in Nishimura et al. (2009). The vegetation in each plot was monitored annually during plant growth seasons, i.e., July or August, from 2002 to 2007. The cover of each species was visually estimated in each plot divided into 25 20×20 cm cells. Nomenclature refers to Ohwi (1975) for seed plants, Tagawa (1983) for ferns, and Iwatsuki and Mizutani (1972) for mosses.

Ground Water Sampling

To measure groundwater level, 92 PVC pipes (1 m in length and 4 cm in diameter) were buried into 85 cm below the peat surface in 2002. The pipes had holes (5 mm in diameter) at about 10 cm intervals and the end of pipe was sealed. Water level defined as the length between soil level and surface water inside PVC pipes was measured 36 times during snow-free period from June 2002 to October 2007 with the use of a ruler. Positive value on water level indicates groundwater appears above the ground surface in

this study. For measuring water chemistry, 100-ml ground water was collected from the inside of the pipes in each month. Water sampling was undertaken seven times on 92 sampling points from April to November 2005. The acidity-alkalinity and the fertility gradient controlling the distribution of plant species and vegetation types in peatlands have often been measured through water pH and EC. Additionally, peatlands generally are limited by nitrogen or phosphorus (VerHoeven et al. 1990), the balances between *Sphagnum* and vascular plant is maintained by the use of different sources of nutrients (Malmer et al. 1994). Therefore, the competitive balance may shift toward *Sphagnum* species or vascular plants depending on amount of N and P concentration. In this study, water chemistry was analyzed with a focus on four macro-nutrient factors (TN, TP, pH and EC). pH and electrical conductivity (EC) were measured by a pH meter (MP120, Mettler Toledo, Tokyo) and an EC meter (MP126, Mettler Toledo, Tokyo), respectively, in a laboratory within a day or two soon after returning to laboratory. These values were calibrated at 25 °C. All water samples were kept at 0 °C in a refrigerator until the analyses of nitrogen and phosphorus. Total nitrogen (TN) was determined by UV spectroscopic measurement after acid digestion (Keeney & Nelson 1982). Total phosphorus (TP) was determined by the molybdenum blue method after alkaline digestion (Wetzel & Likens 2000). The repeated measurement was one time because of the large number of samples ($n=92$).

Data Analysis

Species richness and cover on each species were calculated in each plot every year. Shannon's species diversity (H') and evenness (J) were calculated in each plot as: $H' = -\sum p_i \ln p_i$, and $J = H'/\ln S$. Here, S is the species richness and p_i is the proportion of the plant cover of each species to the total cover. Plant community changes from 2002 to 2007 were investigated by detrended correspondence analysis (DCA). Canonical correspondence analysis (CCA) was performed using data on plant community and environments measured in 2005. Since TP in ground water did not differ significantly between sites, pH, EC, TN and water level were used for CCA. Mean and range (between the maximum and minimum) of environmental factors were calculated to investigate the different effects on plant community development. A variable is considered to contribute significantly to the regression when it is higher than an absolute t -value > 4 (Jongman et al. 1987). To ensure relationships between the five environmental factors, water level, pH, EC, TN and TP, Kendall's rank correlations were calculated.

Species cover, plot cover, species richness, diversity and evenness were compared between 9 sites and between years after mining. Generalized linear mixed-effects models (GLMM) were applied to investigate significant temporal changes in cover and species richness. The probability distribution of cover was assumed as binomial, and species richness Poisson. H' and J

were investigated by linear mixed-effects model (LMM) with a Gaussian distribution. LMM with a Gaussian distribution was also applied for comparing chemical properties in groundwater between sites and between months, and for water level between sites and between years. For these analyses, all the combinations of sites with different ages after mining were modeled and examined. The first model assumed that the dependent variable was explained by each site and thus eight fitting curves were obtained. Then, 2 of 8 sites were merged and modeled. Like this way, number of merged sites increased. The last model was made by merging all sites with a single fitting line. The best-fit LMM and GLMM models of the combinations were selected by Akaike's information criteria (AIC) (Burnham and Anderson 1998). Except for CCA and DCA performed by CANOCO (version 4.5, Center for Biometry, Wageningen), all statistical analyses were conducted by the statistical software R (R Development Core Team 2009).

Results

Plant Community Structures

During 2002 and 2007, 59 taxa (49 vascular plants and 10 mosses) were recorded from all the plots. There were 30 species recorded from 18 plots in unmined site (control) while there were 34 species in 8 mined sites. The predominant species in control was *Sphagnum papillosum* of which cover was more than 70 % and did not change from 2002 to 2007 (Fig. 2). On the mined sites, *Sphagnum papillosum* did not establish in 1992 and 1994 sites, but established in the 1975, 1978 and 1984 sites with more than 10 % in cover. In particular, the cover of *Sphagnum* was ca 40 % in the 1975 sites and 20 % in the 1978 site. In contrast, the cover was less than 4 % in the two old sites mined in 1970 and 1972.

In the mined peatland, the cover was lowest in 1992 and 1994 sites, and was highest (30 %) in the 1972 site (Table 1). On vascular plants in the post-mined peatland, three grasses, *Rhynchospora alba*, *Phragmites communis* and *Moliniopsis japonica* were most common. *R. alba* established in all the sites, and had the highest cover on sites mined in 1975. *M. japonica* showed more than 15 % cover in the 1970, 1972 and 1978 sites, while it was only 4 % in control. *P. communis* established in all the sites except in the 1982 site where the revegetation was slow, while it did not establish in control. *Carex middendorffii* established in six of eight mined sites, did not establish in the 1982 and 1992 sites, and showed the highest cover in control.

Temporal Changes in Vegetation

Plot cover and species richness were higher in control sites than in mined sites (Fig. 1). Plot cover increased with time in

Table 1 Mean percent cover of species in sites mined in different years and site unmined used as control. The appearance frequency in 2002 is shown in parentheses

Year of mining	Control	1970	1972	1975	1978	1982	1984	1992	1994	Total
Number of plots	9	27	27	27	21	27	27	18	18	201
Years after mining		32	30	27	24	20	18	10	8	
Plot cover (%)*	100±0.0	76.8±23.8	68.1±28.5	92.0±17.8	74.5±18.6	15.0±26.5	64.5±33.8	14.1±27.5	2.0±4.9	56.2±40.1
Species richness*	11.9±1.2	8.0±2.9	6.6±3.7	5.8±2.0	6.8±2.0	1.6±1.6	5.2±3.4	1.3±1.3	1.1±1.5	5.1±3.8
Species										
<i>Rhynchospora alba</i>	-	22.9 (26)	14.9 (21)	55.2 (26)	21.3 (13)	13.5 (21)	31.5 (22)	12.8 (12)	1.0 (5)	22.0 (150)
<i>Phragmites communis</i>	-	13.9 (25)	30.7 (24)	9.5 (15)	17.1 (21)	-	11.9 (23)	0.4 (1)	0.6 (2)	10.8 (111)
<i>Moliniopsis japonica</i>	1.2 (8)	36.6 (24)	14.6 (17)	4.5 (11)	21.9 (20)	2.1 (5)	8.1 (14)	0.6 (2)	0.1 (2)	11.4 (103)
<i>Drosera rotundifolia</i>	0.4 (8)	0.8 (18)	0.6 (12)	1.8 (20)	1.5 (17)	0.4 (6)	0.4 (11)	0.3 (2)	0.1 (2)	0.8 (96)
<i>Vaccinium oxycoccus</i>	1.2 (9)	1.9 (13)	0.4 (5)	9.0 (23)	2.5 (14)	+ (1)	2.3 (7)	-	-	2.1 (72)
<i>Lovelia sessilifolia</i>	-	4.6 (25)	2.3 (13)	2.4 (12)	1.6 (8)	0.3 (5)	1.6 (8)	-	-	1.7 (71)
<i>Carex middendorffii</i>	15.9 (9)	5.4 (17)	4.7 (11)	3.8 (7)	8.1 (10)	-	7.6 (12)	-	0.7 (2)	4.5 (68)
<i>Sphagnum papillosum</i>	85.0 (9)	3.9 (7)	0.7 (3)	42.3 (19)	21.3 (8)	-	12.0 (8)	-	-	14.0 (54)
<i>Eriophorum vaginatum</i>	-	0.8 (3)	7.4 (15)	0.9 (1)	2.2 (7)	-	5.7 (11)	0.1 (1)	+ (1)	2.2 (39)
<i>Gentiana triflora</i>	-	0.6 (14)	1.3 (13)	-	0.5 (7)	+ (1)	+ (2)	-	-	0.3 (37)
<i>Solidago virgarea</i>	4.0 (8)	0.4 (11)	1.6 (13)	-	-	-	+ (1)	-	-	0.5 (33)
<i>Hosta rectifolia</i>	13.3 (9)	0.4 (3)	-	0.2 (4)	-	+ (1)	1.0 (7)	0.2 (1)	0.1 (2)	0.8 (27)
<i>Andromeda polifolia</i>	0.8 (9)	+ (1)	0.3 (2)	2.4 (6)	-	0.2 (1)	0.6 (4)	-	-	0.5 (23)
<i>Sanguisorba tenuifolia</i>	0.2 (3)	0.5 (7)	0.4 (5)	0.2 (1)	0.1 (4)	-	0.1 (3)	-	-	0.2 (22)
<i>Empetrum nigrum</i>	1.3 (8)	1.1 (5)	-	-	-	-	-	-	-	0.2 (13)
<i>Myrica gale</i>	0.4 (1)	0.9 (5)	-	-	0.7 (2)	+ (1)	+ (1)	+ (1)	-	0.2 (11)
<i>Trientalis europaea</i>	0.6 (8)	-	-	+ (1)	0.1 (1)	-	-	-	-	+ (10)
<i>Hemerocallis middendorffii</i>	6.3 (9)	-	-	-	-	-	-	-	-	+ (9)
<i>Osmunda cinnamomea</i>	-	-	0.4 (4)	-	0.2 (1)	-	0.1 (4)	-	-	0.1 (0)
<i>Polytrichum juniperinum</i>	-	-	1.2 (6)	0.1 (1)	-	-	-	0.1 (1)	+ (1)	0.2 (9)
<i>Parnassia palustris</i>	-	0.2 (6)	-	0.3 (3)	-	-	-	-	-	0.1 (9)
<i>Iris laevigata</i>	0.1 (2)	-	-	+ (1)	0.1 (1)	-	+ (1)	-	0.1 (2)	+ (7)
<i>Sphagnum</i> spp	0.2 (9)	+ (2)	0.1 (2)	-	1.0 (2)	-	-	-	-	0.1 (15)

Other species included: *Hydrangea paniculata*, *Gentiana thunbergii*, *Scheuchzeria palustris*, *Agrostis scabra*, *Rubus chamaemorus*, *Eriophorum gracile*, *Eriocaulon monococcon*, *Lycapadium annotinum*, *Sasa kurilensis*, *Chamaedaphne calyculata*, *Hypochoeris radicata*, *Lycopus uniflorus*, *Scirpus wichurage*, and one unknown species. Frequency of each of the other species is less than five

+: cover <0.1 %. -: no individuals observed. The effects of years after peat mining on plot cover and species richness are analyzed by generalized linear mixed-effects model. *: significantly different at $p < 0.01$

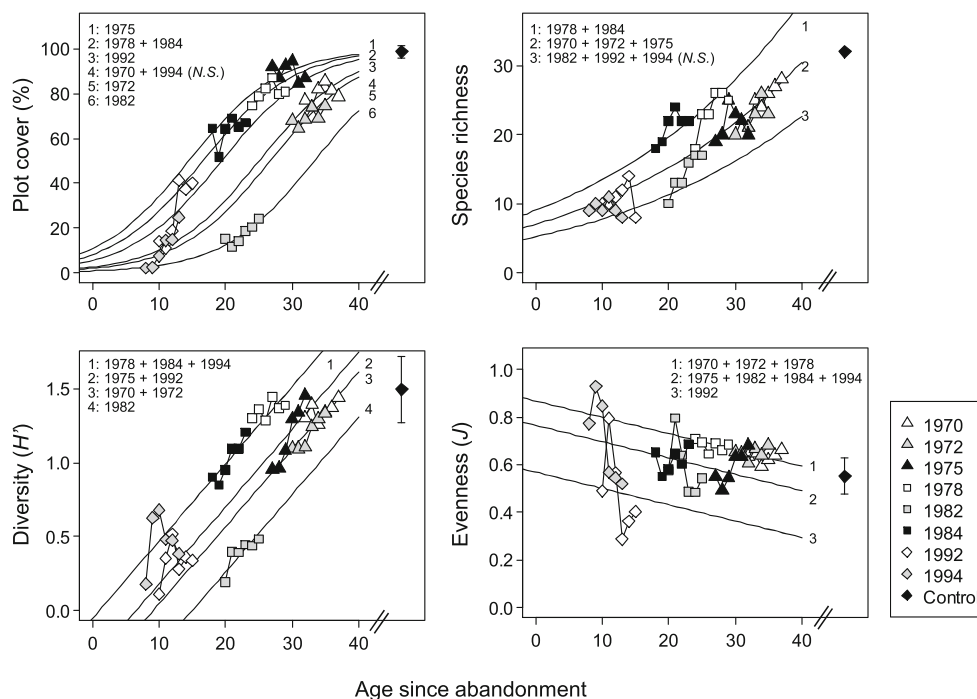
the mined sites, but the patterns differed between most sites, indicated by six fitting curves. As well as plot cover, species richness annually increased (Fig. 1). The changes in species richness were explained by three fitting curves, showing that the determinants on species richness differed from those of plot cover. Annual rate of increase in species richness was faster in sites mined in 1978 and 1984. Sites mined in 1982, 1992 and 1994 did not change the lowest species richness across years. Diversity was lower in the mined peatland than in the unmined peatland. The diversity was explained by four fitting curves. The fastest increases in diversity were observed in the 1978, 1984 and 1994 sites, while the slowest one was on the 1982 site. In total, plot cover, species richness and diversity increased faster in the sites mined in 1975 and 1978 and

did slower in site mined in 1982. The other five sites recovered with moderate paces per year between them. Evenness decreased with ages in all the mined sites (Fig. 1), although the richness and diversity increased. The decrease of evenness was derived mostly from the increase in the cover of dominant species. For example, *R. alba* greatly increased relative dominance in young sites, i.e., mined in 1992 and 1994, and *M. japonica* did well in middle-aged sites, i.e., mined in 1972 and 1978 (Fig. 2).

Temporal Changes in Common Species

R. alba drastically increased the plant cover in the 1992 and 1994 sites (Fig. 2). The cover of *R. alba* could be significantly

Fig. 1 Yearly fluctuations in plot cover, species richness, diversity (H') and evenness (J) in different ages after mining. The fittest GLMM and LMM for explaining plot cover, species richness, H' and J adopt two independent variables, age and site, and are selected by AIC. Four digit numerals indicate mined years. Plus signs mean the sites are merged to explain the fluctuations



explained by four increasing patterns due to using linear-model method, but actually peaked at middle ages, i.e., more than 20 years after abandonment, and then decreased like a parabolic curve. In addition, the establishment failed in 1978 and 1982 sites. *M. japonica* recovered the cover in all the sites. The recovery paces were divided into three types, fast, moderate and slow, although the fitting curves were not statistically significant. *M. japonica* ran behind *R. alba*, but increased the cover faster than *R. alba* once established. The annual fluctuations of cover on three monocotyledonous species, *P. communis*, *C. middendorffii* and *M. japonica* resembled to each other. However, the well-established sites were different between these three species; viz. *M. japonica* recovered fastest in the 1970 site, *R. alba* in the 1972 site, and *C. middendorffii* in the 1978 site.

Sphagnum papillosum annually increased the cover even on the sites with the slowest recovery when it established (Fig. 2). The six fitting curves were summarized into three patterns: fast, slow, and none. The fast recovery site could be defined by high increase rate of the cover of *S. papillosum*. Thus, *S. papillosum* could recover about 40 % of cover for 30 years after abandonment. The fast recovery occurred in the 1975 site with the highest water level, while five sites showed slow *Sphagnum* colonization. The slow recovery sites could be defined by low increase rate of the cover of *S. papillosum* such as 1978 and 1984 sites, or *Sphagnum* colonization did not increase very little for 30 years in spite of the success at the colonization after peat-mining such as 1970 and 1972 sites. On sites mined in 1982, 1992 and 1994, no *Sphagnum* colonized.

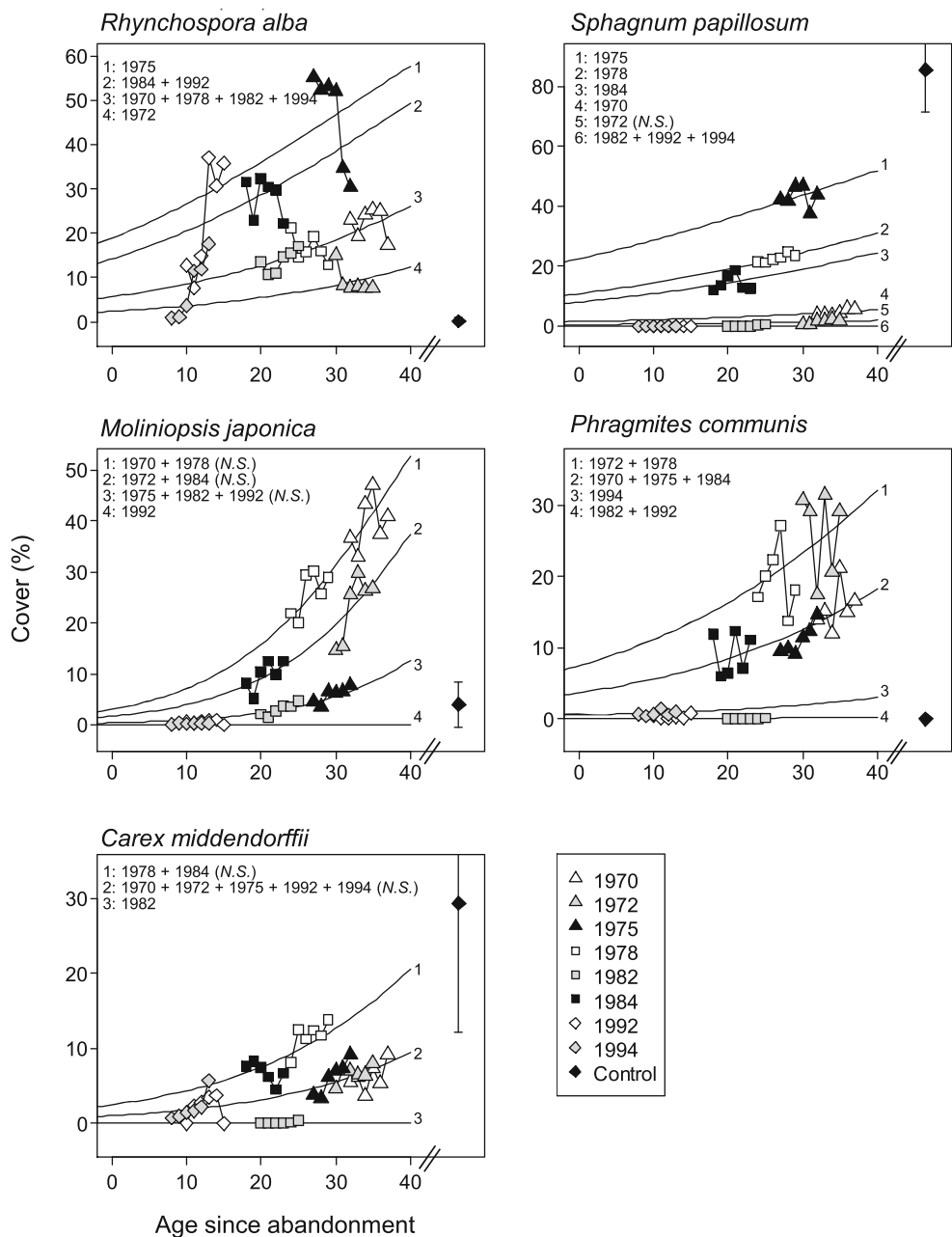
Vegetation and its Related Environmental Factors

Eigenvalues on the axes I and II of DCA were 0.610 and 0.318, respectively. The plot scores in control were aggregated on the right side in the graph, and fluctuated least (Fig. 3), showing that the community structure did not change across years. In contrast, the plot scores in the mined sites fluctuated along both the axes I and II. The scores of plots mined in 1992 and 1994 fluctuated highly, showing that the plant community structures changed faster soon after mining. However, even in old-mined sites, the plot scores fluctuated along both the axes I and II, and did not go towards the scores of the unmined site, i.e., the control.

The peaks of precipitation occurred in fall rainy seasons during late August and late September in most years (Fig. 4). From April to early May, water level was high because of snowmelt. Water level gradually decreased until rainy seasons, and then increased. Mean water level was significantly different between sites. The 1975 site where *Sphagnum* cover was highest of the mined sites always showed the highest water level. The 1992 and 1978 sites followed the 1975 site, i.e., the secondly highest water level. The 1972 and 1982 sites, both of which had high plant cover, showed the lowest water level. *Sphagnum papillosum* established well in old sites, i.e., the 1975 and 1978 sites, with high water level, but established least in the 1972 site that showed the lowest water level.

On water chemistries in 2005, pH, EC and TN in the groundwater were different between sites and between months (Fig. 5). TP was not different between sites, because of low concentration in every site. pH was higher in all mined sites

Fig. 2 Yearly fluctuations in percentage cover of the five frequent species after mining. The fittest GLMM for explaining cover of five species adopt independent variables, age and site. The significant variables are indicated within each figure. Symbols on curves, refer to Fig. 1



than in un-mined control site. In particular, the two youngest sites mined in 1992 and 1994 showed the highest pH. EC was higher in the 1982 and 1994 sites where plant cover was low. The 1975 and 1978 sites with high *Sphagnum* cover showed low EC. EC in the control plots was higher than that in *Sphagnum*-establishing mined sites, but was lower than in that in mined plots without *Sphagnum*. TN decreased after June in old mined sites (i.e., 1970 sites) and the control, and was high and stable in the low-vegetated, youngest site mined in 1994. Water level was lowest in June and September in most sites (Fig. 4). Synchronizing with this fluctuation of the water level, pH, TN and TP were high in June and September (Fig. 5). All of these four variables, water level, pH, TN and TP, were

correlated to each other (Kendall's rank test, $P < 0.05$), except between pH and EC. These results implied that water level determined mostly by precipitation affected various water chemistries.

The contribution rates of the first two CCA axes on plot-environmental relationships were 41.8 % and 26.0 %, respectively, when plots only in post-mined sites were used, and 41.4 % and 29.1 % when all the plots including unmined site were used. Monte Carlo permutation test confirmed that the two overall ordinations were significant at $P < 0.01$. In mined sites, axis I on CCA was significantly correlated to mean water level ($t = 6.81$), (Fig. 6a). No water chemistries were related to axis I. All the measured environmental factors were not

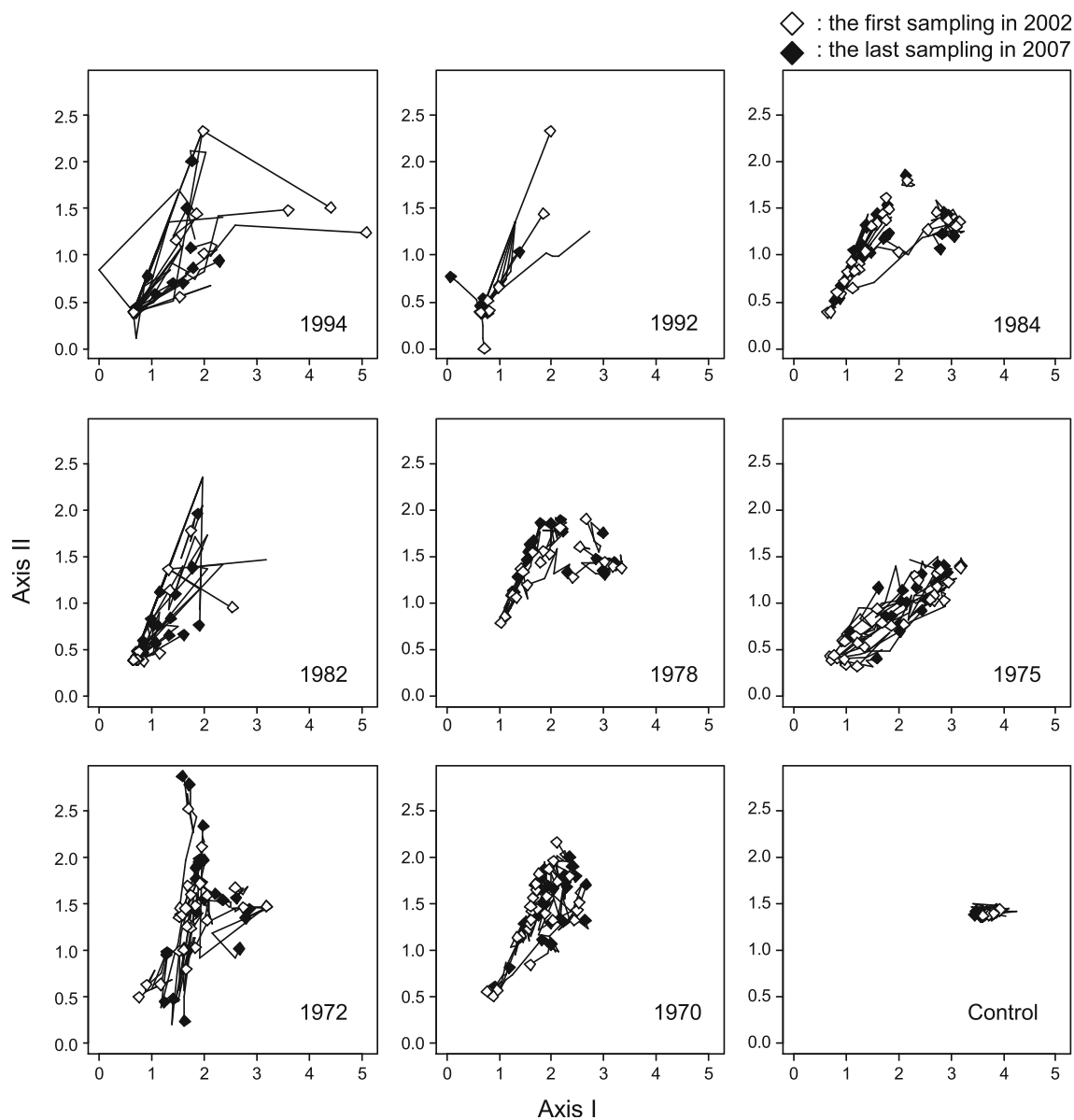


Fig. 3 Detrended correspondence analysis (DCA) diagram showing plot scores. The same plots surveyed from 2002 to 2007 are indicated by connected lines. Symbols show the first and last survey-year only, so the open symbols indicate the first sampling in 2002 and the closed symbols

the last sampling in 2007. The open end of lines show that the removal of plots due to zero-data or the plots for failure to survey until last year due to some plots submergence

related to axis II (absolute $t < 4$), although the highest t -value was -3.94 shown by the range of water level. Most plots in the 1992 and 1994 sites showed the highest scores on axis II, showing that the vegetation development were influenced by the small fluctuations of water level. In contrast, plots in the 1972 site established with the high fluctuations of water level. In total, therefore, the vegetation structures in the mined sites were determined more by mean water level than the range and water chemistries.

When all the plots, i.e., in un-mined and mined sites, were investigated by CCA, axis I was related most to pH ($t = 7.71$) (Fig. 6b). Mean water level was not related to axis I ($t = -3.61$),

even though that was the prime determinant on the revegetation in the post-mined peatland. Axis II was correlated to the mean ($t = 4.97$) and range ($t = -4.09$) of water level. The other water chemistries were not related to both axes I and II.

Discussion

Successional Patterns

Mean plant cover and richness were lower in mined sites than in unmined sites even 25 years after mining, showing that

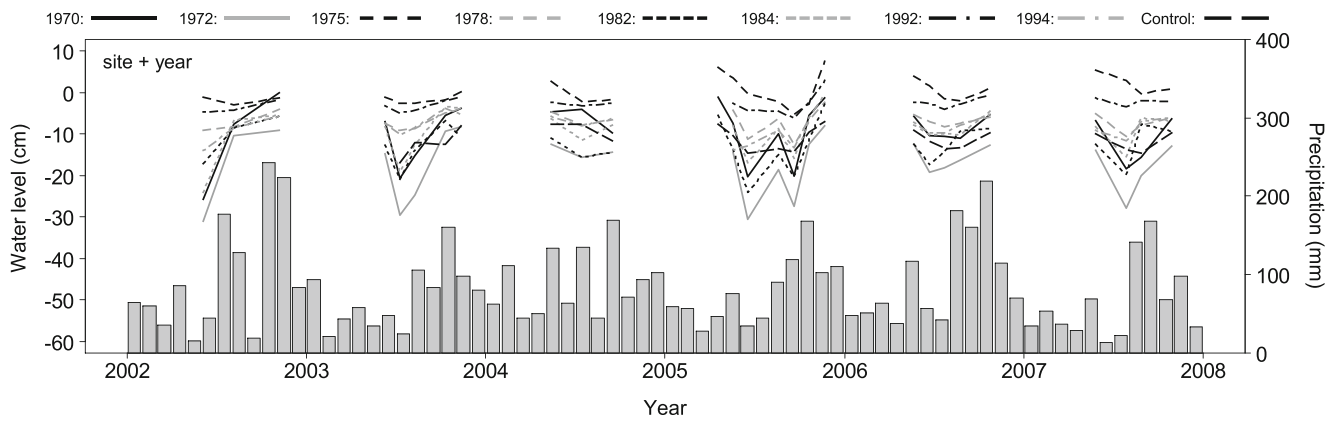


Fig. 4 Monthly precipitation and water level from 2002 to 2007 in nine sites with different ages, including control. LMM for explaining water level adopt two independent variables, site and year. The water level is significantly different between years and sites ($P < 0.01$)

plant communities in mined sites could not recover to the original bog for 30 years. A few decades were insufficient to develop *Sphagnum*-dominated community. The plot cover gradually recovered in each mined site but was greatly influenced by site-specific environments. While the recovery of species richness developed three patterns (Fig. 1), therefore, the determinants on species richness differed from those of plot cover. In the earliest stages on the mined peatlands, *Rhynchospora. alba* immigrated faster than any other plants

to bare ground where nitrogen in water was higher (Nishimura et al. 2009). Aerobic bacteria promote peat decomposition after peat mining and the subsequent nutrient concentrations become high (Wind-Mulder et al. 1996). Since *R. alba* has a shallow root system, this species have an advantage in the colonization to the bare ground, which is soft and mud substrate, after peat-mining (Ohlson and Malmer 1990). Late colonizers delay the immigration, when the early colonizers develop large seedbank and regenerate by the seedlings

Fig. 5 Seasonal fluctuations in averaged pH, electric conductivity (EC), total nitrogen (TN) and total phosphorus (TP) in sites with different ages. Groundwater was sampled 10 times from April to November 2005. LMM for explaining pH, EC, TN and TP in groundwater adopt two independent variables, site and month. The significant variables are indicated within each figure ($P < 0.01$). Plus signs mean the two factors are significant

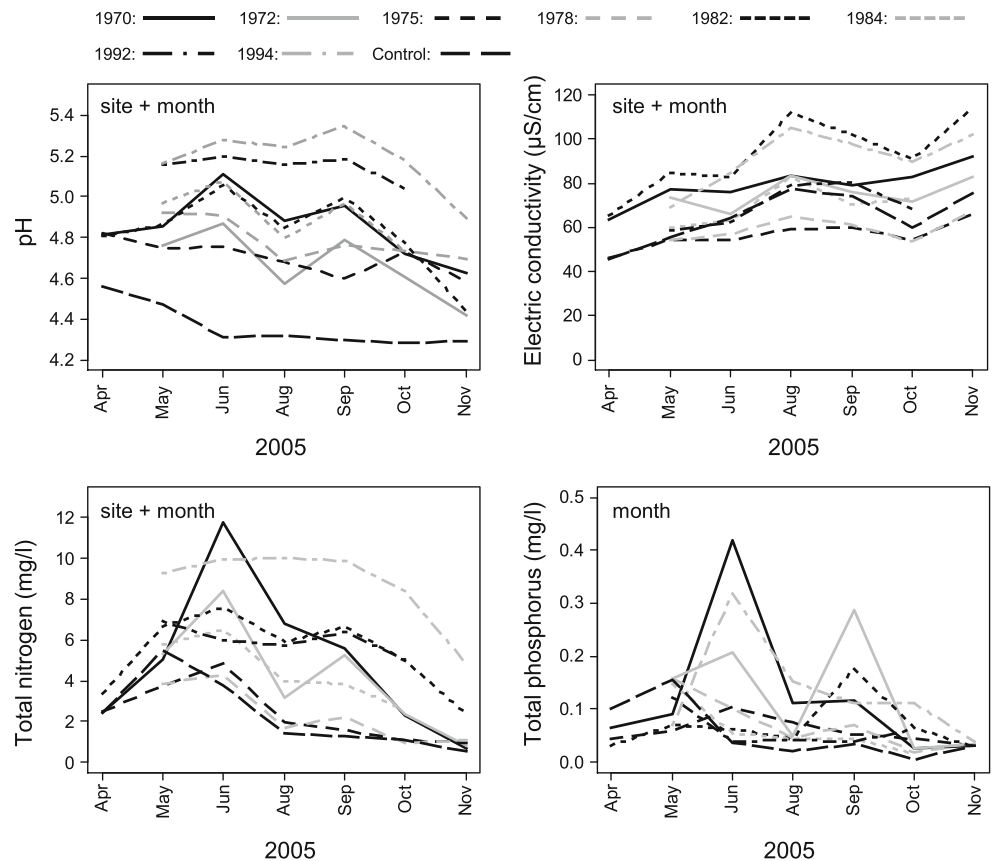
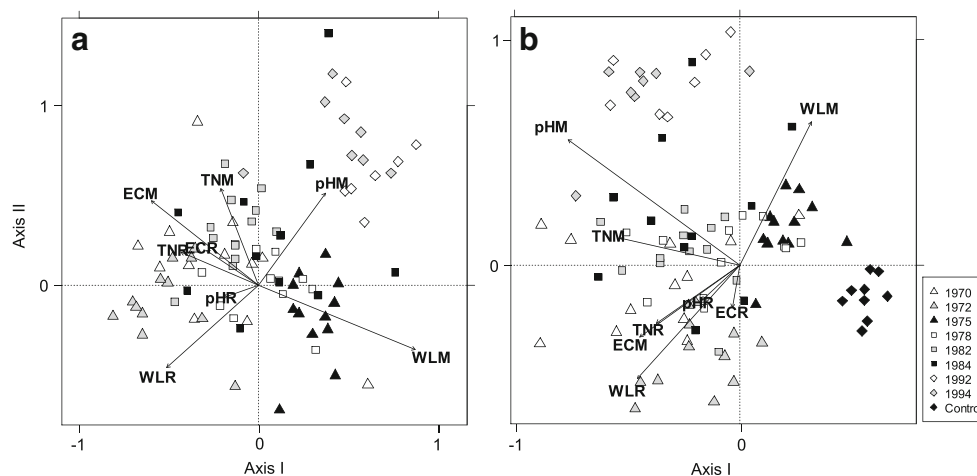


Fig. 6 Plot-environmental factor ordination diagram obtained by canonical correspondence analysis (CCA) (a) in post-mined sites and (b) in all sites, i.e., pre- and post-mined sites. Each variable is expressed by three letters in the figure. The first two letters indicate environmental factors: WL = water level, EC = electric conductivity, TN = total nitrogen, and pH = pH. The third letter, M or R, means the mean and range on each environmental factor, respectively



(Kleijn 2003). *R. alba* develops small and short-term persistent seedbank (Egawa et al. 2009), and thus is considered to restrict weakly to the establishment of the late colonizers. In addition, *R. alba* is a weak competitor for acquiring nutrients because of shallower roots than later colonizers (Ohlson and Malmer 1990). Subsequently, three grasses such as *M. japonica*, *P. communis* and *C. middendorffii*, were later colonizers than *R. alba*, and *C. middendorffii* seemed to be somehow later for immigration than *M. japonica* and *P. communis*. These late colonizers enlarge the cover mostly by vegetative reproduction (Tomassen et al. 2003; Alvarez et al. 2005) and can utilize nutrients in deep peat by belowground organs (Malmer et al. 2003). Therefore, *R. alba* declined in cover on the old mined sites, and large grasses and sedges replaced from *R. alba*. In addition, these large herbs did not overlap their dominant sites, differentiated by mean water level.

Scale-Dependent Environmental Factors and *Sphagnum* Colonization

After declining *Rhynchospora alba*, *Moliniopsis japonica* and *Phragmites communis* colonized. *Carex middendorffii* sometimes followed the two latter species. *Sphagnum papillosum* also colonized when water level was higher than -20 cm from peat surface on annual average. Within the post-mined peatland, the establishment of these species was primarily determined by the mean water level. In particular, *S. papillosum* established in the mined peatlands when the water level was as high as in the unmined peatlands, whilst *Sphagnum* did not immigrate even to the aged sites when the water level was low. *Sphagnum* colonizes a bare ground created by peat mining if suitable habitats, such as high water level, are provided and the diaspores are sufficiently immigrated (Robert et al. 1999). In contrast, *Sphagnum* colonized least in vacuum-mined bogs, Canada, when water level was lower than 40 cm below the ground surface (Lavoie et al. 2005). High water level less than 40 cm deep is a prerequisite for the immigration of *Sphagnum*

to bare ground after peat mining, while the chemical properties in groundwater regulate the growth (Grosvernier et al. 1997).

In this study, annual changes of water chemistry from 2002 to 2007 could not be monitored. Alternatively, chronosequence approach is useful method to understand the temporal dynamics of plant communities and soil development across multiple time-scale (Walker et al. 2010). CCA results with using chronological data on 2005 could explain revegetation pattern after peat-mining. Therefore, CCA analysis from this study showed that pH was the prime determinant on the development of plant community in Sarobetsu peatlands, including un-mined and mined peatlands (Fig. 6). Either groundwater chemistry or water level is a prime determinant on species composition and plant community structure with various spatial scales in wetlands (Bragazza and Gerdol 1999; Hajkova et al. 2004). In the Carpathian spring fens, when compared species distribution along ecological gradients at two scales, i.e., among and within vegetation types, the crucial role of water chemistry, such as pH, for large-scale variation is not always evident at a smaller spatial scale, (Hajkova et al. 2004). Many large-scale studies report a bimodal distribution of water pH across mires, these pH split reflect the region of most rapid floristic changes (Wheeler and Proctor 2000, Sjors and Gunnarsson 2002). Meanwhile, water level was the second determinants within mined peatlands in Sarobetsu peatland, supported by the CCA analysis (Fig. 6). A boundary between alder (*Alnus japonica*) thicket and *P. communis* marshland in eastern Hokkaido, Japan, is developed firstly by water level, and water chemistry secondly promotes vegetation differentiation within each of the thicket and marshland (Tsuyuzaki et al. 2004). Therefore, on and around the boundary, water level develops the boundary with large scale, and water chemistry differentiates the vegetation with small scale. Scale-dependent environmental factors, i.e., water level with small scale and water chemistry with large scale on Sarobetsu mire, should explain the patterns of vegetation differentiation in the post-mined peatland and vegetation recovery towards the original *Sphagnum* bog.

Restoration Keys for *Sphagnum* Recovery

When the goal of restoration is returning ecosystem function (Rocheftort 2000), the recovery of *Sphagnum* is the criterion in bogs. Even a few decades after peat mining, the plant community structures were unstable and often did not go towards the original vegetation dominated by *Sphagnum papillosum*. To promote the re-colonization of *Sphagnum* in the post-mined peatland, water level was a key determinant, i.e., water level that is equivalent to level in the original bog, should be maintained. It has been found that *Sphagnum* can regenerate on mined peat surface (Andersen et al. 2010). But, these possibilities of *Sphagnum* colonization are influenced by hydrologic conditions on mined peat surfaces. A large fluctuating water level reduced water storage capacity and decrease in upward capillary flow that lead to a drier surface, so that *Sphagnum* cannot survive extended dry periods (Price and Whitehead 2001). Thus the water level directly affected the *Sphagnum* re-introduction in the inside of mined peatland. Additionally, the position of water level affects to evapotranspiration and oxido-reduction processes on peatlands (Proctor 1994). High water level has the effects to limit the mineralization of peat soil by anaerobic condition and dilute the nutrient concentrations by groundwater, which lead to decreases nutrients in groundwater. As a result, high water level is optimum condition, i.e., similar to natural habitat, to promote *Sphagnum* recovery in post-mined peatlands. Also, low pH was related to nutrient uptake by vascular plants (Fig. 5), and was advantageous for *Sphagnum* establishment. Therefore, operating wetland hydrology has more benefits than operating peat properties, such as chemistry and texture, for the restoration of *Sphagnum* recolonization, because the wetland hydrology determines water and peat quality (Bruland et al. 2003, Price et al. 2003). Water level directly affects plant recovery expressed by plant cover in the post-mined peatland, i.e., with small scale, and indirectly affects plant growth through affecting water chemistry represented by pH, with large scale. Restoration keys for *Sphagnum* recovery are primarily water level on small scale such as within the peat-mining area, and secondly water chemistry on large scale such as over all *Sphagnum*-dominated original bog including peat-mining area in Sarobetsu mire. In conclusion, hydrological manipulation on water level was desirable for the effective restoration to return *Sphagnum* bog.

Conclusion

By analyzing data from eight chronosequence plots series and one permanent plot (6 years of observation), the vegetation of each mined-site locally developed through different restoration-patterns as predicted. In particular, the recovery of *Sphagnum* species was identified to be slow and to follow a path different to other mined-sites by the results of GLMM analysis.

Hydrological factors explained more the variability of the vegetation than the successional age. Water level was the highest on the mined-sites where *Sphagnum* colonization was successful. The growth rate of *Sphagnum* species did not clearly respond to high increasing rate *P. communis* and *M. japonica* for about 30 years since abandonment. Therefore, the relationships between *Sphagnum* species and vascular plants could not really show a clear trend over time. The fluctuation pattern of water level was synchronizing with that of water chemistry, which would directly provide a cue for *Sphagnum*-dominated community to develop, and indirectly determine the community type of types on mined-sites including original vegetation.

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