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5 Effects of water level via controlling water chemistry on revegetation patterns after peat mining

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16

1 **Abstract**

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

18

19 **Keywords:** Direct and indirect effects; Permanent plot; Chronosequence; pH in groundwater;  
20 *Sphagnum papillosum*; Water level.

21

## 1 **Introduction**

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

22       Here, we reported the promoters on *Sphagnum* wetland revegetation clarified by monitoring for  
23 six years. On Sarobetsu mire in the northern Hokkaido of Japan, peat mining had been undertaken  
24 annually from 1970 to 2003. Inter-specific relationships, i.e., competition and facilitation, often  
25 determine more to revegetation patterns than environmental limitations (Tilman and Wedin 1991;  
26 Mahaney et al. 2004; Koyama and Tsuyuzaki 2010). Because individual species differ in their  
27 nutrient-use properties, species composition influences nutrient retention of ecosystem (Tilman et al.  
28 1997). In undisturbed peatlands, the balance *Sphagnum* mosses and vascular plants is maintained  
29 by their use of different sources of nutrient (Malmer et al. 1994). Some fertilization experiments

1 showed that increasing nutrients availability in the rhizosphere, i.e., nitrogen, phosphorus or both,  
2 involved the growth of vascular plants by drawdown of *Sphagnum* mosses (Gusewell et al. 2002;  
3 Heijmans et al. 2002; Limpens et al. 2003). More increasing nutrients than those of natural habitat  
4 have the positive effects for the growth of vascular plants and *Sphagnum* mosses, respectively.  
5 But, the decreasing through the use of nutrients in the rhizosphere have the negative effects for only  
6 vascular plants (Malmer et al. 2003), because *Sphagnum* mosses can use nutrients derived from  
7 rainwater on the surface. The exposure of peat by the excavation has resulted in higher nutrient  
8 concentrations for water and peat chemistry than those of original peatland. Therefore, the  
9 competitive balance may shift toward *Sphagnum* mosses or vascular plants depending on amount of  
10 nutrient concentration, then the revegetation patterns of *Sphagnum* mosses may be altered. The  
11 hydrological or hydro-chemical conditions directly influence nutrient availability in wetlands, and  
12 indirectly influence plant growth through root completion to nutrients in water (Kotowski, et al.  
13 2001). The temporal changes in environmental conditions, such as hydrological and  
14 hydro-chemical conditions, generate the spatial heterogeneity due to topography or geomorphology  
15 variation (Abreu et al. 2009). These spatial heterogeneity are linked with trends in vegetation  
16 structure over time, thus the variability of the successional vegetation in disturbed peatland is  
17 expected that follow multiple trajectories. Hydrological conditions would have mainly the effects  
18 on their threshold when divergence occurs. In particular, the high and stable conditions in water  
19 level promote the restoration toward the original *Sphagnum*-dominated vegetation that could be  
20 expected to occur. Forecasting trajectories and identifying factors that regulate their development  
21 is crucial to understanding community mechanisms. Additionally, these spatial heterogeneity  
22 complicate the interpretation of successional trends with the application of a synchronic approach.  
23 Therefore, the major objectives of this study is to combine chronological and synchronic analysis to  
24 detect 1) revegetation patterns, in particular, for *Sphagnum*, by monitoring  
25 chronologically-established permanent plots, 2) relationships between *Sphagnum* colonization and  
26 the environmental factors and between *Sphagnum* and vascular plants, and 3) the effects of water  
27 level and chemistry and their fluctuation patterns on revegetation patterns. Based on these results,  
28 the keys for restoration were discussed.

29

## 1 **Materials and methods**

### 2 Study area

3 Sarobetsu mire, consisting of 2,773 ha, is situated on the downstream of the Teshio River Basin,  
4 5 km east of Japan Sea, northern Hokkaido, Japan (45°06'N, 141°42'E, 7 m a.s.l.) (Hotes et al.  
5 2004). The original mire is classified into raised-ombrotrophic bog with peat about 6 m deep.  
6 Climate is warm-cool temperate. Mean annual temperature is 6.6°C during 2002 and 2007 with a  
7 maximum of 25.4°C in August 2006, and a minimum of -13.7°C in January 2003. Annual  
8 precipitation averages 996 mm. Snow-free period is usually from May to November. The  
9 maximum snow depth was recorded at 135 cm in 2004 at Toyotomi Town 6 km far from the mire  
10 (Japan Meteorological Agency 2008).

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

18

### 19 Field measurements

20 In 2002, a total of 192 1 × 1 m plots were set up in eight differently-aged sites mined between  
21 1970 and 1994. The sites were more than 50 m apart to each other within ca. 370 ha. In an  
22 unmined area adjacent to the mined area, 9 plots were set up in 2002 and additional 9 plots were set  
23 up in 2003 for control. More explanations about the location of surveyed sites and the setup  
24 method of plots have been described in Nishimura et al. (2009). The vegetation in each plot was  
25 monitored annually during plant growth seasons, i.e., July or August, from 2002 to 2007. The  
26 cover of each species was visually estimated in each plot divided into 25 20 cm × 20 cm cells.  
27 Nomenclature refers to Ohwi (1975) for seed plants, Tagawa (1983) for ferns, and Iwatsuki and  
28 Mizutani (1972) for mosses.

29

## 1 Ground water sampling

2 To measure groundwater level, 92 PVC pipes (1 m in length and 4 cm in diameter) were buried  
3 into 85 cm below the peat surface in 2002. The pipes had holes (5 mm in diameter) at about 10 cm  
4 intervals and the end of pipe was sealed. Water level defined as the length between soil level and  
5 surface water inside PVC pipes was measured 36 times during snow-free period from June 2002 to  
6 October 2007 with the use of a ruler. Positive value on water level indicates groundwater appears  
7 above the ground surface in this study. For measuring water chemistry, 100-ml ground water was  
8 collected from the inside of the pipes in each month. Water sampling was undertaken seven times  
9 on 92 sampling points from April to November 2005. The acidity-alkalinity and the fertility  
10 gradient controlling the distribution of plant species and vegetation types in peatlands have often  
11 been measured through water pH and EC. Additionally, peatlands generally are limited by  
12 nitrogen or phosphorus (VerHoeven et al. 1990), the balances between *Sphagnum* and vascular plant  
13 is maintained by the use of different sources of nutrients (Malmer et al. 1994). Therefore, the  
14 competitive balance may shift toward *Sphagnum* species or vascular plants depending on amount of  
15 N and P concentration. In this study, water chemistry was analyzed with a focus on four  
16 macro-nutrient factors (TN, TP, pH and EC). pH and electrical conductivity (EC) were measured  
17 by a pH meter (MP120, Mettler Toledo, Tokyo) and an EC meter (MP126, Mettler Toledo, Tokyo),  
18 respectively, in a laboratory within a day or two soon after returning to laboratory. These values  
19 were calibrated at 25°C. All water samples were kept at 0°C in a refrigerator until the analyses of  
20 nitrogen and phosphorus. Total nitrogen (TN) was determined by UV spectroscopic measurement  
21 after acid digestion (Keeney & Nelson 1982). Total phosphorus (TP) was determined by the  
22 molybdenum blue method after alkaline digestion (Wetzel & Likens 2000). The repeated  
23 measurement was one time because of the large number of samples (n = 92).

24

## 25 Data analysis

26 Species richness and cover on each species were calculated in each plot every year.  
27 Shannon's species diversity ( $H'$ ) and evenness ( $J$ ) were calculated in each plot as:  $H' = -\sum p_i \ln p_i$ , and  
28  $J = H' / \ln S$ . Here,  $S$  is the species richness and  $p_i$  is the proportion of the plant cover of each  
29 species to the total cover. Plant community changes from 2002 to 2007 were investigated by

1 detrended correspondence analysis (DCA). Canonical correspondence analysis (CCA) was  
2 performed using data on plant community and environments measured in 2005. Since TP in  
3 ground water did not differ significantly between sites, pH, EC, TN and water level were used for  
4 CCA. Mean and range (between the maximum and minimum) of environmental factors were  
5 calculated to investigate the different effects on plant community development. A variable is  
6 considered to contribute significantly to the regression when it is higher than an absolute  $t$ -value  $> 4$   
7 (Jongman et al. 1987). To ensure relationships between the five environmental factors, water level,  
8 pH, EC, TN and TP, Kendall's rank correlations were calculated.

9 Species cover, plot cover, species richness, diversity and evenness were compared between 9  
10 sites and between years after mining. Generalized linear mixed-effects models (GLMM) were  
11 applied to investigate significant temporal changes in cover and species richness. The probability  
12 distribution of cover was assumed as binomial, and species richness Poisson.  $H'$  and  $J$  were  
13 investigated by linear mixed-effects model (LMM) with a Gaussian distribution. LMM with a  
14 Gaussian distribution was also applied for comparing chemical properties in groundwater between  
15 sites and between months, and for water level between sites and between years. For these analyses,  
16 all the combinations of sites with different ages after mining were modeled and examined. The  
17 first model assumed that the dependent variable was explained by each site and thus eight fitting  
18 curves were obtained. Then, 2 of 8 sites were merged and modeled. Like this way, number of  
19 merged sites increased. The last model was made by merging all sites with a single fitting line.  
20 The best-fit LMM and GLMM models of the combinations were selected by Akaike's information  
21 criteria (AIC) (Burnham and Anderson 1998). Except for CCA and DCA performed by CANOCO  
22 (version 4.5, Center for Biometry, Wageningen), all statistical analyses were conducted by the  
23 statistical software R (R Development Core Team 2009).

24

## 25 **Results**

### 26 Plant community structures

27 During 2002 and 2007, 59 taxa (49 vascular plants and 10 mosses) were recorded from all the  
28 plots. There were 30 species recorded from 18 plots in unmined site (control) while there were 34  
29 species in 8 mined sites. The predominant species in control was *Sphagnum papillosum* of which

1 cover was more than 70% and did not change from 2002 to 2007 (Fig. 2). On the mined sites,  
2 *Sphagnum papillosum* did not establish in 1992 and 1994 sites, but established in the 1975, 1978  
3 and 1984 sites with more than 10% in cover. In particular, the cover of *Sphagnum* was ca 40% in  
4 the 1975 sites and 20% in the 1978 site. In contrast, the cover was less than 4% in the two old  
5 sites mined in 1970 and 1972.

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

14

#### 15 Temporal changes in vegetation

16 Plot cover and species richness were higher in control sites than in mined sites (Fig. 1). Plot  
17 cover increased with time in the mined sites, but the patterns differed between most sites, indicated  
18 by six fitting curves. As well as plot cover, species richness annually increased (Fig. 1). The  
19 changes in species richness were explained by three fitting curves, showing that the determinants on  
20 species richness differed from those of plot cover. Annual rate of increase in species richness was  
21 faster in sites mined in 1978 and 1984. Sites mined in 1982, 1992 and 1994 did not change the  
22 lowest species richness across years. Diversity was lower in the mined peatland than in the  
23 unmined peatland. The diversity was explained by four fitting curves. The fastest increases in  
24 diversity were observed in the 1978, 1984 and 1994 sites, while the slowest one was on the 1982  
25 site. In total, plot cover, species richness and diversity increased faster in the sites mined in 1975  
26 and 1978 and did slower in site mined in 1982. The other five sites recovered with moderate paces  
27 per year between them. Evenness decreased with ages in all the mined sites (Fig. 1), although the  
28 richness and diversity increased. The decrease of evenness was derived mostly from the increase  
29 in the cover of dominant species. For example, *R. alba* greatly increased relative dominance in

1 young sites, i.e., mined in 1992 and 1994, and *M. japonica* did well in middle-aged sites, i.e., mined  
2 in 1972 and 1978 (Fig. 2).

3

#### 4 Temporal changes in common species

5 *R. alba* drastically increased the plant cover in the 1992 and 1994 sites (Fig. 2). The cover of  
6 *R. alba* could be significantly explained by four increasing patterns due to using linear-model  
7 method, but actually peaked at middle ages, i.e., more than 20 years after abandonment, and then  
8 decreased like a parabolic curve. In addition, the establishment failed in 1978 and 1982 sites. *M.*  
9 *japonica* recovered the cover in all the sites. The recovery paces were divided into three types,  
10 fast, moderate and slow, although the fitting curves were not statistically significant. *M. japonica*  
11 ran behind *R. alba*, but increased the cover faster than *R. alba* once established. The annual  
12 fluctuations of cover on three monocotyledonous species, *P. communis*, *C. middendorffii* and *M.*  
13 *japonica* resembled to each other. However, the well-established sites were different between  
14 these three species; viz. *M. japonica* recovered fastest in the 1970 site, *R. alba* in the 1972 site, and  
15 *C. middendorffii* in the 1978 site.

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

25

#### 26 Vegetation and its related environmental factors

27 Eigenvalues on the axes I and II of DCA were 0.610 and 0.318, respectively. The plot scores  
28 in control were aggregated on the right side in the graph, and fluctuated least (Fig. 3), showing that  
29 the community structure did not change across years. In contrast, the plot scores in the mined sites

1 fluctuated along both the axes I and II. The scores of plots mined in 1992 and 1994 fluctuated  
2 highly, showing that the plant community structures changed faster soon after mining. However,  
3 even in old-mined sites, the plot scores fluctuated along both the axes I and II, and did not go  
4 towards the scores of the unmined site, i.e., the control.

5 The peaks of precipitation occurred in fall rainy seasons during late August and late September  
6 in most years (Fig. 4). From April to early May, water level was high because of snowmelt.  
7 Water level gradually decreased until rainy seasons, and then increased. Mean water level was  
8 significantly different between sites. The 1975 site where *Sphagnum* cover was highest of the  
9 mined sites always showed the highest water level. The 1992 and 1978 sites followed the 1975  
10 site, i.e., the secondly highest water level. The 1972 and 1982 sites, both of which had high plant  
11 cover, showed the lowest water level. *Sphagnum papillosum* established well in old sites, i.e., the  
12 1975 and 1978 sites, with high water level, but established least in the 1972 site that showed the  
13 lowest water level.

14 On water chemistries in 2005, pH, EC and TN in the groundwater were different between sites  
15 and between months (Fig. 5). TP was not different between sites, because of low concentration in  
16 every site. pH was higher in all mined sites than in un-mined control site. In particular, the two  
17 youngest sites mined in 1992 and 1994 showed the highest pH. EC was higher in the 1982 and  
18 1994 sites where plant cover was low. The 1975 and 1978 sites with high *Sphagnum* cover  
19 showed low EC. EC in the control plots was higher than that in *Sphagnum*-establishing mined  
20 sites, but was lower than in that in mined plots without *Sphagnum*. TN decreased after June in old  
21 mined sites (i.e., 1970 sites) and the control, and was high and stable in the low-vegetated, youngest  
22 site mined in 1994. Water level was lowest in June and September in most sites (Fig. 4).  
23 Synchronizing with this fluctuation of the water level, pH, TN and TP were high in June and  
24 September (Fig. 5). All of these four variables, water level, pH, TN and TP, were correlated to  
25 each other (Kendall's rank test,  $P < 0.05$ ), except between pH and EC. These results implied that  
26 water level determined mostly by precipitation affected various water chemistries.

27 The contribution rates of the first two CCA axes on plot-environmental relationships were  
28 41.8% and 26.0%, respectively, when plots only in post-mined sites were used, and 41.4% and  
29 29.1% when all the plots including unmined site were used. Monte Carlo permutation test

1 confirmed that the two overall ordinations were significant at  $P < 0.01$ . In mined sites, axis I on  
2 CCA was significantly correlated to mean water level ( $t = 6.81$ ), (Fig. 6a). No water chemistries  
3 were related to axis I. All the measured environmental factors were not related to axis II (absolute  
4  $t < 4$ ), although the highest  $t$ -value was  $-3.94$  shown by the range of water level. Most plots in the  
5 1992 and 1994 sites showed the highest scores on axis II, showing that the vegetation development  
6 were influenced by the small fluctuations of water level. In contrast, plots in the 1972 site  
7 established with the high fluctuations of water level. In total, therefore, the vegetation structures  
8 in the mined sites were determined more by mean water level than the range and water chemistries.

9 When all the plots, i.e., in un-mined and mined sites, were investigated by CCA, axis I was  
10 related most to pH ( $t = 7.71$ ) (Fig. 6b). Mean water level was not related to axis I ( $t = -3.61$ ), even  
11 though that was the prime determinant on the revegetation in the post-mined peatland. Axis II was  
12 correlated to the mean ( $t = 4.97$ ) and range ( $t = -4.09$ ) of water level. The other water chemistries  
13 were not related to both axes I and II.

14

## 15 **Discussion**

### 16 Successional patterns

17 Mean plant cover and richness were lower in mined sites than in unmined sites even 25 years  
18 after mining, showing that plant communities in mined sites could not recover to the original bog  
19 for 30 years. A few decades were insufficient to develop *Sphagnum*-dominated community. The  
20 plot cover gradually recovered in each mined site but was greatly influenced by site-specific  
21 environments. While the recovery of species richness developed three patterns (Fig. 1), therefore,  
22 the determinants on species richness differed from those of plot cover. In the earliest stages on the  
23 mined peatlands, *Rhynchospora. alba* immigrated faster than any other plants to bare ground where  
24 nitrogen in water was higher (Nishimura et al. 2009). Aerobic bacteria promote peat  
25 decomposition after peat mining and the subsequent nutrient concentrations become high  
26 (Wind-Mulder et al. 1996). Since *R. alba* has a shallow root system, this species have an  
27 advantage in the colonization to the bare ground, which is soft and mud substrate, after peat-mining  
28 (Ohlson and Malmer 1990). Late colonizers delay the immigration, when the early colonizers  
29 develop large seedbank and regenerate by the seedlings (Kleijn 2003). *R. alba* develops small and

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

11

#### 12 Scale-dependent environmental factors and *Sphagnum* colonization

13 After declining *Rhynchospora alba*, *Moliniopsis japonica* and *Phyramites communis* colonized.  
14 *Carex middendorffii* sometimes followed the two latter species. *Sphagnum papillosum* also  
15 colonized when water level was higher than -20 cm from peat surface on annual average. Within  
16 the post-mined peatland, the establishment of these species was primarily determined by the mean  
17 water level. In particular, *S. papillosum* established in the mined peatlands when the water level  
18 was as high as in the unmined peatlands, whilst *Sphagnum* did not immigrate even to the aged sites  
19 when the water level was low. *Sphagnum* colonizes a bare ground created by peat mining if  
20 suitable habitats, such as high water level, are provided and the diaspores are sufficiently  
21 immigrated (Robert et al. 1999). In contrast, *Sphagnum* colonized least in vacuum-mined bogs,  
22 Canada, when water level was lower than 40 cm below the ground surface (Lavoie et al. 2005).  
23 High water level less than 40 cm deep is a prerequisite for the immigration of *Sphagnum* to bare  
24 ground after peat mining, while the chemical properties in groundwater regulate the growth  
25 (Grosvernier et al. 1997).

26 In this study, annual changes of water chemistry from 2002 to 2007 could not be monitored.  
27 Alternatively, chronosequence approach is useful method to understand the temporal dynamics of  
28 plant communities and soil development across multiple time-scale (Walker et al. 2010). CCA  
29 results with using chronological data on 2005 could explain revegetation pattern after peat-mining.

1 Therefore, CCA analysis from this study showed that pH was the prime determinant on the  
2 development of plant community in Sarobetsu peatlands, including un-mined and mined peatlands  
3 (Fig. 6). Either groundwater chemistry or water level is a prime determinant on species  
4 composition and plant community structure with various spatial scales in wetlands (Bragazza and  
5 Gerdol 1999; Hajkova et al. 2004). In the Carpathian spring fens, when compared species  
6 distribution along ecological gradients at two scales, i.e., among and within vegetation types, the  
7 crucial role of water chemistry, such as pH, for large-scale variation is not always evident at a  
8 smaller spatial scale, (Hajkova et al. 2004). Many large-scale studies report a bimodal distribution  
9 of water pH across mires, these pH split reflect the region of most rapid floristic changes (Wheeler  
10 and Proctor 2000, Sjors and Gunnarsson 2002). Meanwhile, water level was the second  
11 determinants within mined peatlands in Sarobetsu peatland, supported by the CCA analysis (Fig. 6).  
12 A boundary between alder (*Alnus japonica*) thicket and *P. communis* marshland in eastern Hokkaido,  
13 Japan, is developed firstly by water level, and water chemistry secondly promotes vegetation  
14 differentiation within each of the thicket and marshland (Tsuyuzaki et al. 2004). Therefore, on and  
15 around the boundary, water level develops the boundary with large scale, and water chemistry  
16 differentiates the vegetation with small scale. Scale-dependent environmental factors, i.e., water  
17 level with small scale and water chemistry with large scale on Sarobetsu mire, should explain the  
18 patterns of vegetation differentiation in the post-mined peatland and vegetation recovery towards  
19 the original *Sphagnum* bog.

20

#### 21 Restoration keys for *Sphagnum* recovery

22 When the goal of restoration is returning ecosystem function (Rocheffort 2000), the recovery of  
23 *Sphagnum* is the criterion in bogs. Even a few decades after peat mining, the plant community  
24 structures were unstable and often did not go towards the original vegetation dominated by  
25 *Sphagnum papillosum*. To promote the re-colonization of *Sphagnum* in the post-mined peatland,  
26 water level was a key determinant, i.e., water level that is equivalent to level in the original bog,  
27 should be maintained. It has been found that *Sphagnum* can regenerate on mined peat surface  
28 (Andersen et al. 2010). But, these possibilities of *Sphagnum* colonization are influenced by  
29 hydrologic conditions on mined peat surfaces. A large fluctuating water level reduced water

1 storage capacity and decrease in upward capillary flow that lead to a drier surface, so that  
2 *Sphagnum* cannot survive extended dry periods (Price and whitehead 2001). Thus the water level  
3 directly affected the *Sphagnum* re-introduction in the inside of mined peatland. Additionally, the  
4 position of water level affects to evapotranspiration and oxido-reduction processes on peatlands  
5 (Proctor 1994). High water level has the effects to limit the mineralization of peat soil by  
6 anaerobic condition and dilute the nutrient concentrations by groundwater, which lead to decreases  
7 nutrients in groundwater. As a result, high water level is optimum condition, i.e., similar to natural  
8 habitat, to promote *Sphagnum* recovery in post-mined peatlands. Also, low pH was related to  
9 nutrient uptake by vascular plants (Fig. 5), and was advantageous for *Sphagnum* establishment.  
10 Therefore, operating wetland hydrology has more benefits than operating peat properties, such as  
11 chemistry and texture, for the restoration of *Sphagnum* recolonization, because the wetland  
12 hydrology determines water and peat quality (Bruland et al. 2003, Price et al. 2003). Water level  
13 directly affects plant recovery expressed by plant cover in the post-mined peatland, i.e., with small  
14 scale, and indirectly affects plant growth through affecting water chemistry represented by pH, with  
15 large scale. Restoration keys for *Sphagnum* recovery are primarily water level on small scale such  
16 as within the peat-mining area, and secondly water chemistry on large scale such as over all  
17 *Sphagnum*-dominated original bog including peat-mining area in Sarobetsu mire. In conclusion,  
18 hydrological manipulation on water level was desirable for the effective restoration to return  
19 *Sphagnum* bog.

20

## 21 Conclusion

22 By analyzing data from eight chronosequence plots series and one permanent plot (six years of  
23 observation), the vegetation of each mined-site locally developed through different  
24 restoration-patterns as predicted. In particular, the recovery of *Sphagnum* species was identified to  
25 be slow and to follow a path different to other mined-sites by the results of GLMM analysis.  
26 Hydrological factors explained more the variability of the vegetation than the successional age.  
27 Water level was the highest on the mined-sites where *Sphagnum* colonization was successful. The  
28 growth rate of *Sphagnum* species did not clearly respond to high increasing rate *P. communis* and *M.*  
29 *japonica* for about 30 years since abandonment. Therefore, the relationships between *Sphagnum*

1 species and vascular plants could not really show a clear trend over time. The fluctuation pattern  
2 of water level was synchronizing with that of water chemistry, which would directly provide a cue  
3 for *Sphagnum*-dominated community to develop, and indirectly determine the community type of  
4 types on mined-sites including original vegetation.

5

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10

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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. +: 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  $p < 0.01$ .

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
<b>Species</b>										
<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.

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

6  
7 **Fig. 2** Yearly fluctuations in percentage cover of the five frequent species after mining. The  
8 fittest GLMM for explaining cover of five species adopt independent variables, age and site.  
9 The significant variables are indicated within each figure. Symbols on curves, refer to Fig. 1

10  
11 **Fig. 3** Detrended correspondence analysis (DCA) diagram showing plot scores. The same plots  
12 surveyed from 2002 to 2007 are indicated by connected lines. Symbols show the first and last  
13 survey-year only, so the open symbols indicate the first sampling in 2002 and the closed  
14 symbols the last sampling in 2007. The open end of lines show that the removal of plots due  
15 to zero-data or the plots for failure to survey until last year due to some plots submergence.

16  
17 **Fig. 4** Monthly precipitation and water level from 2002 to 2007 in nine sites with different ages,  
18 including control. LMM for explaining water level adopt two independent variables, site and  
19 year. The water level is significantly different between years and sites ( $P < 0.01$ )

20  
21 **Fig. 5** Seasonal fluctuations in averaged pH, electric conductivity (EC), total nitrogen (TN) and  
22 total phosphorus (TP) in sites with different ages. Groundwater was sampled 10 times from  
23 April to November 2005. LMM for explaining pH, EC, TN and TP in groundwater adopt two  
24 independent variables, site and month. The significant variables are indicated within each  
25 figure ( $P < 0.01$ ). Plus signs mean the two factors are significant

26  
27 **Fig. 6** Plot-environmental factor ordination diagram obtained by canonical correspondence  
28 analysis (CCA) (a) in post-mined sites and (b) in all sites, i.e., pre- and post-mined sites.  
29 Each variable is expressed by three letters in the figure. The first two letters indicate

1 environmental factors: WL = water level, EC = electric conductivity, TN = total nitrogen, and  
2 pH = pH. The third letter, M or R, means the mean and range on each environmental factor,  
3 respectively