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Author(s)	Nishimura, Aiko; Tsuyuzaki, Shiro
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1 The names of the authors:

2 Aiko Nishimura & Shiro Tsuyuzaki

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4 Title:

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

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7 The affiliations and addresses of the authors:

8 **Nishimura, A.** (Corresponding author)

9 National Agricultural Research Center, Kannondai 3-1-1, Tsukuba, Ibaraki 305-8666, Japan.

10 E-mail: ainishi@affrc.go.jp

11 Tel: +81 29-838-8514

12 Fax: +81 29-838-8515

13 **Tsuyuzaki, S.**

14 Graduate School of Environmental Earth Science, Hokkaido University, Kita 10 Nishi 5, Kitaku,

15 Sapporo, Hokkaido 060-0810, Japan.

16

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.

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 *Sphganum* 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 (Rocheftort 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

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 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 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

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

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 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 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 (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 *Phragmites 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.

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 (Rochefort 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

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*

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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Reference

- Abreu Z, Llambi LD, Sarmiento L (2009) Sensitivity of soil restoration indicators during Paramo succession in the high tropical Andes: Chronosequence and permanent plot approaches. *Restoration Ecology* 17: 619-628
- Alvarez MG, Tron F, Mauchamp A (2005) Sexual versus asexual colonization by *Phragmites australis*: 25-year reed dynamics in a Mediterranean marsh, southern France. *Wetlands* 25: 639-647
- Andersen R, Rochefort L, Poulin M (2010) Peat, water and plant tissue chemistry monitoring: A seven-year case-study in a restored peatland. *Wetlands* 30: 159-170
- Benscoter BW, Vitt DH (2008) Spatial patterns and temporal trajectories of the bog ground layer along post-fire chronosequence. *Ecosystems* 11: 1054-1064
- Bragazza L, Gerdol R (1999) Hydrology, groundwater chemistry and peat chemistry in relation to habitat conditions in a mire on the South-eastern Alps of Italy. *Plant Ecology* 144: 243-256
- Bruland GL, Hanchey MF, Richardson CJ (2003) Effects of agriculture and wetland restoration on hydrology, soils, and water quality of a Carolina Bay complex. *Wetlands Ecology and Management* 11: 141-156
- Burnham PB, Anderson DR (1998) Model selection and multimodel inference: *a practical information-theoretic approach*. Springer-Verlag, New York, USA
- Campbell DR, Lavoie C, Rochefort L (2002) Wind erosion and surface stability in abandoned

milled peatlands. Canadian Journal of Soil Science 82: 85-95

Egawa C, Koyama A, Tsuyuzaki S (2009) Relationships between the developments of seedbank standing vegetation and litter in a post-mined peatland. Plant Ecology 203: 217-228

Graf MD, Rochefort L, Poulin M (2008) Spontaneous revegetation of cutaway peatlands of North America. Wetlands 28: 28-39

Grosvernier P, Matthey Y, Buttler A (1997) Growth potential of three *Sphagnum* species in relation to water level and peat properties with implications for their restoration in cut-over bogs. Journal of Applied Ecology 34: 471-483

Gusewell S, Willem K, Verhoeven JTA (2002) Time-dependent effects of fertilization on plant biomass in floating fens. Journal of Vegetation Science 13: 705-718

Hajek M, Hekera P, Hajkoca P (2002) Spring fen vegetation and water chemistry in the western Carpathian flysch zone. Folia Geobotanica 37: 205-224

Hajek M, Hekera P (2004) Can seasonal variation in fen water chemistry influence the reliability of vegetation-environment analyses? Preslia 76: 1-14

Hajkova P, Wolf P, Hajek M (2004) Environmental factors and Carpathian spring fen vegetation: the importance of scale and temporal variation. Annales Botanici Fennici 41: 249-262

Heijmans MMPD, Klees H, de Visser W, Berendse F (2002) Response of *Sphagnum* bog plant community elevated CO₂ and N supply. Plant Ecology 162: 123-134

Hotes S, Poschold P, Takahashi H, Grootjans AP, Adema E (2004) Effects of tephra deposition on mire vegetation: a field experiment in Hokkaido, Japan. Journal of Ecology 92: 624-634

Iwatsuki Y, Mizutani M (1972) Colored illustrations of bryophytes of Japan. Hoikusya Publishing, Osaka

Jongman RHG, ter Braak CJF, van Tongeren OFR (1987) Data analysis in community and landscape ecology. Cambridge University Press, Cambridge

Keeney DR, Nelson DW (1982) Nitrogen-inorganic forms. In: Page, Miller RH, Keeney DR (eds) Methods of soil analysis. Part 2. Chemical and microbiological properties, 2nd edn. American Society of Agronomy and Soil Science of America, Madison, pp 643-698

Kleijn D (2003) Can establishment characteristics explain the poor colonization success of late successional grassland species on Ex-Arable land? Restoration Ecology 11: 131-138

- 1 Kotowski W, van Andel J, van Diggelen R, Hogendorf J (2001) Responses of fen plant species to
2 groundwater level and light intensity. *Plant Ecology* 155: 147-156
- 3 Koyama A, Tsuyuzaki S (2010) Effects of sedge and cottongrass tussocks on plant establishment
4 patterns in post-mined peatland, northern Japan. *Wetland Ecology and Management* 18:
5 135-148
- 6 Lamers LPM, Smolders AJP, Roelofs JGM (2002) The restoration of fens in the Netherlands.
7 *Hydrobiologia* 478: 107-130
- 8 Lavoie C, Grosfernier P, Girard M, Marcoux K (2003) Spontaneous revegetation of mined
9 peatlands: An useful restoration tool? *Wetlands Ecology and Management* 11: 97-107
- 10 Lavoie C, Saint-Louis A, Lachanve D (2005) Vegetation dynamics on an abandoned vacuum-mined
11 peatland: 5 years of monitoring. *Wetlands Ecology and Management* 13: 621-633
- 12 Limpens J, Berendse F, Klees H (2003) N deposition affects N availability in interstitial water,
13 growth of *Sphagnum* and invasion of vascular plants in bog vegetation. *New Phytologist* 157:
14 339-347
- 15 Mahaney WM, Wardrop DH, Brooks RP (2004) Impacts of sedimentation and nitrogen enrichment
16 on wetland plant community development. *Plant Ecology* 175: 227-243
- 17 Malmer N, Sevensson BM and Wallen B (1994) Interaction between *Sphagnum* mosses and field
18 layer vascular plants in the development of peat-forming systems. *Folia Geobotanica* 29:
19 483-496
- 20 Malmer N, Albinsson C, Svensson BM, Wallen B (2003) Interferences between *Sphagnum* and
21 vascular plants: effects on plant community structure and peat formation. *Oikos* 100: 469-482
- 22 Nishimura A, Tsuyuzaki S, Haraguchi A (2009) A chronosequence approach for detecting
23 revegetation patterns after *Sphagnum*-peat mining, northern Japan. *Ecological Research*
24 24:237-246
- 25 Ohlson M, Malmer N (1990) Total nutrient accumulation and seasonal variation in resource
26 allocation in the bog plant *Rhynchospora alba*. *Oikos* 58: 100-108
- 27 Ohwi J (1975) *Flora of Japan* (revised edn). Shibundo, Tokyo
- 28 Price JS, Whitehead GS (2001) Developing hydrologic thresholds for *Sphagnum* recolonization on
29 an abandoned cutover bog. *Wetlands* 21: 32-40

1 Price JS, Heathwaite AL, Baird AJ (2003) Hydrological processes in abandoned and restored
2 peatlands: An overview of management approaches. *Wetlands Ecology and Management* 11:
3 65-83

4 Proctor MCF (1994) Seasonal and shorter-term changes in surface-water chemistry on four English
5 ombrogenous bogs. *Journal of Ecology* 82: 597-610

6 Robert EC, Rochefort L, Garneau M (1999) Natural revegetation of two block-cut mined peatlands
7 in eastern Canada. *Canadian Journal of Botany* 77: 447-459

8 Rochefort L (2000) *Sphagnum* - A keystone genus in habitat restoration. *The Bryologist* 103:
9 503-508

10 Tagawa M (1983) Colored illustrations of the Japanese pteridophyta. Hoikusya Publishing, Osaka

11 Tsuyuzaki S, Haraguchi A, Kanda F (2004) Effects of scale-dependent factors on herbaceous
12 vegetation patterns in a wetland, norther Japan. *Ecological Research* 19: 349-355

13 Tilman D, Wedin D (1991) Dynamics of nitrogen competition between successional grasses.
14 *Ecology* 72: 1038-1049

15 Tilman D, Knops J, Wedin D, Reich P, Ritchie M, Siemann E (1997) The influence of functional
16 diversity and composition on ecosystem processes. *Science* 277: 1300-1302.

17 Tomassen HM, Smolders AJP, Lamers LPM, Roelofs JGM (2003) Stimulated growth of *Betula*
18 *pubescens* and *Molinia caerulea* on ombrotrophic bogs: role of high levels of atmospheric
19 nitrogen deposition. *Journal of Ecology* 91: 357-370

20 Verhoeven JTA, Maltby E and Schmitz MZ (1990) Nitrogen and Phosphorus mineralization in fens
21 and bogs. *Journal of Ecology* 78: 713-726

22 Vitt DH, Chee W (1990) The relationships of vegetation to surface water chemistry and peat
23 chemistry in fens of Alverta, Canada. *Vegetatio* 89: 87-106

24 Walker LR, Wardle DA, Bardgett RD, Clarkson BD (2010) The use of chronosequences in studies
25 of ecological succession and soil development. *Journal of Ecology* 98: 725-736

26 Wetzel RG, Likens GE (2000) Inorganic nutrients: nitrogen, phosphorus, and other nutrients. In:
27 *Limnological analyses*, 3rd edn. Springer, New York, pp 85-111

28 Wind-Mulder HL, Rochefort L, Vitt DH (1996) Water and peat chemistry comparisons of natural
29 and post-harvested peatlands across Canada and their relevance to peatland restoration.

- 1 Ecological Engineering 7: 161-181
- 2 Zoltai SC, Vitt DH (1995) Canadian wetlands: Environmental gradients and classification. Vegetatio
- 3 118: 131-137

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
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)	+	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)	+	2.2 (39)
<i>Gentiana triflora</i>	-	0.6 (14)	1.3 (13)	-	0.5 (7)	+	+	-	-	0.3 (37)
<i>Solidago virgarea</i>	4.0 (8)	0.4 (11)	1.6 (13)	-	-	-	+	-	-	0.5 (33)
<i>Hosta rectifolia</i>	13.3 (9)	0.4 (3)	-	0.2 (4)	-	+	1.0 (7)	0.2 (1)	0.1 (2)	0.8 (27)
<i>Andromeda polifolia</i>	0.8 (9)	+	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)	+	+	+	-	0.2 (11)
<i>Trientalis europaea</i>	0.6 (8)	-	-	+	0.1 (1)	-	-	-	-	+
<i>Hemerocallis middendorffii</i>	6.3 (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)	+	0.2 (9)
<i>Parnassia palustris</i>	-	0.2 (6)	-	0.3 (3)	-	-	-	-	-	0.1 (9)
<i>Iris laevigata</i>	0.1 (2)	-	-	+	0.1 (1)	-	+	-	0.1 (2)	+
<i>Sphagnum</i> spp	0.2 (9)	+	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*, *Lycopodium 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.

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

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

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.

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 ($P < 0.01$)

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

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