Effect of Different Hydrological Restoration Measures in Aukštumala Raised Bog Damaged by Peat Harvesting Activities

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Abstract

Anthropogenic disturbance (drainage and peat harvesting works in adjacent area) accelerates water outflow from and mineralization of top peat layer in the raised bog of Aukštumala Telmological Reserve (Western Lithuania) thus inducing peatland degradation and promoting penetration of atypical plant species and woody vegetation. Possibilities of restoration of the most affected parts of the Aukštumala raised bog (contact zone of the bog and peat harvesting fields) were investigated. Specifically, we aimed to assess effectiveness of two different means of hydrological regime restoration installed in the contact zone: (i) bog isolation from peat harvesting fields (to prevent direct water runoff) using polyethylene membrane (PM measure, installed in November 2006) and "peat lock" system (PL measure: water runoff blocked by highly decomposed peat; installed in November 2010), and (ii) blocking of ditches of the old drainage system using peat dams (PD measure, installed in November 2012). The research was carried out by performing monthly (from April to October) water level measurements in a system of water level monitoring profiles installed in zones of impact of each measure and non-treated (control) areas. Moreover, dendrochronological analysis of pine growth was performed in PM-treated and control areas.

Although in general positive effect of the applied treatments (raised water table, reduced amplitudes of seasonal water level fluctuation, reduced radial increment of pine trees, re-establishment of *Sphagnum* cover) could be observed, none of the three measures has fully restored hydrological regime to create favourable conditions for peat accumulation and thriving of typical raised bog communities. The results of the present study suggest that aiming to more efficiently regulate hydrological regime in drainage-affected parts of the Aukštumala raised bog, blocking or filling of the old drainage system should always be applied in combination with the installation of water insulation measures along the contact zone of the bog and peat harvesting fields. Longer observation time is needed to fully assess the effect of the installed restoration measures on hydrology and ecosystem functioning in the raised bog of Aukštumala Telmological Reserve.

Key words: anthropogenic disturbance, drainage, hydrological restoration (rewetting), Lithuania, peatland degradation, raised bog, water table depth

Introduction

Peatlands occupy about 3% (4 × 10^6 km^2) of the global land surface and contain about 30% of the terrestrial soil carbon (Gorham 1991, Joosten and Clarke 2002, Gorham and Rochefort 2003). Active drainage for agriculture, forestry and commercial peat harvesting in the last centuries is the main cause of pristine peatland loses. Since 1800's the global area of peatlands has been reduced at least by 10–20% (Joosten and Clarke 2002, MacDonald et al. 2006). Herewith, valuable ecosystems, which are vitally important in the global carbon cycle for protection of biodiversity, soil, preserving water supply and its quality, and other functions of ecosystem services, are being lost. Moreover, damaged peatlands are getting less and less resilient in the face of the environmental change (Joosten and Clarke 2002).

Lithuania has lost about two thirds of its total peatland area during the 20th century (Mierauskas et al. 2005, Jukoniene et al. 2009). Currently, about 70% of the inventoried peatlands in Lithuania are anthropogenically damaged (Povilaitis et al. 2011, Taminskas et al. 2011), and 1.6–2.5 mln. tons of carbon are lost every year as a result of intensified peat mineralization (Minayeva and Sirin 2009). During the Holocene, climate-driven variations affecting moisture balance of the acrotelm have simultaneously changed the rates of peat decomposition and structure of sensitive bog ecosystems (plant species composition, in particular) (Aaby 1976). Those changes also continuously influenced the proportion of trees in peatland vegetation cover (Eckstein et al. 2009). However, a large fraction of new tree establishments observed in peatlands during the last century has been caused by anthropogenic impact such as mire drainage and/or peat harvesting, what usually results in lowering of water level. The drainage increases water table depth on average by 20–60 cm thus enhancing aeration of the upper peat layer, which accelerates peat decomposition and its nutrient mineralization (Laine and Vanha-Majamaa 1992, Haapalehto et al. 2011, Jarašius et al. 2014). Changes in these abiotic factors are inevitably reflected in plant species composition: for example, in drained bogs of the north-temperate climate zone of Europe, typical raised bog species are commonly replaced by forest vegetation, where pioneer tree species such as Scots pine (*Pinus sylvestris* L.) and birch (*Betula pendula* Roth, *B. pubescens* Ehrh.) usually prevail (Laine et al. 1995). In natural bogs, *Sphagnum* mosses keep the eco-hydrologic self-regulating systems favourable to their own growth (van Breemen 1995), and reduction or complete loss of the *Sphagnum* carpet may considerably increase water table fluctuations (Ingram 1983, Wheeler 1999). Also these fluctuations may increase due to the increased bulk density of the surface peat after drainage (Minkkinen and Laine 1998).

Such changes are also observed in one of the largest and most famous Lithuanian peatlands – Aukštumala raised bog (total area 3,702 ha, western Lithuania), where in its drained areas typical open raised bog vegetation is replaced by forest species including trees and shrubs (Jarašius et al. 2010, 2014). First negative changes in the vegetation cover and intensified decomposition of the peat layer of the Aukštumala raised bog were noticed by a German naturalist and botanist C. A. Weber already in the beginning of the 20th century (Weber 1902). Weber's monograph was the first scientific publication dedicated to the main concepts of the raised bog ecology and botany, geology and paleogeography in the world.

Currently, about two-thirds (2,417 ha) of the former Aukštumala raised bog have been turned into the peat harvesting fields, and only in 1995 the remaining the least affected part (1,285 ha) was declared as a Telmological Reserve (TR). Although the reserve status has protected the western part of the Aukštumala raised bog from further peat harvesting, it did not safeguard this area from a negative influence of the draining. Areas adjacent to peat harvesting fields are drained most intensively by deep water-collecting ditches; although a network of smaller primary ditches across the territory of Aukštumala TR has also a certain negative effect on hydrology and condition of ecosystems in the raised bog. Recent penetration of trees into Aukštumala TR was noted by Edvardsson et al. (2015): in 2013, 73% of the examined Scots pine (*Pinus sylvestris* L.) trees were less than 20 years in age. Our previous dendrochronological studies in the Aukštumala raised bog showed that radial increment of *P. sylvestris* growing in degraded areas of the raised bog (zone of impact of peat harvesting and intensive drainage) has increased four times during last 40 years (Pakalnis et al. 2009).

Peatland restoration is a relatively new field of investigation that was the object of significant advances in the 1990s (Lode 2001, Price et al. 2003, Rochefort et al. 2003). Currently the conservation and restoration of peatlands in Europe stem from the fact that Europe has lost or degraded the major part of its peatlands (Rochefort and Lode 2006). Despite the fact that more than 15% of Lithuanian peatlands are protected and the largest ones have a status of strict nature reserves, most of these territories are strongly affected by drainage. As a result, the process of peat formation in more than 600 Lithuanian peatlands (about 75% of all peatlands in a country) is negative (Mierauskas et al. 2005). Therefore, urgent decisions must be taken in order to stop or prevent these negative processes aiming to preserve unique Lithuanian peatland ecosystems. Natural conditions and ecological processes can be re-established in the damaged peatlands much more rapidly with a help of well-planned restoration measures than by leaving them to return to a near-natural state through slow natural processes during spontaneous succession (Similä et al. 2014). Ecological restoration of peatlands is put in practice in many countries of the north-temperate climate zone, where it aims at reversing the trend of degradation by partial rehabilitation or complete restoration of the original structure and function of the ecosystem (Bradshaw 1990, Dobson et al. 1997, Vanha-Majamaa et al. 2007). One of the critical problems to be solved is restoration of the previous (normal) water regime in bogs, and this could be achieved through blocking of water drainage and run-off (Anonymous 2010, Haapalehto et al. 2011). Proper restoration measures may return seminatural vegetation cover with its typical species and habitats, reduce or halt carbon loss and, ideally, may allow peat accumulation to take place again (Simila et al. 2014).

Numerous success stories across north-temperate climate zone imply that restoration of the anthropogenically damaged peatlands is possible but requires considerable time and resource allocations (Joosten and Clarke 2002, Quinty and Rochefort 2003, Wieder and Vitt 2006). On the other hand, every peatland is unique and their restoration usually can not follow a common scenario. Different degree of peatland damage (peat decomposition, establishment of woody cover), different site geomorphology and hydrology, structure of drainage systems and other factors may require application of specific measures. The idea of this study was therefore to investigate possibilities of restoration of the anthropogenically affected Aukštumala raised bog. Specifically, we aimed to assess effectiveness of two different means of hydrological regime restoration installed in the raised bog of Aukštumala TR: (i) bog isolation from peat harvesting fields using polyethylene membrane and so-called "peat lock" system, and (ii) blocking of ditches of the old drainage system using peat dams.

Materials and Methods

Investigation area

The Aukštumala raised bog (total area 3,702 ha) is situated in Nemunas Delta Plain (western Lithuania; 55°242 N; 21°202 E). In this region, large-scale land reclamation works were implemented already in the 19th century to regulate water regime in fertile lands of the delta, which were readily used for agriculture (Basalykas 1958). Almost two-thirds of the former Aukštumala bog area is now used for intensive peat harvesting (Figure 1). This area is surrounded by deep water-collecting ditches to prevent rising of the water level in the industrial area. The rest of the bog territory has relatively recently (in 1995) been declared a Telmological Reserve (TR), yet large part of this area is still negatively affected by an old drainage system (created in about 1970) and by significant water runoff into water collecting ditches surrounding peat harvesting fields. The old drainage system in Aukštumala TR consists of 1–2-m-wide and up to 1-m-deep ditches with an average distance of 20–30 m from each other. The system is located in the eastern part of the TR and currently is not maintained. Many ditches are naturally overgrown by vegetation, although closer to the ditches their draining effect is still noticeable (lowered water table, increased peat mineralization, changes in plant communities). The contact zone of the Aukštumala TR and peat harvesting fields is about 6 km long (Figure 1); therefore about 30–60 ha of the TR is under continuous influence of the intensive drainage (Pakalnis et al. 2009, Jarašius et al. 2010, 2014).

Since 2004, the territory of the Aukštumala TR has been included into a NATURA 2000 network. As a result of a thorough survey performed by us in 2012 (Jarašius et al. 2013), 210 plant species and five habitats of European importance were inventoried here: (i) active raised bogs (7110*), (ii) degraded raised bogs (7120), (iii) bog woodlands (91D0*), (iv) natural dystrophic lakes (3160), and (v) depressions on peat sub-

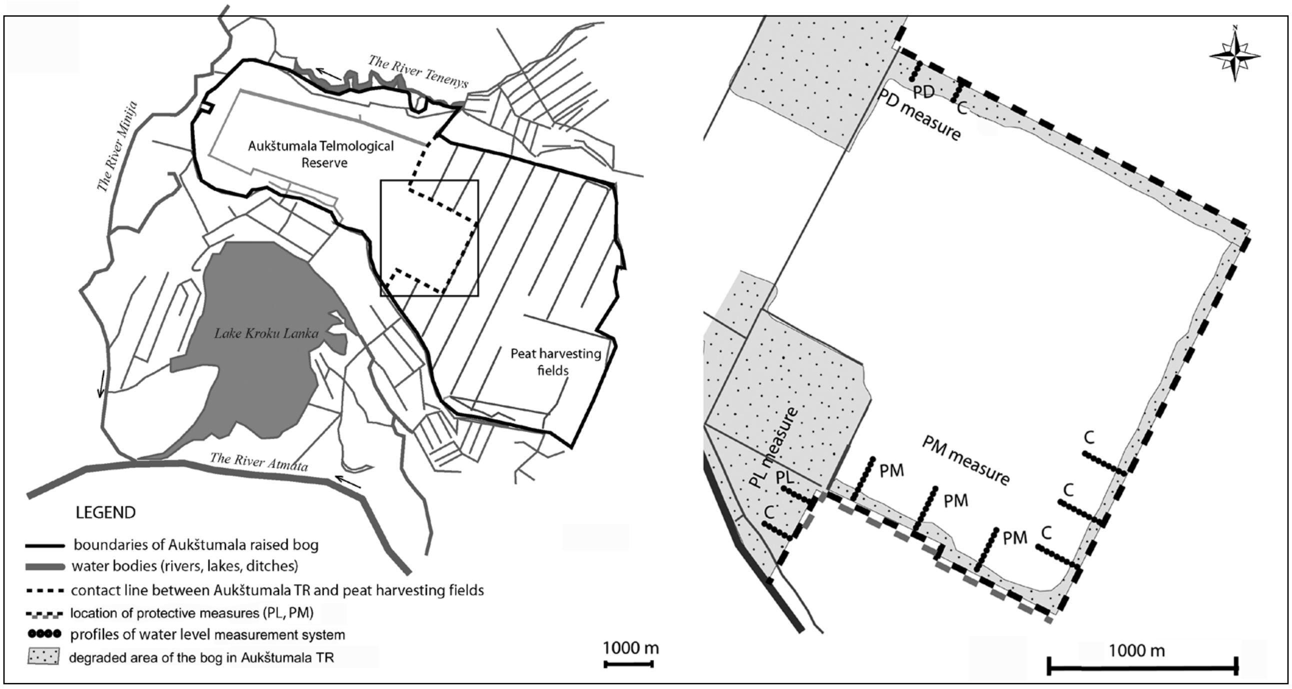

Figure 1. A map of the Aukštumala raised bog. Left, raised bog divided into Aukštumala Telmological Reserve (TR, north-western part) and peat harvesting fields (south-eastern part). Right, enlarged area of investigation in Aukštumala TR with indicated locations of the applied treatments (PM, PL and PD measures) and water level monitoring profiles. C = is control profiles (untreated area) associated with the respective measures (for more information see Materials and methods section)

strates of the *Rhynchosporion* (7150). However, a large part of the TR territory (237 ha, or 23%) does not meet the requirements for habitats of European importance because of significant habitat shifts towards peatland degradation. These belt-shaped habitats (40–500-m-wide) with dominating woody vegetation occur on the margins of the TR (Figure 1). Currently, the largest part of the territory of Aukštumala TR is represented by habitats of active raised bogs (605 ha, or 47%) and degraded raised bogs still capable of natural regeneration (161 ha, or 12%) (Jarašius et al. 2013). Hydrological changes in the damaged area (degraded raised bogs habitat) are reflected in species composition (about 50–60% of the inventoried plant species were atypical to ombrotrophic bogs) and hydrochemical parameters (increased electrical conductivity and pH values) of the top peat layer (Jarašius et al. 2014).

Average annual precipitation in the region is 770 mm. Most of the precipitation (449 mm) falls during the warm season (May-October) (Bukantis 1994). During the investigation period (2007–2014), the average annual precipitation was about 800 mm and showed a tendency to decrease (Figure 2).

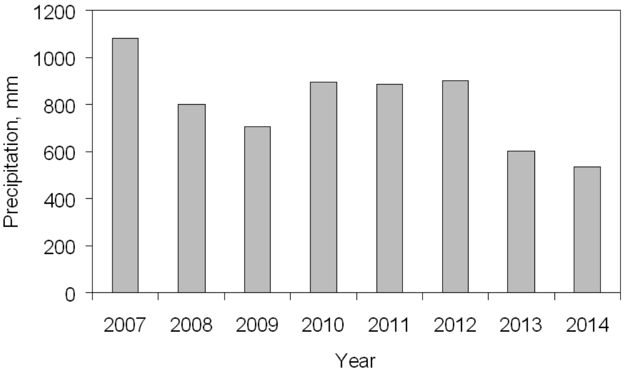

Figure 2. Average annual precipitation in the Aukštumala raised bog during the investigation period (2007–2014, data provided by Šilutė Meteorological Station)

Measures to prevent direct water runoff from the raised bog

Two types of measures were applied to isolate the raised bog of the Aukštumala TR from adjacent peat harvesting fields (Figure 1):

1) polyethylene membrane (PM). In November 2006, a 3-m-wide and 0.5-mm-thick polyethylene membrane was installed vertically in a 1-km-long, 3-m-deep and 1.5-m-wide trench excavated along the contact zone of peat harvesting fields and the TR. Immediately after installation of the membrane, the trench was filled up with the excavated raised bog peat;

2) "peat lock" (PL) system. A 0.3-km-long, 3-m-deep and 1.5-m-wide trench was excavated along the contact zone of peat harvesting fields and the TR and filled up with highly decomposed peat excavated from a bottom layer of the bog. This peat is characterized by a very low water filtration rate (Čebatoriovas 1983). The means was installed in November 2010.

Both means were installed along the edge of the TR (Figure 1). To prevent runoff of the surface water, a 50-cm-high protective embankment was formed on top of each means using excessive peat excavated from the trenches (for detailed information on installation of those meanssee Pakalnis et al. (2009)).

Blocking of old drainage system in Aukštumala TR

In order to reduce the negative effect of the old drainage system, twenty 2-m-wide bog peat dams (further referred to as PD measure) were built in November 2012 on four drainage ditches closest to the contact zone with 50 m intervals. Five dams were built per ditch. The dams were made of decomposed peat and squeezed down. This measure was set in a degraded raised bog habitat (the north-eastern part of the TR, Figure 1) characterized by noticeable peat mineralization and changed vegetation cover towards domination of *Calluna vulgaris* (L.) Hull.

Assessment of efficiency of the applied measures

To assess efficiency of the applied measures, a hydrological monitoring system has been installed (Figure 1). Ten profiles consisting of water level measurement wells were installed perpendicularly to the contact zone of the TR and peat harvesting fields. The minimum distance between the profiles was 300 m. The first well of each profile was installed at a 10 m distance from each water insulation means (either PM or PL) or a hither edge of a deep water-collecting ditch surrounding peat harvesting fields in case of PD and all controls (Figure 1). Further in text, a term "contact line" is used to refer to this "starting position" of all profiles. The distance between wells in each profile was 20 m and the number of wells per profile varied from four to nine. For installation of the wells, PVC tubes (diameter 50 mm, length 2.0 m, perforated with 5-mm holes along the full length) were inserted 1.8 m into a peat deposit. To prevent peat filling, the bottom side of each tube was covered with a dense nylon mesh. Following installation, the top of each well was capped. Measurements of water table depth (WTD) were carried out with monthly intervals during vegetation season (from April till October). Further in text, mean WTD calculated from data collected during one vegetation season is treated as "mean yearly WTD", while mean WTD calculated from data collected during vegetation seasons of the whole observation period is treated as “mean observation-period WTD”.

To monitor effectiveness of the PM measure, three parallel 170-m-long profiles, each consisting of nine water level measurement wells, were installed in March 2007 in an “influence zone” of the protective measure (this “influence zone” of each applied measure is further referred to as a “treated area”). For control, three identical profiles were installed in an untreated area (Figure 1). All PM profiles (treated area and control) were established in raised bog with a rather narrow (about 10–20-m-wide) zone of noticeable peat mineralization and changed vegetation cover towards domination of *C. vulgaris* and typical forest species. No ditches of the old drainage system were present in the investigated area.

To monitor effectiveness of the PL measure, two parallel 110-m-long profiles, each consisting of six water level measurement wells, were installed in March 2011: one in treated and one in untreated area (Figure 1). Here, two profiles have been set only because of limited length of the installed PL measure (300 m) aiming to keep a minimum distance of 150 m between a profile installed in treated area and a putative border of an untreated area. A minimum distance of 150 m was also kept between the “control” profile and this putative border. Control profiles established to assess effectiveness of the PM could not be used for PL and *vice versa* because these measures were installed in areas with a rather different level of degradation. Both PL profiles (treated area and control) were established in a heavily degraded part of the raised bog drained by an old drainage system with noticeable peat mineralization and domination of *C. vulgaris* and typical forest species (established woody cover).

Effectiveness of the PD measure was assessed by installation of two parallel 70-m-long profiles (each consisting of four water level measurement wells). The profiles were installed in March 2011, two vegetation seasons before the setting of the PD measure: one in the area assigned for damming and one in the control area. Two profiles were installed only because of a limited width of a presumed putative influence zone (roughly 300-m-wide) of the PD measure, aiming to keep a minimum distance of 150 m between a profile installed in the treated area and a putative border of the untreated area (Figure 1). A minimum distance of 150 m was also set between the “control” profile and this putative border.

In addition, a dendrochronological method (Stravinskienė 1994, 2002) was applied to assess the effectiveness of the PM measure to restore hydrological regime unfavourable for tree growth. In March 2014, a total of 50 wood cores were extracted using Pressler’s increment borer from 50 pine (*P. sylvestris*) trees growing in a 20-m-wide stripe stretching along the contact line: 25 trees have been sampled in the PM-treated area and 25 trees in untreated area adjacent to the PM-treated area. Growing conditions were more or less equal in both areas before the installation of the PM measure. Growth ring width in each extracted core was measured in the laboratory with a preciseness of 0.01 mm. Dendrochronological method was not applied to assess the efficiency of PL and PD treatments because of too short period of these measures being in force.

Statistical analyses

Significance of differences in mean yearly WTD and mean observation-period WTD and mean annual radial increment of pines between the control and treated sites were assessed using a *t*-test. Spearman’s correlation analysis was used to outline the relationship between mean yearly WTD and annual precipitation, between mean observation-period WTD and a distance of water level measurement well from the contact line, and between radial increment of pines and mean yearly WTD and annual precipitation. All statistical tests were performed using *STATISTICA 6* software.

Results

Effectiveness of polyethylene membrane

Hydrological monitoring data collected during vegetation seasons of 2007 to 2014 showed a strong and significant positive correlation between mean observation-period WTD and a distance from the contact line in both PM-treated ($r = 0.85$, $p < 0.05$) and control ($r = 0.95$, $p < 0.05$) sites. At a distance of 10–50 m from the contact line, in treated area mean yearly WTD was in all cases significantly ($p < 0.05$) lower compared to control (Table 1, Figure 3). The highest difference in mean WTD was observed at a 10 m distance: during first two years after the installation of the PM measure (in 2007 and 2008) this difference reached 64.7 ± 2.1 and 56.4 ± 6.1 cm, respectively. During subsequent years (2009–2014), the differences at this distance became smaller (yet, remained significant at $p < 0.01$), and, depending on a year, ranged from 28.4 ± 6.0 to 42.2 ± 8.4 cm (Table 1). On the other hand, mean observation-period water table in profiles with the PM measure at 10–50 m distance from the contact line rose up to -33.6 ± 1.2 cm depth (mean ±SE below mean topography), i.e. to a level, which is still regarded too low for peat accumulation and thriving of typical raised bog plant communities (Eggelsmann 1984, Ruseckas and Grigaliūnas 2008, Haapalehto et al. 2011, Jarašius et al. 2014).

The mean yearly water table rose above -30 cm level at a 50 m distance from the contact line in 2007 and during 2011–2013; however, in 2008 and in 2009 it fell below -40 cm level (Table 1).

Table 1. Significance of differences between water table depth (WTD) measured in profiles established in area insulated with a protective measure (polyethylene membrane) and without it (control) in a Telmological Reserve (TR) of the Aukštumala raised bog. Presented are mean WTD values ± standard error. The measurements were made during vegetation seasons (April–October) of 2007 to 2014. Level of significance: *0.01 < $p \le 0.05$, **0.001 < $p \le 0.01$, ***$p \le 0.001$, n.s. – non-significant difference ($p > 0.05$)

Distance from the contact line[1], m	Applied measure	Mean WTD ± standard error								
		2007	2008	2009	2010	2011	2012	2013	2014	Mean, 2007–2014
10	membrane	-34.4±3.2	-41.8±2.9	-52.1±3.1	-53.2±2.5	-41.1±2.7	-36.4±5.5	-41.9±3.0	-49.6±4.6	-43.8±1.4
	control	-99.1±5.5	-98.4±8.3	-89.4±8.3	-95.4±6.5	-76.4±7.5	-78.2±6.3	-80.8±1.5	-78.0±7.4	-86.9±3.7
	difference	64.7±2.1***	56.4±6.1***	37.3±6.1**	42.2±8.4***	35.3±8.0***	41.8±9.7***	38.9.±4.2***	28.4±6.0**	43.1±6.5***
30	membrane	-36.0±2.3	-52.1±2.9	-57.0±2.6	-52.1±1.9	-40.2±2.2	-36.8±4.1	-38.4±2.2	-49.1±4.2	-45.2±1.3
	control	-77.0±3.1	-90.4±3.9	-96.0±3.3	-93.1±3.7	-79.3±4.7	-81.0±4.8	-81.0±3.5	-84.0±3.1	-85.2±2.1
	difference	41.0±2.7***	38.3±2.0***	39.0±2.4***	41.0±2.6***	39.1±2.7***	44.2±3.1***	42.6±2.3***	34.9±4.5***	40.0±2.1***
50	membrane	-30.3±2.1	-41.3±2.9	-43.5±2.4	-38.0±2.1	-28.1±1.8	-23.3±5.6	-27.8±2.7	-36.4±3.1	-33.6±1.2
	control	-45.2±4.9	-58.3±3.8	-59.4±3.6	-57.0±3.6	-46.4±3.9	-50.0±4.6	-50.4±3.5	-47.4±5.4	-51.8±1.9
	difference	14.9±5.7*	17.0±1.6*	15.9±1.8*	19.0±1.9***	18.3±1.5***	26.7±4.2**	22.6±1.3**	11.0±3.5*	18.2±2.4**
70	membrane	-25.9±2.7	-37.2±2.8	-36.7±2.8	-35.2±2.6	-27.9±1.7	-26.3±1.7	-26.2±1.7	-35.0±3.9	-31.3±1.2
	control	-32.1±3.8	-42.2±5.6	-48.1±2.1	-43.4±3.3	-31.3±3.8	-31.0±2.4	-32.2±1.7	-37.2±3.4	-37.2±2.0
	difference	6.2±1.5 n.s.	5.0±3.2 n.s.	11.4±2.1 n.s.	8.2±1.9 n.s.	3.4±3.3 n.s.	4.7±2.2 n.s.	6.0±1.9 n.s.	2.2±2.4 n.s.	5.9±2.3 n.s.
90	membrane	-30.2±2.8	-39.5±2.1	-43.1±1.9	-42.1±1.7	-29.0±2.1	-32.0±2.5	-32.2±3.3	-36.8±3.4	-35.6±1.1
	control	-31.2±1.2	-36.1±3.6	-37.1±1.3	-34.4±3.0	-30.0±2.7	-30.5±2.9	-32.0±3.5	-36.0±2.4	-33.4±2.0
	difference	1.0±1.2 n.s.	-3.4±1.7 n.s.	-6.0±2.0 n.s.	-7.7±2.8 n.s.	1.0±1.7 n.s.	-1.5±2.4 n.s.	-0.2±0.9 n.s.	-0.8±1.7 n.s.	-2.2±1.8 n.s.
110	membrane	-26.1±3.2	-38.3±2.4	-40.0±2.1	-35.5±2.1	-29.1±1.6	-30.5±2.5	-29.8±1.4	-33.6±3.6	-32.7±0.9
	control	-30.4±2.8	-32.3±3.4	-32.0±3.4	-33.4±2.5	-29.1±2.7	-29.0±2.7	-27.4±2.9	-28.4±3.1	-30.3±1.4
	difference	4.3±1.9 n.s.	-6.0±0.9 n.s.	-8.0±1.6 n.s.	-2.1±1.6 n.s.	0.0±1.2 n.s.	-1.5±2.4 n.s.	-2.4±2.1 n.s.	-5.2±0.8 n.s.	-2.4±1.5 n.s.
130	membrane	-23.8±2.0	-28.3±2.3	-30.1±2.7	-25.1±2.4	-28.7±2.0	-26.6±2.2	-24.8±2.5	-30.1±2.7	-27.1±1.1
	control	-30.4±3.0	-34.0±2.8	-34.4±2.9	-32.2±1.9	-36.1±4.1	-34.0±3.6	-32.4±1.9	-33.1±4.1	-32.9±1.7
	difference	6.4±2.1 n.s.	5.7±1.2 n.s.	4.3±2.3 n.s.	7.1±1.8 n.s.	7.4±2.5 n.s.	7.4±3.6 n.s.	7.6±1.4 n.s.	3.0±2.8 n.s.	5.8±2.3 n.s.
150	membrane	-20.1±1.3	-25.1±1.4	-26.2±2.3	-22.6±1.5	-21.3±1.4	-22.4±2.3	-21.5±1.7	-29.7±3.0	-23.7±1.0
	control	-19.4±1.8	-21.1±2.0	-22.1±2.1	-20.4±1.8	-26.4±1.6	-20.1±2.0	-17.3±1.8	-21.3±2.1	-21.1±1.1
	difference	-0.7±1.9 n.s.	-4.0±0.8 n.s.	-4.1±1.4 n.s.	-2.2±1.7 n.s.	5.1±2.0 n.s.	-2.3±0.8 n.s.	-4.2±1.4 n.s.	-8.4±1.9 n.s.	-2.6±1.4 n.s.
170	membrane	-24.3±2.5	-31.0±2.9	-33.2±3.0	-28.1±2.7	-26.4±2.9	-23.7±2.7	-24.2±1.6	-32.3±2.9	-27.9±1.4
	control	-28.4±2.2	-31.2±3.0	-32.3±2.9	-30.1±3.0	-36.3±3.1	-27.4±2.1	-26.0±1.2	-31.3±3.0	-30.3±1.4
	difference	4.1±1.8 n.s.	0.2±1.1 n.s.	-0.9±1.3 n.s.	2.0±1.6 n.s.	9.9±0.9 n.s.	3.7±1.8 n.s.	1.8±1.1 n.s.	-1.0±2.2 n.s.	2.4±1.2 n.s.

[1] for definition see subsection "Assessment of effectiveness of the applied measures" in Materials and Methods section

At larger distances (≥ 70 m) from the contact line, mean yearly WTD values in the PM-treated area did not differ significantly ($p > 0.05$) from control (Table 1). Subsequently, the differences in mean observation-period WTD between treated and control areas were non-significant at $p \le 0.05$ and ranged between -2.2 ± 1.8 cm and 5.9 ± 2.3 cm (Table 1, Figure 3). At distances ≥70 m, mean observation-period WTD in the PM-treated area ranged between -23.7 ± 1.0 cm and -35.6 ± 1.1 cm with a minimum value of mean yearly WTD reaching -20.1 ± 1.3 cm at a 150 m distance (recorded in 2007) and a maximum value of -43.1 ± 1.9 cm at a 90 m distance (recorded in 2009) (Table 1).

The effect of the applied PM measure was also noticeable on amplitude of seasonal water level fluctuation (i.e., according to WTD values assessed every month from April to October during the whole observation period), although this effect could be observed only at 10 m and 50 m distance from the contact line (data not shown). At the 10 m and 50 m distances, mean respective absolute values of seasonal

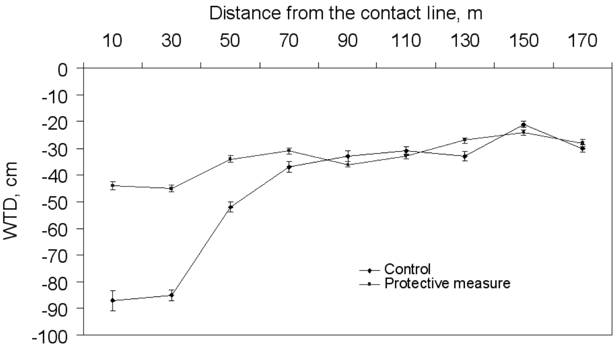

Figure 3. Mean water table depth (WTD) ± standard error measured in Telmological Reserve (TR) of the Aukštumala raised bog. Values obtained in areas insulated with a polyethylene membrane (protective measure) and without it (control) during vegetation seasons (April-October) of 2007 to 2014 are presented. For definition of the "contact line" see subsection "Assessment of effectiveness of the applied measures" in Materials and Methods section

water level fluctuation amplitude during the whole observation period (2007–2014) in the control area reached 54.1 ± 4.5 cm and 29.8 ± 2.4 cm, and were significantly (p = 0.011–0.033) higher than in the PM-treated area (38.0 ± 3.2 cm and 22.2 ± 2.4 cm). At 30 m distance and distances ≥70 m from the contact line, the difference in mean absolute amplitudes between control and treated areas was non-significant ($p > 0.05$). At short distances (10–30 m), seasonal water level fluctuation amplitude in the PM-treated area often exceeded 30 cm, whereas at larger distances (≥50 m) the amplitude was usually below 30 cm (ranged between 5 and 39 cm, data not shown). Figure 4 shows amplitudes of monthly water table fluctuation (min-max values) in 10–50 m distance zone, where significant differences in mean WTD between the PM-treated and control areas were found (Table 1). The Figure clearly shows that the fluctuation during whole observation period was more prominent in control profiles (overall monthly amplitude range 9–73 cm) compared to profiles in the PM-treated area (12–50 cm).

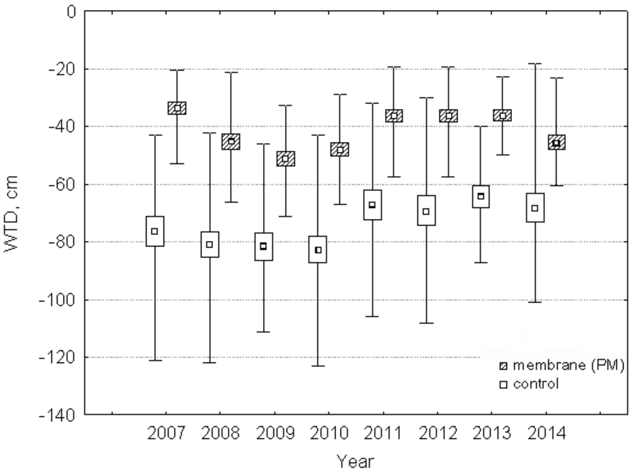

Figure 4. Amplitudes of monthly water table fluctuation (min-max water table depth (WTD) values) in area of Aukštumala raised bog insulated with a polyethylene membrane (PM, hatched boxes) and in an untreated area (control, empty boxes) during vegetation seasons (April-October) of 2007 to 2014. Values obtained from water level measurement wells at distances of 10, 30 and 50 m from a contact line (combined) are presented. Boxes show mean yearly WTD ± standard error

Although in many cases (yet, mostly in the PM-treated area) mean WTD showed an increase in 2014 (the driest year of the observation period) (Table 1), no significant correlation was found between mean yearly WTD and annual precipitation at either distance from the contact line in both treated (r = 0.30–0.71, $p < 0.05$) and control sites (r = -0.34–0.60, $p < 0.05$).

Dendrochronological analysis showed that mean annual radial increment of pines growing in the PM-treated area started to decrease in 2008, i.e., one year after the installation of this measure, continued to decrease till 2010 and then levelled out to about 2 mm per annum. Radial increment of pines sampled in control area showed the opposite trend: increased from 2007 till 2010 and then started to slightly decrease (Figure 5). Nevertheless, during the period from 2009 to 2013, the annual increment of control pines remained significantly ($p < 0.05$) larger compared to that in the treated area. In treated area (at 10 m distance from the contact line), the radial increment of pines did not correlate to mean yearly WTD ($r = 0.23$; $p = 0.613$), whereas in control area this correlation was very strong and significant ($r = -0.88$; $p < 0.01$).

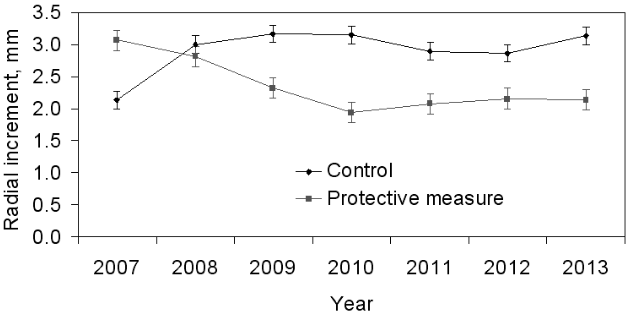

Figure 5. Annual radial increment (± standard error) of *Pinus sylvestris* trees assessed in a Telmological Reserve (TR) of the Aukštumala raised bog following installation of a protective measure (polyethylene membrane, installed in November 2006)

Effectiveness of "peat lock" measure

Similarly to PM, the effect of PL measure was noticeable at a relatively short distance (up to about 30 m) from the contact line (Table 2, Figure 6). At 10–30 m distance, the mean observation-period WTD was significantly ($p < 0.001$) lower in the PL-treated area compared to the control area, although from year to year this difference was not always significant at $p \leq 0.05$ (Table 2, Figure 6). Interestingly, the highest difference in mean observation-period WTD was observed not at the shortest (10 m) distance from the contact line (22.4 ± 4.3 cm), but at the 30 m distance (28.0 ± 3.0 cm). Despite this positive effect of the PL measure on bog water retention, mean yearly WTD at the 10-30 m distance was high (ranged between -38.2 ± 6.5 cm and -66.6 ± 6.3 cm). At larger distances (≥ 50 m) from the contact line, mean yearly WTD values in the PL-treated area were also comparably high (mean water table never rose higher than -30.7 ± 3.1 cm) and did not differ significantly ($p > 0.05$) from control (Table 2).

Table 2. Significance of differences between water table depth (WTD) measured in area insulated with a protective "peat lock" measure and without it (control) in a Telmological Reserve (TR) of the Aukštumala raised bog. Mean WTD values ± standard error are presented. The measurements were made during vegetation seasons (April-October) of 2011 to 2014. Level of significance: 0.01 < $p \le 0.05$, **0.001 < $p \le 0.01$, ***$p \le 0.001$, n.s. = means non-significant difference ($p > 0.05$)

Distance from the contact line[1], m	Applied measure	Mean WTD ± standard error				
		2011	2012	2013	2014	2011–2014
10	"peat lock"	-66.6±6.3	-61.3±6.1	-65.7±3.2	-65.9±6.2	-64.9±2.7
	control	-81.7±8.2	-78.1±9.6	-93.0±12.2	-96.3±13.2	-87.3±5.3
	difference	15.1±4.9 n.s.	16.8±9.3 n.s.	27.3±11.5 n.s	30.4±8.6 n.s.	22.4±4.3***
30	"peat lock"	-51.9±6.2	-38.9±2.0	-38.2±6.5	-56.1±7.8	-46.2±3.2
	control	-69.6±6.0	-69.8±5.4	-75.5±5.3	-82.0±10.0	-74.2±3.5
	difference	17.7±7.6 n.s.	30.9±5.7***	37.3±3.9***	25.9±4.6 n.s.	28.0±3.0***
50	"peat lock"	-52.9±2.3	-52.6±4.2	-49.7±4.5	-63.0±5.3	-54.6±2.2
	control	-50.0±3.5	-55.0±4.8	-51.5±3.9	-69.9±14.0	-56.6±2.3
	difference	-2.9±4.4 n.s.	2.4±2.1 n.s.	1.8±1.0 n.s.	6.9±1.9 n.s.	2.0±1.4 n.s.
70	"peat lock"	-34.0±3.8	-30.7±3.1	-31.0±3.3	-48.3±7.2	-36.0±2.6
	control	-30.0±1.9	-30.3±2.1	-29.8±2.0	-49.4±5.6	-34.9±2.3
	difference	-4.0±3.8 n.s.	-0.4±3.4 n.s.	-1.2±2.0 n.s.	1.1±1.8 n.s.	-1.1±1.4 n.s
90	"peat lock"	-41.6±3.0	-40.4±4.0	-41.5±6.4	-57.1±9.0	-45.2±3.1
	control	-41.7±4.7	-46.0±1.6	-39.8±5.3	-58.3±7.7	-47.5±2.8
	difference	0.1±3.3 n.s.	5.6±3.6 n.s.	1.7±2.0 n.s.	1.2±2.9 n.s.	2.3±1.5 n.s.
110	"peat lock"	-45.3±5.1	-40.7±3.	-39.3±4.	-51.0±7.6	-44.1±2.7
	control	-54.0±7.9	-50.1±8.3	-47.2±9.2	-58.4±14.3	-52.4±5.1
	difference	8.7±8.4 n.s.	9.4±6.1 n.s	7.9±5.6 n.s.	7.4±7.1 n.s.	8.3±3.4 n.s.

[1] for definition see subsection "Assessment of effectiveness of the applied measures" in Materials and Methods section

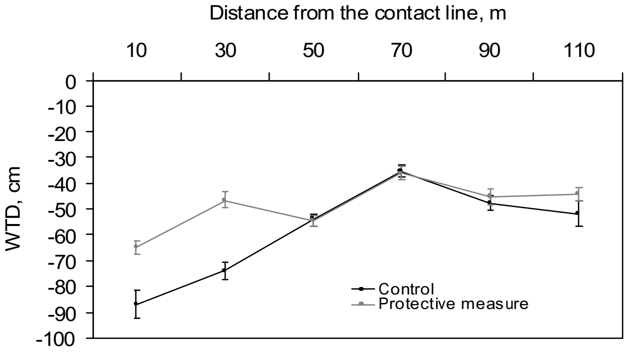

Figure 6. Mean water table depth (WTD) ± standard error measured in Telmological Reserve (TR) of Aukštumala raised bog. Values obtained in areas insulated with a protective "peat lock" measure and without it (control) during vegetation seasons (April–October) of 2011 to 2014 are presented. For definition of the "contact line" see subsection "Assessment of effectiveness of the applied measures" in Materials and Methods section

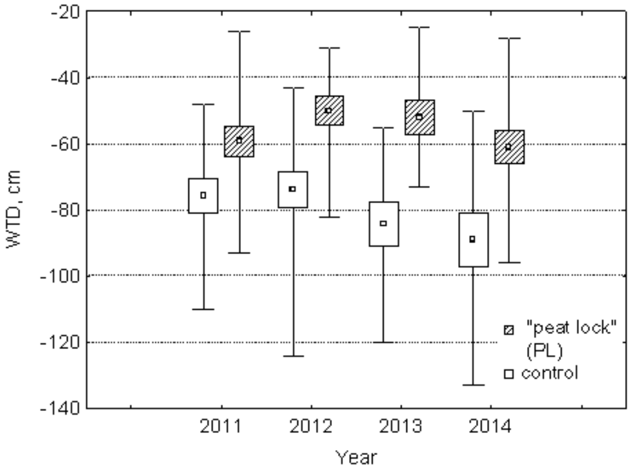

Figure 7. Amplitudes of monthly water table fluctuation (min-max water table depth (WTD) values) in area of the Aukštumala raised bog insulated with a "peat lock" measure (PL, hatched boxes) and in an untreated area (control, empty boxes) during vegetation seasons (April–October) of 2011 to 2014. Values obtained from water level measurement wells at distances of 10 and 30 m from a contact line (combined) are presented. Boxes show mean yearly WTD ± standard error

Similarly to that of the PM measure, the effect of the PL measure was also noticeable on amplitude of seasonal water level fluctuation, but only at 10 m distance from the contact line the difference between mean absolute observation-period amplitude values in PL-treated (43.0 ± 8.4) and control (68.8 ± 5.7) areas was statistically significant ($p = 0.041$). Figure 7 shows amplitudes of monthly water table fluctuation (min-max values) in 10–30 m distance zone, where significant differences between mean WTD in PL-treated and control areas were found (Table 2). The Figure shows that during whole observation period the fluctuation in control profiles (overall monthly amplitude range 36–83 cm) was only slightly larger compared to profiles in the PL-treated area (overall monthly amplitude range 16–61 cm). In the treated area (at either distance from the contact line), seasonal water level fluctuation amplitude in most cases exceeded 30 cm (data not shown).

Moderate to strong, yet non-significant positive correlation ($r = 0.32–0.95$, $p < 0.05$) was found between mean yearly WTD and annual precipitation at either distance from the contact line in the PL profile, whereas in control profile this correlation was stronger ($r = 0.40–1.00$), but significant (at $p \le 0.05$) it was only at 10 m distance from the contact line.

Effectiveness of ditch blocking using peat dams

According to visual observations, water table started to rise in the blocked ditches already in November

2012, right after setting up the dams. However, WTD measurements made before and after the dams were built showed that decrease of mean yearly WTD following ditch blocking was noticeable just at a 10 m distance from the contact line (in a well installed between the contact line and the closest ditch of the old drainage system) (Table 3). Figure 8 shows that monthly WTD at the 10 m distance became low after the ditch blocking, and only in driest months it dropped below -30 cm. The WTD values were extremely low in September 2013 and in April 2014, when water table has reached the peat surface (Figure 8). At this distance, the difference in mean WTD assessed before (-33.1±3.8 cm) and after (-19.2±2.8 cm) the ditch blocking was statistically significant ($p < 0.01$) (Figure 8). No significant differences ($p > 0.05$) were found between mean monthly WTD values assessed during these two periods at larger distances from the contact line (data not shown).

After damming, the differences between treated and untreated areas in mean yearly WTD assessed at a 10 m distance from the contact line became statistically significant at $p \leq 0.01$, whereas at larger distances those differences were in general (with a couple of exceptions) non-significant ($p > 0.05$) (Table 3). At larger distances (≥30 m) from the contact line, mean yearly WTD values in the PD-treated area were rather large (this was likely due to a somehow higher site elevation at 30–50 m distance from the contact line), except a 70 m distance, where both pre-damming and post-damming WTD values were less than 25 cm (Table 3). Amplitudes of seasonal water level fluctuation and correlations between mean yearly WTD and annual precipitation are not presented in the Results due to a short post-damming observation period (no reliable statistical analyses could be performed).

Discussion

Anthropogenic disturbance (peat harvesting works and drainage) accelerates water outflow and mineralization of top peat layer in the Aukštumala TR thus promoting peatland degradation and penetration of woody vegetation to the raised bog (Pakalnis et al. 2009, Jarašius et al. 2013, 2014, Edvardsson et al. 2015). In peatland restoration projects the most commonly used measures for raising and stabilising of water levels are ditch blocking by dams, building artificial bunds and/or sluices. In addition to the ditch blocking, some

Table 3. Significance of differences between water table depth (WTD) measured in area with a protective measure (peat dams) and without it (control) in a Telmological Reserve (TR) of the Aukštumala raised bog. Mean WTD values ± standard error are presented. The measurements were made during vegetation seasons of 2011 to 2014. Level of significance: $0.01 < p \leq 0.05$, $^{**}0.001 < p \leq 0.01$, $^{***}p \leq 0.001$, n.s. – means non-significant difference ($p > 0.05$)

Distance from the contact line[1], m	Applied measure	Mean WTD ± standard error					
		2011	2012	Mean 2011–2012	2013	2014	Mean 2013–2014
10	peat dams	-40.0±4.1	-26.1±4.2	-33.1±3.8	-17.1±3.0	-21.3±4.8	-19.2±2.8
	control	-51.0±7.1	-35.4±2.3	-43.2±4.7	-36.4±1.8	-47.4±4.9	-42.2±2.9
	difference	11.0±3.6 n.s.	9.3±2.1 n.s.	10.1±2.0 n.s.	19.3±2.5***	26.1±0.9**	23.0±1.5***
30	peat dams	-32.1±3.0	-34.2±2.7	-33.2±1.9	-33.1±1.9	-36.4±4.7	-34.8±2.6
	control	-41.3±4.5	-43.4±3.0	-42.3±2.4	-42.4±1.9	-50.4±4.8	-46.2±2.7
	difference	9.2±2.3 n.s.	9.2±1.5 n.s.	9.1±2.1 n.s.	9.3±1.1**	14.0±0.9*	11.4±1.0**
50	peat dams	-32.1±3.0	-35.2±2.9	-33.7±2.1	-35.2±2.6	-41.3±4.4	-38.3±2.6
	control	-38.4±4.1	-38.1±3.3	-38.0±2.4	-34.3±2.5	-36.2±5.3	-35.4±2.8
	difference	6.3±1.5 n.s.	2.9±1.5 n.s.	4.3±1.0 n.s.	-0.9±1.5 n.s.	-5.1±1.3 n.s.	-2.9±1.0 n.s.
70	peat dams	-21.2±1.3	-23.2±2.0	-22.2±1.5	-20.9±2.2	-25.3±3.0	-23.3±1.9
	control	-25.3±1.7	-28.2±2.7	-27.0±2.0	-29.3±2.2	-32.9±4.5	-31.4±2.5
	difference	4.1±1.6 n.s.	5.0±1.3 n.s	4.8±1.4 n.s.	8.4±0.9*	7.6±2.1 n.s.	8.1±1.1**

[1] for definition see subsection "Assessment of effectiveness of the applied measures" in Materials and Methods section

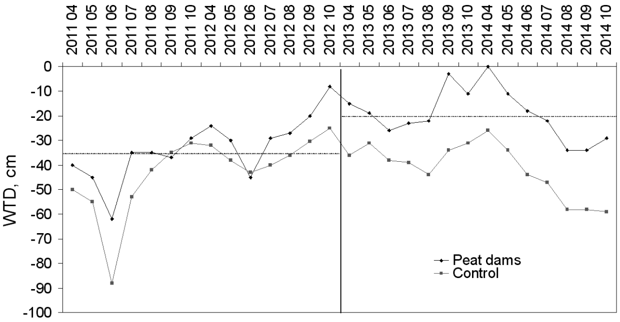

Figure 8. Monthly water table depth (WTD) fluctuations in area, where old drainage system was blocked with peat dams and in an untreated area (control) of Aukštumala Telmological Reserve (TR). WTD values obtained at a 10 m distance from a contact line which is a hither edge of deep water collecting ditch separating the TR from peat harvesting fields are presented. Bold vertical line indicates the moment of damming (November 2012), while dotted horizontal lines show within-vegetation-season WTD means for pre-damming (left) and post-damming (right) periods of observation. The means are significantly different from each other ($p < 0.01$)

sites (for example where peat harvesting field is adjacent to an existing peatland) are isolated using compacted peat berms (Anonymous 2010). However, almost every peatland is unique in its properties and each needs to be dealt individually. Even within a single peatland variation will occur, which may demand different approaches (Anonymous 2010).

In Aukštumala case, comparably low water table level (mostly below -30 cm) found at distances up to about 100 m from the peat harvesting area indicates that negative impact of the drainage is affecting large territories, and if no effective measures to restore hydrological regime are undertaken, degradation of the raised bog will likely continue. All three protective measures applied in the Aukštumala raised bog (PM, PL and PD) proved to be to a certain extent effective in isolating the bog from peat harvesting fields and in controlling hydrological regime. However, this effect was noticeable just at relatively short distances from the installed measures and favourable conditions for the restoration of self-regulating bog could not always be ensured.

As regards PM measure, in most cases the water table in a zone of clear influence of drainage (up to about 100 m from the peat harvesting area) has not been raised to a level higher than -30 cm. The water table lower than -30 cm is regarded too low for peat accumulation and preserving/restoration of typical *Sphagnum*-dominated raised bog communities (Eggelsmann 1984, Ruseckas and Grigaliūnas 2008, Haapalehto et al. 2011, Jarašius et al. 2014). At short distances from the contact line (10–30 m), seasonal water level fluctuation amplitude in the PM-treated area often exceeded 30 cm keeping conditions for peat accumulation unfavourable (according to Balyasova (1974) and Eggelsmann (1984), in the undisturbed bogs of Europe the amplitude should normally be within 20–30 cm). Nevertheless, dendrochronological analysis showed a clear negative effect of the PM measure on radial increment of pines growing in a contact zone of the TR and peat harvesting fields indicating that raised water table is already acting as tree growth limiting factor (Stravinskienė 2002, Smilijanic et al. 2014). On the other hand, annual radial increment of pines after the installation of this measure (about 2.0 mm, Figure 5) was still significantly higher than reported from pines growing in pristine raised bogs of the north-temperate climate zone (0.41–0.87 mm annual increment was reported by Cedro and Lamentowicz (2008), Pakalnis et al. (2009) and Smilijanic et al. (2014)). This suggests that water table has not been raised high enough by the applied measure to stop bog degradation processes.

PL means was installed in the degraded part of the bog, where water table was initially very low. Presence of the draining ditches in the area likely continues to facilitate a significant seasonal water loss and high rates of water level fluctuation. This low water table in combination with a presence of tree vegetation (according to Price et al. (2003), trees may increase the evapotranspirative water losses by as much as 25%) and limited water inflow from outside could be the factors that have determined rather poor effect of the “peat lock” measure. On the other hand, mean observation-period WTD in the treated area, differently from control, rarely exceeded -50 cm (Table 2), and this at least may prevent evaporation of osmotic water from the top peat layer thus slowing-down its mineralization processes (Povilaitis et al. 2011). Nevertheless, it can be concluded that PL treatment alone was not effective at controlling water regime to the acceptable level.

Ditch blocking using peat dams proved to be effective only at a short distance (10 m) from the contact line and this could be explained by a relief-mediated high water runoff through the ditch closest to the contact line prior to its damming. Blocking of this ditch has helped to significantly raise water table in a zone of its influence, and even during an extremely dry season of 2014 water table decreased only few cm below the critical -30 cm level (Figure 8). At larger distances from the contact line no significant increase in water table level was observed following the ditch blocking (this could be due to a very low precipitation in 2013 and 2014), however at 30 and 70 m distances the mean post-damming observation-period WTD was significantly lower compared to the control site (Table 3). Two years of observation of the effect of this measure is definitely too short time to draw clear conclusions, yet the potential of the ditch blocking could not be neglected. Positive effect of the ditch blocking in peatland restoration has widely been acknowledged also by other authors (e.g., Worrall et al. 2007, Haapalehto et al. 2011, Holden et al. 2011, Wilson et al. 2011, Priede 2013).

A study performed by Ruseckas and Grigaliūnas (2008) in Kamanos raised bog (Northern Lithuania) showed that correlation between mean yearly WTD and annual precipitation in drained sites was stronger compared to non-drained (pristine) ones. In Aukštumala case, however, significant (and very strong) correlation between these two variables was found only in a control profile of the PL means just at the shortest (10 m) distance from the contact line. No significant correlation was found in PL-treated area and in both treated and control sites of the PM means~~ure~~. Likely some self-regulation of the hydrological regime is still present even in the degraded parts of the Aukštumala raised bog. The WTD was largely dependent on precipitation only in the most badly affected contact zone of the drained bog and peat harvesting fields characterized by the deepest water table and the highest amplitude of seasonal water level fluctuation.

Monitoring of vegetation responses to rewetting in treated areas has been started in 2011, although no noticeable successions have occurred yet except for PD-treated area. However, due to the very short observation period, analysis of results of the vegetation monitoring is not presented in this paper. Briefly, typical ombrotrophic species (*Sphagnum* spp. in particular) responded positively to the raised water table in the PD-treated area: a clear shift from domination of *C. vulgaris* and *B. pendula* towards domination of *Sphagnum* spp. was observed near the dammed ditches (at distances up to 4 m) already in two years after the ditch blocking. Results from Finnish (Haapalehto et al. 2011) and Latvian (Priede 2013) studies suggest that in raised bog areas rewetted by ditch blocking, the total cover of *Sphagnum* mosses might increase up to 50% in a 10-year period. It is obvious that a longer time series of data is necessary to present vegetation responses to the increased water table, thus monitoring will continue until it can be shown.

The results of the present study clearly indicate that aiming to more efficiently regulate hydrological regime in the drainage-affected parts of the Aukštumala raised bog, blocking or filling of the old drainage system should always be applied in combination with water insulation measures along the contact zone of the bog and peat harvesting fields. In most degraded areas, complete or partial removal of woody vegetation may be recommended to reduce transpiration rates (Vasander et al. 2003). Longer observation time is needed to fully assess the effect of the installed restoration measures on hydrology and ecosystem functioning in the raised bog of Aukštumala TR.

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References

Aaby, B. 1976. Cyclic variations in climate over past 5,500 yr reflected in raised bogs. *Nature* 263: 281-284.

Anonymous 2010. Guidelines for peatland restoration. Report by Peatlands and Uplands Biodiversity Delivery Group http://www.qpani.org/documents/PeatlandRestoration guidelinesfinal.pdf. Accessed May 29, 2015.

Balyasova, Y. 1974. Variations in the level regime of high-moor bogs in the European USSR. *Soviet Hydrology: Selected Papers* 13(5): 281-285.

Basalykas, A. (Editor) 1958. Lietuvos TSR fizinė geografija [Physical geography of Lithuanian SSR], vol. 1. Mintis, Vilnius, 504 pp. (in Lithuanian).

Bradshaw, A. D. 1990. The reclamation of derelict land and the ecology of ecosystems. In: W. R. Jordan III, M. E. Gilpin and J. D. Aber (Editors), Restoration ecology: a synthetic approach to ecological research. Cambridge University Press, Cambridge, p. 53-74.

Bukantis, A. 1994. Lietuvos klimatas. [Lithuanian climate]. Vilnius University Press, Vilnius, 188 pp. (in Lithuanian).

Cedro, A. and Lamentowicz, M. 2008. The last hundred years Dendroecology of Scots pine (*Pinus sylvestris* L.) on a Baltic bog in Northern Poland: Human Impact and Hydrological changes. *Baltic Forestry* 14(1): 26-33.

Čebatoriovas, A. 1983. Bendroji hidrologija. [General hydrology]. Mokslas, Vilnius, 461 pp. (in Lithuanian).

Dobson, A. P., Bradshaw, A. D. and Baker, A. J. 1997. Hopes for the future: restoration ecology and conservation biology. *Science* 277: 515-522.

Eckstein, J., Leuschner, H. H., Bauerochse, A. and Sass-Klassen, U. 2009. Subfossil bog-pine horizons document climate and ecosystem change during the Mid-Holocene. *Dendrochronologia* 27: 129-146.

Edvardsson, J., Šimanauskienė, R., Taminskas, J., Baužienė, I. and Stoffel, M. 2015. Increased tree establishment in Lithuanian peat bogs – insights from field and remotely sensed approaches. *Science of The Total Environment* 505: 113-120.

Eggelsmann, R. F. 1984. Annual ground water course in peatlands with different using (vegetation). Proc. 7th Int. Peat Congress, 1984: 134-147.

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecological Applications* 1: 182-195.

Gorham, E. and Rochefort, L. 2003. Peatland restoration: A brief assessment with special reference to *Sphagnum* bogs. *Wetlands Ecology and Management* 11(1-2): 109-119.

Haapalehto, T. O., Vasander, H., Jauhiainen, S., Tahvanainen, T. and Kotiaho, J. S. 2011. The effect of peatland restoration on water-table depth, elemental concentrations, and vegetation: 10 years of changes. *Restoration Ecology* 19: 587-598.

Holden, J., Wallage, Z. E., Lane, S. N. and McDonald, A. T. 2011. Water table dynamics in undisturbed, drained and restored blanket peat. *Journal of Hydrology* 402: 103-114.

Ingram, H. A. P. 1983. Hydrology. In: A.J.P. Gore (Editor), Mires: swamp, bog, fen and moor. Elsevier, New-York, pp. 67-158.

Jarašius, L., Pakalnis, R., Sendžikaitė, J. and Avižienė, D. 2010. Durpių kasybos įtaka aukštapelkėms ir ekologinio atkūrimo perspektyvos Lietuvoje. [Peat mining impact on raised bogs and perspectives of ecological restoration in Lithuania] Aplinkos apsaugos inžinerija. Proc. 13th Conf. of Lithuanian Junior Researchers "Science - Future of, Lithuania", 2010: 95-102 (in Lithuanian).

Jarašius, L., Pakalnis, R., Sendžikaitė, J. and Matulevičiūtė, D. 2013. Experiments with restoration of raised bog vegetation in Aukštumala raised bog in Lithuania. In: M. Pakalne and L. Srazdina (Editors), Raised bog management for the biological diversity conservation in Latvia. University of Latvia, Riga, p. 225-231.

Jarašius, L., Matulevičiūtė D., Pakalnis, R., Sendžikaitė, J. and Lygis, V. 2014. Drainage impact on plant cover and hydrology of Aukštumala raised bog (Western Lithuania). *Botanica Lithuanica* 20(2): 109-120.

Joosten, H. and Clarke, D. 2002. Wise use of mires and peatlands – Background and principles including a framework for decision-making. International Mire Conservation Group / International Peat Society, Saarrijärvi, 304 pp.

Jukoniene, I., Rašomavicius, V. and Pakalnis, R. 2009. Lithuania. In: T. Minayeva and A. Sirin (Editors), A quick scan of peatlands in Central and Eastern Europe. Wetlands International, Wageningen, p. 65-70.

Laine, J. and Vanha-Majamaa, I. 1992. Vegetation ecology along a trophic gradient on drained pine mires in southern Finland. *Annales Botanici Fennici* 29(3): 213-233.

Laine, J., Vasander, H. and Laiho, R. 1995. Long-term effects of water level drawdown on the vegetation of drained pine mires in southern Finland. *Journal of Applied Ecology* 32: 785-802.

Lode, E. 2001. Natural mire hydrology in restoration of peatland functions. Doctoral thesis, Acta Universitatis Agriculturae Sueciae, Silvestria, Uppsala, 234 pp.

MacDonald, G. M., Beilman, D. W., Kremenetski, K. V., Sheng, Y., Smith, L. C. and Velichko, A. A. 2006. Rapid early development of circumarctic peatlands and atmospheric CH_4 and CO_2 variations. *Science* 314: 285-288.

Mierauskas, P., Pranaitis, A., Sinkevičius, S. and Taminskas, J. 2005. Pelkių ekosistemos [Ecosystems of mires]. Lietuvos Gamtos Fondas, Vilnius. 130 pp. (in Lithuanian).

Minayeva, T. and Sirin, A. (Editors) 2009. A quick scan of peatlands in Central and Eastern Europe. Wetlands International, Wageningen, 132 pp.

Minkkinen, K. and Laine, J. 1998. Long-term effect of forest drainage on the peat carbon stores of pine mires in Finland. *Canadian Journal of Forest Research* 28: 1267-1275.

Pakalnis, R., Sendžikaitė, J., Jarašius, L. and Avižienė, D. 2009. Problems of peatlands restoration after peat cutting. In: N.A. Laman, N.D. Grummo, O. Galanina, O. V. Sozinov and N. A. Zeliankevich (Editors), Vegetation of mires: modern problems of classification, mapping, use and protection. Proc. Int. Theoretical and Practical Seminar, Minsk, 2009: 33–44.

Povilaitis, A., Taminskas, J., Gulbinas Z., Linkevičienė, R. and Pileckas, M. 2011. Lietuvos šlapynės ir jų vandensauginė reikšmė [Lithuanian wetlands and their water protective importance]. Apyaušris publishers, Vilnius, 327 pp. (in Lithuanian with English summary).

Price, J. S., Heathwaite, A. L. and Baird, A. J. 2003. Hydrological processes in abandoned and restored peatlands: an overview of management approaches. *Wetlands Ecology and Management* 11: 65-83.

Priede, A. 2013: Impact of restoration measures on the raised bog habitats in Rožu, Aklais and Aizkraukle mire. In: M. Pakalne and L. Srazdina (Editors), Raised bog management for the biological diversity conservation in Latvia. Riga, p. 192-197.

Quinty, F. and Rochefort, L. 2003. Peatland restoration guide, 2nd edn. Canadian Sphagnum Peat Moss Association, New Brunswick Department of Natural Resources and Energy, Quebec, 107 pp.

Rochefort, L., Quinty, F., Campeau, S., Johnson, K. and Malterer, T. 2003. North American approach to the restoration of *Sphagnum* dominated peatlands. *Wetlands Ecology and Management* 11: 3-20.

Rochefort, L. and Lode, E. 2006. Restoration of degraded boreal peatlands. In: R. K. Wieder and D. H. Vitt (Editors), Boreal peatland ecosystems. Ecological Studies, vol. 188. Springer-Verlag, Berlin, p. 381-423.

Ruseckas, J. and Grigaliūnas, V. 2008. Effect of drain-blocking and meteorological factors on groundwater table fluctuations in Kamanos mire. *Journal of Environmental Engineering and Landscape Management* 16(4): 168-177.

Similä, M., Aapala, K., Penttinen, J. 2014. Ecological restoration in drained peatlands – best practices from Finland. Metsähallitus, Finnish Environment Institute, Vantaa, 84 pp.

Smilijanic, M., Wook-Seo, J., Laanelaid, A., Maaten-Theunissen, M. et al. 2014. Peatland pines as a proxy for water table fluctuations: Disentangling tree growth, hydrology and possible human influence. *Science of The Total Environment* 500-501: 52-63.

Stravinskienė, V. 1994. Medžių gręžinių paėmimas ir radialinio prieaugio matavimas, atliekant dendrochronologinius ir dendroindikacinius tyrimus. Metodinės rekomendacijos. [Wood core extraction and estimation of radial increment in dendrochronological and dendroindicational studies. Methodological recommendations]. Lithuanian Forest Research Institute, Kaunas-Girionys, 22 pp. (in Lithuanian).

Stravinskienė, V. 2002. Klimato veiksnių ir antropogeninių aplinkos pokyčių dendrochronologinė indikacija [Dendrochronological indication of climatic factors and anthropogenic environmental trends]. Lututė, Kaunas, 172 pp. (in Lithuanian with English summary).

Taminskas, J., Pileckas, M., Šimanauskienė, R. and Linkevičienė, R. 2011. Lietuvos šlapynės: klasifikacija ir sklaida [Lithuanian wetlands: classification and distribution]. *Baltica* 24: 151-162. (in Lithuanian with English abstract).

van Breemen, N. 1995. How *Sphagnum* bogs down other plants. *Tree* 10: 270-275.

Vanha-Majamaa, I., Lilja, S., Ryömä, R. et al. 2007. Rehabilitating boreal forest structure and species composition in Finland through logging, dead wood creation and fire: the EVO experiment. *Forest Ecology and Management* 250: 77-88.

Vasander, H., Tuittila, E.-S., Lode, E. et al. 2003. Status and restoration of peatlands in Northern Europe. *Wetlands Ecology and Management* 11: 51-63.

Weber, C. A. 1902. Über die Vegetation und Enstehnung des Hochmoors von Augstumal im Memeldelta mit vergleichenden Ausblicken auf andere Hochmoore der Erde.[Vegetation and development of the raised bog of Aukštumala in the Memel delta including comparative views on other raised bogs of the world]. Verlagsbuchhandlung Paul Par, Berlin, 252 pp.

Wheeler, B. D. 1999. Water and plants in freshwater wetlands. In: A. J. Baird and R. L. Wiby (Editors), Eco-hydrology. Plants and water in terrestrial and aquatic environments. Routledge, London, p. 127-180.

Wieder, R. K. and Vitt, D. H. (Editors) 2006. Boreal Peatland Ecosystems. Ecological Studies, vol. 188. Springer-Verlag: Berlin, 435 pp.

Wilson, L., Wilson, J., Holden, J. et al. 2011. Recovery of water tables in Welsh blanket bog after drain blocking: discharge rates, time scales and the influence of local conditions. *Journal of Hydrology* 391: 377-386.

Worrall, F., Armstrong, A. and Holden, J. 2007. Short-term impact of peat drain-blocking on water colour, dissolved organic carbon concentration, and water table depth. *Journal of Hydrology* 337: 315-325.

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