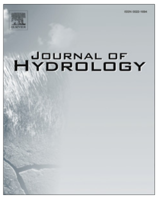
Journal of Hydrology 519 (2014) 1493–1505

Contents lists available at ScienceDirect

Journal of Hydrology

journal homepage: www.elsevier.com/locate/jhydrol



The effects of long-term drainage and subsequent restoration on water table level and pore water chemistry in boreal peatlands ☆

T. Haapalehto [a,b,*], J.S. Kotiaho [b], R. Matilainen [c], T. Tahvanainen [d]

[a] *Metsähallitus, Natural Heritage Services, P.O. Box 36, 40101 Jyväskylä, Finland*
[b] *Department of Biological and Environmental Science, P.O. Box 35, 40014 University of Jyväskylä, Finland*
[c] *Department of Chemistry, P.O. Box 35, 40014 University of Jyväskylä, Finland*
[d] *Department of Biology, University of Eastern Finland, P.O. Box 111, 80101 Joensuu, Finland*

ARTICLE INFO

Article history:
Received 5 February 2014
Received in revised form 10 July 2014
Accepted 7 September 2014
Available online 16 September 2014
This manuscript was handled by Laurent Charlet, Editor-in-Chief, with the assistance of Ewen James Silvester, Associate Editor

Keywords:
Anthropogenic disturbance
Ecosystem function
Ecosystem services
Spatial variation
Hydrology
Wetland

SUMMARY

Degradation by drainage threatens biodiversity and globally important peatland ecosystem functions such as long-term carbon sequestration in peat. Restoration aims at safeguarding peatland values by recovering natural hydrology. Long-term effects of drainage and subsequent restoration, especially related to within-site variation of water table level and pore water chemistry, are poorly known. We studied hydrological variation at 38 boreal *Sphagnum* peatland sites (pristine, drained and restored) in Finland. The average water table level was significantly lower at Drained than Pristine sites especially near the ditches. We also observed large pore water chemical differences between Drained and Pristine sites, such as higher DOC concentration at the sites drained several decades earlier. Furthermore, there were large differences in water chemistry between the samples collected from ditches and from the peat strips between the ditches. For example, the ditch water had apparently higher minerogenic influence, while DOC concentrations were highest in peat strips. The water table level was, on average, at the targeted level of Pristine sites at 5 years ago restored (Res 5) and 10 years ago restored (Res 10) sites. The Res 10 sites were more similar to the Pristine sites in water chemical composition than were the Drained sites. Water chemical differences between ditches and peat strips were smaller at the Res 5 and Res 10 than at Drained sites indicating, on average, successful decrease of drainage-induced within-site variation in water chemistry. Our results suggest more pronounced water table inclination towards the old ditches at Res 10 than at Res 5 sites. While this pattern may be an early warning sign for incomplete recovery of hydrology in long-term, we found no chemical evidence supporting this assumption yet. Our study suggests that restoration can result in significant recovery of peatland hydrology within 10 years, while some deviation from pristine hydrology is still typical. Restoration appears to have potential to reduce leaching of nutrients and DOC to downstream waters in the long term, but practitioners should be prepared for temporary increase of leaching of N and P for at least 5 years after restoration of boreal *Sphagnum* peatlands.

1. Introduction

Hydrological factors regulate central ecosystem functions like the flow of nutrients and development of soils. These functions enable the provision of globally important ecosystem services such as food crops, timber and many other biological products (Millennium Ecosystem Assessment, 2005). By influence on the carrying capacity and niche formation in ecosystems, hydrology is an important driver of biodiversity thus forming the basis for ecosystem services (Konar et al., 2013; Millennium Ecosystem Assessment, 2005). The significance of hydrology on ecosystem functions and services is emphasized in northern boreal and subarctic peatlands that cover only 3% of Earth's land surface but constitute one third of the global terrestrial carbon pool (Yu, 2011). Water level fluctuations and water chemistry largely control the accumulation and decomposition of peat and consequent fluxes of carbon as CO_2, CH_4 and as dissolved organic carbon

---

☆ Haapalehto is responsible for sampling, conducting statistical analysis and writing of the manuscript. Matilainen conducted the chemical analysis of water samples and participated in writing the manuscript. Kotiaho and Tahvanainen were responsible for planning the study and statistical analysis and participated in writing of the manuscript. All authors have approved the final article.

* Corresponding author at: Metsähallitus, Natural Heritage Services, P.O. Box 36, 40101 Jyväskylä, Finland. Mobile: +358 40 3532480.

E-mail addresses: tuomas.haapalehto@metsa.fi, tuomas.o.haapalehto@student.jyu.fi (T. Haapalehto), janne.kotiaho@bytl.jyu.fi (J.S. Kotiaho), rose.b.matilainen@jyu.fi (R. Matilainen), teemu.tahvanainen@uef.fi (T. Tahvanainen).

http://dx.doi.org/10.1016/j.jhydrol.2014.09.013
0022-1694/© 2014 Elsevier B.V. All rights reserved.

(DOC) in peatlands (Belyea and Malmer, 2004; Holden, 2005; Jungkunst and Fiedler, 2007; Moore and Knowles, 1989; Tranvik and Jansson, 2002).

Like many other ecosystems (Foley et al., 2005), peatlands have been severely degraded. Approximately 50 million hectares (13%) of peatlands have been directly altered by human land-use (Lappalainen, 1996; Strack, 2008; Tanneberger and Wichtmann, 2011). One major cause of degradation of peatlands is drainage for timber production, affecting approximately 15 million hectares in the northern boreal and subarctic regions (Strack, 2008). Drainage may also induce significant changes to hydrology of undrained peatland areas beyond considerable distances due to catchment-scale disruption of hydrological connections (Tahvanainen, 2011). The total peatland area impacted negatively by drainage and other land-use may, therefore, be much larger than often reported based on the actual drained areas. Drainage lowers the water table level generally by 20–60 cm often with typical spatial pattern related to the distance from the ditch (Laine and Vanha-Majamaa, 1992; Prévost et al., 1999; Price et al., 2003). In drained boreal *Sphagnum* peatlands ditches act as main water flow channels through peatlands after drainage, and prevent the spread of minerogenic water from the catchment over the peatland surface. Because of the lowered water table level, drainage increases aeration and promotes decomposition and nutrient mineralization in the peat matrix (Niedermeier and Robinson, 2007). Subsequently, pH and concentrations of several chemical elements increase in the pore and outflow water shortly after drainage (Holden et al., 2004; Moore et al., 2013; Prévost et al., 1999; Åström et al., 2001). In contrast, long-term changes of pore water chemistry after drainage are not well understood (Holden et al., 2004). Indeed, understanding the changes in pore water, which is in direct contact to the peat, might help e.g. to explain the apparently contradictory results from studies exploring the effects of drainage and land-use on increased riverine DOC around northern hemisphere (Freeman et al., 2004; Huotari et al., 2013; Räike et al., 2012; Sarkkola et al., 2009).

There is an increasing pressure toward ecological restoration in response to anthropogenic degradation of ecosystems. In general, restoration aims at reversing the degradation by partial rehabilitation or complete restoration of original structure (community composition) and function (e.g. cycling and fluxes of nutrients) of ecosystems (Dobson et al., 1997; Society for Ecological Restoration International, 2004; Suding, 2011). Precise aims of peatland restoration may differ due to different causes and varying extent of degradation. Most importantly, however, peatland restoration aims at recovering the original hydrological patterns (water table level, water chemistry, water flow paths), which would allow re-establishment of viable populations of characteristic peatland species (Aapala et al., 2009; Vasander et al., 2003; Similä et al., 2014). The societal expectations for restoration in securing biodiversity and provision of ecosystem services are monumental; a global target to restore 15% of degraded ecosystems by 2020 was set recently (Convention on Biological Diversity, 2010; European Commission, 2011). However, recent meta-analyses question the projected positive impacts of restoration in general (Benayas et al., 2009), and specifically in the case of peatlands (Moreno-Mateos et al., 2012). Possible failures in reaching restoration targets call for better mechanistic understanding of the underlying key-factors for successful restoration, such as hydrological variation in the case of peatlands.

Early results on the hydrological recovery of peatlands are now starting to accumulate, but they seem to be controversial to some extent. For example, both successes and failures of regaining original water table level (Haapalehto et al., 2011; Hedberg et al., 2012; Klimkowska et al., 2010; Laine et al., 2011; Schimelpfenig et al., 2013; Worrall et al., 2007) as well as both intended and unintended effects on water chemistry (Höll et al., 2009; Koskinen et al., 2011; Wilson et al., 2011a, 2011b) have been reported. While bringing urgently needed data on the poorly understood hydrological effects of peatland restoration, most studies have covered only a few sites and only the time period of first few years after restoration. Indeed, properly replicated studies on the hydrological recovery of peatlands are called for (Armstrong et al., 2010; Holden et al., 2011; Wilson et al., 2011b) to judge the generality and overall impact of restoration in the longer-term. One important but poorly understood hydrological aspect is the recovery of within-site variation in hydrology. Even relatively moderate patterns of peatland surface topography, such as hummocks and hollows, affect water flow paths and the development of plant communities (Bragazza and Gerdol, 1999). Subsidence of peat after drainage is typically uneven and depends on the distance from the ditches (van der Schaaf, 2012). This leads to a considerable increase of topographic variation in drained peatlands and provides a challenge for restoration practitioners. Insufficient blocking of ditches can, for example, redirect water flow along the artificial flow paths formed by the lines of blocked ditches. This may, in turn, act to sustain hydrological differences (related to water table level and water chemistry) between the blocked ditches and the intervening peat strips. Such uneven hydrological recovery is, indeed, suggested to hamper the recovery of communities (Hedberg et al., 2012). Therefore, it is vital for our overarching goal of restoration, to better understand the effects of restoration on the hydrological variation within restored sites.

Here we explore the long-term effects of drainage and subsequent ecological restoration on the hydrology of peatlands with special attention paid to within-site hydrological variation. We use a replicated comparative experimental design in which the 38 study sites on boreal *Sphagnum* peatlands in southern Finland were divided into four categories according to their management status (pristine, forestry drained, restored 5 years ago and restored 10 years ago). We asked:

1. What is the long-term effect of drainage on water table level and pore water chemistry?
2. To what extent is ecological restoration effective in reversing the effects of drainage on water table level and pore water chemistry?

2. Methods

2.1. Study sites

The study area is located in southern Finland between 61°53′ and 62°51′N and 22°53′ and 25°26′E in the south-boreal climatic-phytogeographical zone, where raised bogs are the main type of greater peatland formations. The mean annual temperature is *ca.* +4 °C and precipitation *ca.* 650 mm. The elevation above sea level is around 150 m. The area belongs to the Early Proterozoic bedrock area, characterized by silicaceous granite and granodiorite minerals.

We selected 38 study sites within a 75 km radius (distances between the sites ranged from 200 m to 150 km) and divided them into four categories according to their management status: (i) pristine ($n = 10$), (ii) drained ($n = 9$), (iii) previously drained and restored 3–7 years before the study (restored 5 years ago, $n = 9$), (iv) previously drained and restored 9–12 years before the study (restored 10 years ago, $n = 10$; see Appendix). For simplification, the categories are referred to Pristine, Drained, Res 5 and Res 10 further on. Selection of the sites was based on close examination of old and new aerial photographs accompanied with field observations, such that the vegetation type (weakly minerotrophic pine fen) and tree stands of the drained and restored sites were