Chemical Geology 429 (2016) 75–84

Contents lists available at ScienceDirect

Chemical Geology

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

Invited research article

Structure of peat soils and implications for water storage, flow and solute transport: A review update for geochemists

Fereidoun Rezanezhad [a,*], Jonathan S. Price [b], William L. Quinton [c], Bernd Lennartz [d], Tatjana Milojevic [a], Philippe Van Cappellen [a]

[a] *Ecohydrology Research Group, Water Institute and Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, Canada*
[b] *Department of Geography and Environmental Management, University of Waterloo, Waterloo, Canada*
[c] *Cold Regions Research Centre, Wilfrid Laurier University, Waterloo, Canada*
[d] *Faculty of Agricultural and Environmental Sciences, Rostock University, Rostock, Germany*

ARTICLE INFO

Article history:
Received 6 January 2016
Received in revised form 8 March 2016
Accepted 10 March 2016
Available online 11 March 2016

Keywords:
Peat soil structure
Physical properties
Hydraulic properties
Water flow and storage
Solute migration
Biogeochemical processes and functions

ABSTRACT

Global peatlands are a valuable but vulnerable resource. They represent a significant carbon and energy reservoir and play major roles in water and biogeochemical cycles. Peat soils are highly complex porous media with distinct characteristic physical and hydraulic properties. Pore sizes in undecomposed peat can exceed 5 mm, but significant shrinkage occurs during dewatering, compression and decomposition, reducing pore-sizes. The structure of peat soil consists of pores that are open and connected, dead-ended or isolated. The resulting dual-porosity nature of peat soils affects water flow and solute migration, which influence reactive transport processes and biogeochemical functions. Advective movement of aqueous and colloidal species is restricted to the hydrologically active (or mobile) fraction of the total porosity, i.e. the open and connected pores. Peat may attenuate solute migration through molecular diffusion into the closed and dead-end pores, and for reactive species, also through sorption and degradation reactions. Slow, diffusion-limited solute exchanges between the mobile and immobile regions may give rise to pore-scale chemical gradients and heterogeneous distributions of microbial habitats and activity in peat soils. While new information on the diversity and functionalities of peat microbial communities is rapidly accumulating, the significance of the geochemical and geomicrobial study on peat stands to benefit from a basic understanding of the physical structure of peat soils. In this paper, we review the current knowledge of key physical and hydraulic properties related to the structure of globally available peat soils and briefly discuss their implications for water storage, flow and the migration of solutes. This paper is intended to narrow the gap between the ecohydrological and biogeochemical research communities working on peat soils.

1. Introduction

Peat forms through the accumulation of partially decomposed plant biomass in fens, bogs, salt marshes and some swamps in various parts of the world, including vast peatlands in boreal/taiga landscapes, as well as temperate and tropical locations (Canadian System of Soil Classification, CSSC, 1998). Peat deposits cover large areas of northern North America, northern Europe, western Siberia, Indonesia and south-east Asia; they occur as arctic and alpine tundra, taiga, boreal and sub-boreal bogs, fens and other peatlands, where *Sphagnum* mosses are often the dominant peat-forming species (Kuhry et al., 1993; Glaser et al., 2004a). Peatlands are transitional environments between terrestrial and aquatic ecosystems that provide essential hydrological, ecological and biogeochemical functions (Fraser et al., 2001a,b; Joosten and Clarke, 2002; Chapman et al., 2003; Mitra et al., 2005; Krueger et al., 2015). Although peatlands only cover about 3% of the continents (IMCG, 2008), globally they store on the order of 10% of all freshwater and 30% of land-based organic carbon (300–450 PgC; Mitra et al., 2005; Limpens et al., 2008; Bragazza et al., 2013). There is growing interest in understanding and predicting how soil processes in peatlands respond to anthropogenic pressures, including land-use changes, resource extraction and global climate warming (Strack, 2008; Booth et al., 2012).

The ecology and biogeochemistry of peat soils are closely linked to the movement through and storage of water and reactive solutes (e.g., Ca, Mg, Fe, Na), which, in turn, depend on the chemical composition of the soil water (Hill and Siegel, 1991), microbiological and chemical processes (Todorova et al., 2005) and the physical characteristics of the porous matrix (Päivänen, 1973; Rycroft et al., 1975a,b; Price and Woo, 1988; Ours et al., 1997). The total porosity of peat soils often exceeds 80% (Boelter, 1968). Peat can have relatively large pores (Hayward and Clymo, 1982) that are highly irregular and interconnected (Quinton et al., 2009; Rezanezhad et al., 2010), as well as smaller open pores, dead-end pores and those that are closed or partially closed

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* Corresponding author.
E-mail address: frezanez@uwaterloo.ca (F. Rezanezhad).

http://dx.doi.org/10.1016/j.chemgeo.2016.03.010

(Hoag and Price, 1997). Peat is thus a dual-porosity medium that includes a “mobile region” through which water, solutes and colloids move relatively easily, and an “immobile region” with negligible fluid flow velocity. Exchange of solutes between the two regions occurs primarily via molecular diffusion (van Genuchten and Wierenga, 1976). While advection through the open and connected (or active) pores, and matrix diffusion into and within closed pores are generally assumed to be the dominant mechanisms controlling solute transport in peat, only a relatively small number of studies have investigated the effects of the complex dual-porosity structure of peat on solute transport (e.g., Loxham and Burghardt, 1983; Price and Woo, 1988; Hoag and Price, 1997; Ours et al., 1997; Reeve et al., 2001; Rezanezhad et al., 2012b).

The hydraulic properties of peat strongly depend on the peatland vegetation and the degree of decomposition of the plant debris. Decomposition is mainly carried out by microorganisms that use soil organic compounds as energy substrates. The degree of decomposition and physical make-up of the peat varies with depth, age, plant community and, foremost, the drainage regime (Swanson and Grigal, 1989; Schoephroster and Furbush, 1974). The degree of decomposition is commonly assessed using the 10 classes of humification of the von Post scale (von Post, 1922) where H1 refers to the least, H10 the most decomposed peat. The von Post classification is based on the visual inspection of extracted soil solutions and plant residues, and is therefore particularly useful in the field. Additional characterization methods have been developed to describe the degree of decomposition based on size fractions, density, and fiber content (Boelter, 1969; Lynn et al., 1974; Lishtvan and Kroll, 1975; Malterer et al., 1992) while increasingly, isotopic and spectroscopic approaches are used for assessing soil organic matter decomposition and the associated changes in molecular composition, functionality and reactivity (Moers et al., 1990; Baldock et al., 1997; Macko et al., 1991; Menot and Bums, 2001; Drexel et al., 2002; Grover and Baldock, 2013; Cao et al., 2014). Carbon/nitrogen ratios are also commonly used to assess relative states of decomposition of peat soils (Kuhry and Vitt, 1996; Bridgham et al., 1998).

The degree of decomposition of peat generally increases with depth below the ground surface, while the geometric mean pore diameter and active porosity simultaneously decrease. For example in the Arctic tundra, the active porosity typically drops from values around 80% near the ground surface to <50% at depths of 0.5 m (Quinton et al., 2000). Over the same depth range, however, reductions in permeability of three or more orders of magnitude are not unusual (e.g., Boelter, 1965; Hoag and Price, 1995; Quinton et al., 2000; Beckwith et al., 2003a). The depth variations of porosity and pore-size distribution (McCarter, 2014), as well as the structural alignment of the peat fabric (Landva and Pheeney, 1980), affect water storage and flow in peat, including the partitioning of pore water between the mobile and immobile regions (Caron et al., 2015a). The low permeability and reduced active porosity of deeper, well-humified peat layers limit exchanges of water and solutes with surface waters and the atmosphere.

Climate change and human disturbances in high latitude regions are producing ecosystem changes with largely unknown consequences for the fluxes and storage of water, carbon and nutrients (Rowland et al., 2010). It has been shown that peatlands release substantial volumes of biogenic gases into the atmosphere, in response to changing climate, through plant shoots, slow diffusion across the peat surface, and episodically via ebullition (release of free-phase gas in the form of bubbles), and some of it is converted to carbon dioxide in the oxic portion of the peat (Rosenberry et al., 2003; Baird et al., 2004; Glaser et al., 2004b; Tokida et al., 2005; Strack et al., 2006; Rosenberry et al., 2006). Estimated volumes of gaseous-phase gas in peatlands range from 0 to nearly 20% of the peat volume (Rosenberry et al., 2006). This accumulation and release of trapped gases may affect the peat matrix and, thus alter hydraulic gradients and movement of water and solutes in peat (Kellner et al., 2004; Beckwith and Baird, 2001), which in turn can alter the composition and flux of greenhouse gases (Rosenberry et al., 2006; Strack et al., 2005). In particular, there is a need to reduce the uncertainties associated with potential feedbacks to climate warming of organic matter degradation rates and greenhouse gas emissions in northern peatlands. A better understanding of belowground biogeochemical processes in peat soils must account for the unique transport and water-holding properties of these complex environments. In this paper, we review current knowledge on the structure of globally available peat soils and the resulting effects on flow and solute transport. Our review will, we hope, provide the geochemical community with an entry point to the literature on physical soil properties and processes that are relevant to the biogeochemical functioning of peat soils.

2. Physical properties

Peat soils are organic rich materials, usually containing ≥20 mass % C_{org} (Canadian System of Soil Classification, CSSC, 1998). The unique combination of physical properties of peat, including low bulk density, high total porosity, and the ability to swell and shrink upon wetting and drying (Table 1), means that concepts and methods used to describe the porous media properties of mineral soils may often be inadequate (Dettmann et al., 2014; Caron et al., 2015b). The total porosity of peat includes the relatively large, inter-particle pores that can actively transmit water, as well as relatively small, closed, and dead-end pores formed by the remains of plant cells (Hayward and Clymo, 1982; Kremer et al., 2004). Scanning electron microscopy of peat reveals (*I*) open and connected macropores, (*II*) closed or partially closed cells, and (*III*) dead-end or isolated pore spaces (Fig. 1). These micro-scale pore structures are responsible for the dual-porosity behavior observed at the scales of macroscopic peat samples (e.g., Hoag and Price, 1997; Ours et al., 1997; Rezanezhad et al., 2012a) and field observations (e.g., Hoag and Price, 1995; Baird, 1997): *I* comprises the “active porosity”, and *II* plus *III* comprise the immobile water fraction or “inactive porosity”. Undecomposed peat with high fiber content and a large active porosity yields as much as 80% of its saturated water content to drainage; the most decomposed peat samples release less than 10% of their water to drainage (Radforth and Brawner, 1977; Letts et al., 2000).

Peat decomposition reduces the proportion of large pores by breaking down plant debris into smaller fragments, thereby reducing the inter-particle pore spaces (Moore et al., 2005; Bragazza et al., 2008). Fig. 2 shows an example of decomposition and pore structure differences between *Sphagnum* peat layers collected at 5 and 55 cm cross-sectional depths where a higher decomposition and compression is observed at a depth of 55 cm. In the peatland-dominated zone of discontinuous permafrost, total porosity drops by about 10% between the ground surface and 35 cm depth, however, the active porosity decreases by as much as 40% over the same distance (Quinton et al., 2000). The water storage coefficient of peat and its saturated hydraulic conductivity similarly decrease rapidly with depth in the soil (see Section 3). Decomposition increases the mass of dry material per volume of peat and therefore the bulk density of peat increases with depth from <30 kg m^{-3} near the ground surface to >150 kg m^{-3} at a depth of 35 cm (Quinton et al., 2000). Nonetheless, because of the high organic matter content, even highly decomposed peat has a relatively low bulk density compared to mineral soils (Driessen, 1977).

Peat is a highly compressible material (Hobbs, 1986; Price and Schlotzhauer, 1999; Price et al., 2005). Peatland surfaces may therefore exhibit daily to seasonal vertical movement due to swelling and shrinking. The vertical movement of the ground surface is accompanied by changes in water storage, but also in the hydraulics, biogeochemistry and thermal properties (Waddington et al., 2010). The compressibility of peat is controlled by its physical properties, including the structure and arrangement of its pores (Kennedy and Price, 2005), factors that are largely controlled by the degree of decomposition (Price et al., 2005). Undecomposed peat near the ground surface has both elastic and plastic properties that enable it to expand and contract readily with wetting and drying. Decomposed peat at greater depths typically