Evidence for glacial geological controls on the hydrology of Maine peatlands

Xi Chen[1,2*], Xavier Comas[3], Andrew Reeve[4], Lee Slater[2]

1. *College of Water Resources and Civil Engineering, China Agricultural University, Beijing, China.*
2. *Department of Earth & Environmental Sciences, Rutgers University, Newark, NJ, USA.*
3. *Department of Geosciences, Florida Atlantic University, Davie, FL, USA.*
4. *School of Earth and Climate Sciences, University of Maine, Orono, ME, USA.*

[*]formerly at Rutgers University, now at China Agricultural University, E-mail: chenxioffice@cau.edu.cn

ABSTRACT

Freshwater pools often form eccentric crescent patterns in peatlands, an important atmospheric methane source, and show an apparent spatial association with eskers in some deglaciated regions. However, the role of underlying permeable glacial deposits such as eskers in regulating hydrogeology, and perhaps even carbon cycling, in peatlands is rarely considered. In this study, ground-penetrating radar imaging and direct coring confirmed that clustered pools coincide with buried esker crests in contact with peat soil in Caribou Bog and Kanokolus Bog in Maine (USA). Hydraulic head and geochemical data combined with LiDAR indicate vertical water flow from shallow peat towards the permeable esker crests, suggesting enhanced downward transport of labile organic carbon that presumably accelerates rates of methanogenesis in deep peat. Eskers might therefore serve as proxies for enhanced CH_4 production in deep peat as supported by differences in dissolved CH_4 profiles depending on proximity to pools. Geographic data compiled from multiple sources suggest that many peatlands with eccentric pools appear to be located proximal to esker systems in Maine and Fennoscandia. These geological factors may be important, previously unrecognized, controls on water and the carbon cycle in peatlands.

INTRODUCTION

Peatlands are one of the largest sources of atmospheric methane (CH_4), an important greenhouse gas influencing global climate (IPCC, 2013). On the slightly sloping surfaces of raised bogs, a peatland landform, formation of pools may contribute significantly to atmospheric CH_4 (Moore, 1989; Hamilton et al., 1994; Waddington and Roulet, 1996; Wik et al., 2016). Pools, in troughs, often alternate with ridges, lengthening at right angles to the slope and spatially distributing as eccentric crescents (off center) in raised bogs, leading to the term eccentric bog (Sjörs, 1961; Eurola, 1962; Moore, 1977, 1982; Glaser and Janssens, 1986; Davis and Anderson, 1991; Belyea and Lancaster, 2002). It is possible that pool formation results from characteristic sloping topography (Troll, 1944; Pearson, 1960; Foster et al., 1988; Foster and Wright, 1990; Leuschner and Ellenberg, 2017) or ecological factors (Moore, 1982; Glaser and Janssens, 1986; Belyea and Lancaster, 2002).

While an impermeable mineral substrate or low-permeability deep peat is generally considered essential during bog formation to reduce downward drainage (Davis and Anderson, 1991; Reeve et al., 2000), computational simulations of groundwater flow suggest that permeable sedimentary deposits such as eskers in contact with the peat may enhance vertical groundwater flow (Reeve et al., 2009). Furthermore, these eskers might facilitate pool formation by enhancing peat decomposition and maintaining pools in peatlands (Comas et al., 2005, 2011; Lowry et al., 2009). Since hydrology is a key factor regulating CH_4 fluxes in peatlands (Bartlett and Harriss, 1993; Lai, 2009), underlying permeable deposits such as eskers may also therefore indirectly regulate CH_4 production, consumption and possibly emissions (Bon et al., 2014). Buried sand beach ridges affect peatland hydrology and geochemistry in Glacial Lake Agassiz Peatlands, Minnesota, possibly playing a role similar to eskers in pool formation and CH_4 emission (Siegel, 1981, 1983; Siegel and Glaser, 1987; Reeve et al., 2001).

Here, we integrate geophysical, hydrological, geochemical and soil core datasets acquired over the last 19 years, along with LiDAR, to investigate the relationships between eskers, hydrogeology and dissolved CH_4 concentrations in two raised eccentric bogs in Maine (USA): the Central Unit (44°54'N, 68°43'W) of Caribou Bog and Kanokolus Bog (44°33'N, 69°22'W). The integrated datasets provide insights into the importance of geology as a control on hydrology and deep CH_4 sources in peatlands.

GEOLOGICAL SETTING AND METHODS

Caribou Bog is a large peatland system (~22 km^2) composed of South, Central and North Units in south-central Maine, although only the Central Unit contains pools in a parallel pattern of eccentric crescents (Fig. 1A). Previous studies (Comas et al., 2005, 2011) have identified the presence of esker deposits from the Katahdin esker system buried below the Central Unit`s peat surface. Several ground-penetrating radar (GPR) surveys, constrained with direct soil coring, were performed in previous studies

(Comas et al., 2005, 2011), with additional data acquired in this study (a common offset survey exceeding 2 km crossing the entire peat basin) to confirm peat thickness and lithology using Mala 50 and 100 MHz rough terrain antennas. A total of 673 sample points of GPR data were used to interpolate a two-dimensional map of peat thickness (25×50 grids, grid size 37.8×25.3 m^2) using an Inverse Distance Weighted method (Fig. 1A). GPR surveys and direct soil coring were also performed in Kanokolus Bog (165 hectares) situated about 60 km southwest of Caribou Bog.

Hydraulic head was measured at fourteen well clusters (W1 - W14, Fig. 1A) in Caribou Bog. Heads were manually contoured to determine groundwater flow patterns (Supplementary Text S1). LiDAR data (The North East Project, 2010, Photo Science, Inc; Jones et al., 2008) was used to map water levels in the pools and interpret direction of lateral groundwater flow (Fig. 2K). Porewater samples for dissolved CH_4 concentration (mg CH_4 L^{-1}) were collected at three sites with variable proximity to the cluster of pools (G1 - G3 in Fig. 1D, Supplementary Text S2) (Bon et al., 2014). Another batch of porewater samples for ammonium (NH_4^+) and soluble reactive phosphorus (P) were collected from wells where hydraulic heads were measured, taken to the laboratory and analyzed (Supplementary Text S2).

RESULTS AND DISCUSSION

Relationship between hydrological patterns and eskers

A combination of GPR surveying and coring in the Central Unit of Caribou Bog confirmed previous studies showing a general stratigraphy consisting of, from surface to bottom, peat soil, organic-rich lake sediment (gyttja), and glaciomarine sediment (Presumpscot Formation) presumably underlain by glacial till (Fig. 1C). The peat soil and gyttja are about 5 m thick on average, reaching a maximum thickness of 18 m (Fig. 1A), and esker deposits in direct contact with the peat are present in the vicinity of clustered pools both in Caribou Bog (Fig. 1C), and Kanokolus Bog (Fig. 1E).

Hydraulic head measurements recorded in Caribou Bog (Fig. 2A and 2B, see Reeve et al., 2009 and Bon et al., 2014 for additional data) indicate that divergent vertical groundwater flow in the shallow peat occurs near the pools, leading to downward flow towards the buried permeable esker crests (acting as drains) below the pools (Reeve et al., 2000, 2009). In addition, LiDAR data indicate that the pool water levels far from esker ridges are higher than pool water levels falling directly above them that serve as drains (Fig. 2K).

We foremost argue that eskers regulate hydrology in peatlands, and may also contribute to pool formation, growth and lateral spreading in bogs (Comas et al., 2005, 2011). Extensive geophysical surveys of Caribou Bog`s South Unit, which does not contain pools, show that the confining Presumpscot Formation overlies the peat soil throughout the basin with no presence of esker deposits in direct contact with the peat soil (Slater and Reeve, 2002). It is notable that eccentric bogs in the USA mostly occur in Maine (Davis and Anderson, 1991), which contains more eskers than other glaciated region in the USA. Surficial eskers have been visually confirmed proximal to 7 of 17 eccentric bogs in Maine (Davis and Anderson, 1991), suggesting a relationship between eskers and eccentric bogs. Permeable glacial materials such as eskers, may also influence pool depression formation (Comas et al., 2011) due to the variation in the rates of peat formation (Belyea and Clymo, 2001), or the climate-regulated initiation and development of pools via modifications to the water balance (Glaser and Janssens, 1986).

GPR surveys indicate that the western cluster of pools in the Central Unit of Caribou Bog and Kanokolus Bog are not underlain by shallow esker crests in direct contact with the peat (Comas et al., 2011) (Fig. 1C and 1E). Deeper esker crests may exist but at depths beyond the GPR`s range due to excessive attenuation of the electromagnetic signal. Alternatively, these may be pools spreading laterally from above the esker crests. Probing of pool depths and radiocarbon dating of pool bottoms confirmed that pools far away from eskers are relatively young and shallow compared to pools over esker crests (Comas et al., 2011), suggesting an autogenic model for pool development (Foster and Wright, 1990): downward transport of dissolved oxygen (and possibly other inorganic electron acceptors) (Fig. 2A-2B) might locally accelerate peat decomposition, resulting in the formation of pool depressions (Comas et al., 2011). Bog initiation can also be influenced by the presence of eskers, e.g. splitting the basin into two (Comas et al., 2004). Bog topography is characterized by a dome, a lagg zone along the edge of the bog (where water from surrounding uplands and the dome collects) and/or a saddle that can drive or constrain pool spreading to a specific direction via a hydraulic head gradient (Fig. 3).

Relationship between deep methane sources and eskers

The buried esker crests in contact with peat soil are co-located within a hotspot of dissolved CH_4 concentration and the highest NH_4^+ concentration. The highest value of dissolved CH_4 in peat soil was found at 3.4 m depth at site G1 (Fig. 1D). The highest dissolved CH_4 concentration record was at site G3, near the peat-mineral sediments interface. However, the lowest concentration in terrestrial peat was recorded only 2 m above this location (Fig. 1D). This suggests that older dissolved CH_4 trapped in the low-permeability deep sediment does not recharge (or bypasses) overlying peat. Assuming a limited nitrification rate (Bayley et al., 2005), the high concentrations of dissolved NH_4^+ in deep peat soil (Fig. 2C and 2E) might indicate significant ammonification of organic N around the buried esker crests. Since ammonification and organic matter decomposition are positively correlated, high anaerobic decomposition rates may occur at the peat-esker contact increasing methanogenesis rates (Chanton et al., 1995, 2008; Chasar et al., 2000) and enrichment of dissolved CH_4, in addition to CH_4 transport downwards from the shallow zones of high CH_4 production. Concentration of P decreased from the shallow to the deep peat soil (Fig. 2G – 2J), suggesting that the primary P source is still from the atmosphere as in other ombrotrophic bogs, and that only limited P, (and probably also N and other nutrients) enters the peat soils from the mineral soil via the esker outcrops. The enrichment of

NH_4^+ at depth is likely primarily due to internal cycling, e.g. the *in-situ* ammonification process, rather than additional recharge from the mineral soil via the esker.

Considering persistent water flow toward the permeable deposits (Fig 2A and 2B), Reeve et al. (2009) proposed that surface labile carbon, especially acetate (Lai, 2009; Bon et al., 2014), is transported downward towards the esker, contributing to the development of a hotspot for decomposition and CH_4 production by acetoclastic methanogenesis with depth, and suggesting that eskers may enhance CH_4 production in deep peats (Bon et al., 2014) under wooded heath dominated areas (Fig. 1C, Comas et al., 2004) where more abundant labile organic carbon may exist. This hypothesis is also consistent with the enhanced ammonification around the buried esker crests (Fig. 2C and 2E). Other processes, such as anaerobic oxidation of methane (Segarra et al., 2005), are likely secondary factors in the formation of hotspots of dissolved CH_4.

Future research

Geographic data from northeast Maine, USA, central Finland and south Sweden (Shreve, 1985; Turunen et al., 2002; Gunnarsson and Löfroth, 2009) show that many eccentric bogs appear to be closely located proximal to esker systems (Fig. 4). The distances between bogs and major esker systems exhibit a skewed normal distribution (Mean = 9.06 km, Std. Dev. = 5.85 km, Skewness = 2.05). Assuming surficial esker deposits extend below low-permeability sediment or deep peat units, a connection between eskers and vertical groundwater flow that regulates pool persistence and CH_4 production seems reasonable. However, while supported by evidence from other bogs in Maine (i.e. Kanokolus Bog, Fig. 1B and 1E), further work in other peatland systems is required to confirm that eskers or other underlying permeable glacial deposits are indeed in direct contact with the base of peat soils. The presence of eccentric bogs in the maritime region of southwest Sweden where eskers are generally absent (Fig. 4C) may also indicate a role of other underlying permeable glacial deposits in this region, although other mechanisms of pool persistence unrelated to underlying permeable glacial deposits in eccentric bogs are equally plausible (Moore, 1982; Glaser and Janssens, 1986; Davis and Anderson, 1991).

CONCLUSIONS

Geological controls appear to play a critical role in regulating peatland hydrogeology and thus mediate carbon cycling in two Maine peatlands commonly assumed to be characterized by 1) lateral groundwater flow constrained by an impermeable base; and 2) a CH_4 source from shallow peat soils associated with abundant labile organic carbon. However, buried esker crests in contact with peat soil drive vertical flow, presumably transporting labile organic carbon from the shallow to the deep peat soil, contributing to a hotspot of CH_4 production, in addition to the contribution of CH_4 transport downwards from the shallow zones of high CH_4 production. Therefore, eskers and other underlying permeable glacial deposits at depth might serve as geological proxies for deep CH_4 concentration hotspots. Such geological controls might be an important factor, along with ecology and climate, controlling carbon and water fluxes in peat bogs.

REFERENCES CITED

Bartlett, K.B., and Harriss, R.C., 1993, Review and assessment of methane emissions from wetlands: Chemosphere, v. 26, p. 261–320, doi:10.1016/0045-6535(93)90427-7.

Bayley, S.E., Thormann, M.N., and Szumigalski, A.R., 2005, Nitrogen mineralization and decomposition in western boreal bog and fen peat: Ecoscience, v. 12, p. 455–465, doi:10.2980/i1195-6860-12-4-455.1.

Belyea, L.R., and Clymo, R.S., 2001, Feedback control of the rate of peat formation: Proceedings of the Royal Society of London. Series B: Biological Sciences, v. 268, p. 1315–1321, doi:10.1098/rspb.2001.1665.

Belyea, L.R., and Lancaster, J., 2002, Inferring landscape dynamics of bog pools from scaling relationships and spatial patterns: Journal of ecology, v. 90, p. 223–234, doi:10.1046/j.1365-2745.2001.00647.x.

Bon, C., Reeve, A., Slater, L., and Comas, X., 2014, Using hydrologic measurements to investigate free-phase gas ebullition in a Maine peatland, USA: Hydrology and Earth System Sciences, v. 18, p. 953–965.

Chanton, J.P., Bauer, J.E., Glaser, P.A., Siegel, D.I., Kelley, C.A., Tyler, S.C., Romanowicz, E.H., and Lazrus, A., 1995, Radiocarbon evidence for the substrates supporting methane formation within northern Minnesota peatlands: Geochimica et Cosmochimica Acta, v. 59, p. 3663–3668, doi:10.1016/0016-7037(95)00240-z.

Chanton, J.P., Glaser, P.H., Chasar, L.S., Burdige, D.J., Hines, M.E., Siegel, D.I., Tremblay, L.B., and Cooper, W.T., 2008, Radiocarbon evidence for the importance of surface vegetation on fermentation and methanogenesis in contrasting types of boreal peatlands: Global Biogeochemical Cycles, v. 22, p. GB4022, doi:10.1029/2008gb003274.

Chasar, L.S., Chanton, J.P., Glaser, P.H., Siegel, D.I., and Rivers, J.S., 2000, Radiocarbon and stable carbon isotopic evidence for transport and transformation of dissolved organic carbon, dissolved inorganic carbon, and CH4in a northern Minnesota peatland: Global Biogeochemical Cycles, v. 14, p. 1095–1108, doi:10.1029/1999gb001221.

Comas, X., Slater, L., and Reeve, A., 2004, Geophysical evidence for peat basin morphology and stratigraphic controls on vegetation observed in a Northern Peatland: Journal of Hydrology, v. 295, p. 173–184, doi:10.1016/j.jhydrol.2004.03.008.

Comas, X., Slater, L., and Reeve, A., 2011, Pool patterning in a northern peatland:

Geophysical evidence for the role of postglacial landforms: Journal of hydrology, v. 399, p. 173–184, doi:10.1016/j.jhydrol.2010.12.031.

Comas, X., Slater, L., and Reeve, A., 2005, Stratigraphic controls on pool formation in a domed bog inferred from ground penetrating radar (GPR): Journal of Hydrology, v. 315, p. 40–51, doi:10.1016/j.jhydrol.2005.04.020.

Davis, R.B., and Anderson, D.S., 1991, The eccentric bogs of maine: A rare wetland type in the United States: Maine Agricultural Experiment Station Technical Bulletin 146, and Maine State Planning Office, Critical Areas Program, Planning Report 93.

Eurola, S., 1962, Über die regionale Einteilung der südfinnischen Moore. [The regional classification of peatlands in south Finland]: Annales Botanici Societatis Zoologicae Botanicae Fennicae Vanamo, v. 33, p. 163–243.

Foster, D.R., and Wright, H.E., 1990, Role of Ecosystem Development and Climate Change in Bog Formation in Central Sweden: Ecology, v. 71, p. 450–463, doi:10.2307/1940300.

Foster, D., Wright Jr, H., Thelaus, M., and King, G., 1988, Bog development and landform dynamics in central Sweden and south-eastern Labrador, Canada: The Journal of Ecology,, p. 1164–1185.

Glaser, P.H., and Janssens, J.A., 1986, Raised bogs in eastern North America: transitions in landforms and gross stratigraphy: Canadian Journal of Botany, v. 64, p. 395–415, doi:10.1139/b86-056.

Gunnarsson, U., and Löfroth, M., 2009, Våtmarksinventeringen resultat från 25 års inventeringar : nationell slutrapport för våtmarksinventeringen (VMI) i Sverige: Stockholm, Naturvårdsverket.

Hamilton, J.D., Kelly, C.A., Rudd, J.W., Hesslein, R.H., and Roulet, N.T., 1994, Flux to the atmosphere of CH4 and CO2 from wetland ponds on the Hudson Bay lowlands (HBLs): Journal of Geophysical Research: Atmospheres, v. 99, p. 1495–1510.

IPCC, 2013, Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley, Eds.): Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, p. 1533.

Jones, K.L., Poole, G.C., OtextquotesingleDaniel, S.J., Mertes, L.A.K., and Stanford, J.A., 2008, Surface hydrology of low-relief landscapes: Assessing surface water flow impedance using LIDAR-derived digital elevation models: Remote Sensing of Environment, v. 112, p. 4148–4158, doi:10.1016/j.rse.2008.01.024.

Lai, D., 2009, Methane dynamics in northern peatlands: a review: Pedosphere, v. 19, p. 409–421, doi:10.1016/S1002-0160(09)00003-4.

Leuschner, C., and Ellenberg, H., 2017, Mires, *in* Ecology of Central European Non-Forest Vegetation: Coastal to Alpine, Natural to Man-Made Habitats: Vegetation Ecology of Central Europe, Volume II, Cham, Springer International Publishing, p. 117–187, doi:10.1007/978-3-319-43048-5_3.

Lowry, C.S., Fratta, D., and Anderson, M.P., 2009, Ground penetrating radar and spring formation in a groundwater dominated peat wetland: Journal of Hydrology, v. 373, p. 68–79.

Moore, T., 1989, Plant production, decomposition, and carbon efflux in a subarctic patterned fen: Arctic and Alpine Research,, p. 156–162, doi:10.2307/1551627.

Moore, P.D., 1982, Pool and ridge patterns in peat mires: Nature, v. 300, p. 110, doi:10.1038/300110b0.

Moore, P.D., 1977, Stratigraphy and pollen analysis of Claish Moss, north-west Scotland: significance for the origin of surface-pools and forest history: Journal of Ecology, v. 65, p. 375–397, doi:10.2307/2259489.

Pearson, M., 1960, Muckle Moss, Northumberland: I. Historical: The Journal of Ecology,, p. 647–666, doi:10.2307/2257340.

Reeve, A., Siegel, D., and Glaser, P., 2000, Simulating vertical flow in large peatlands: Journal of Hydrology, v. 227, p. 207–217, doi:10.1016/S0022-1694(99)00183-3.

Reeve, A., Tyczka, Z., Comas, X., and Slater, L., 2009, The influence of permeable mineral lenses on peatland hydrology: Carbon Cycling in Northern Peatlands,, p. 289–297.

Reeve, A.S., Warzocha, J., Glaser, P.H., and Siegel, D.I., 2001, Regional ground-water flow modeling of the Glacial Lake Agassiz Peatlands, Minnesota: Journal of Hydrology, v. 243, p. 91–100, doi:10.1016/s0022-1694(00)00402-9.

Segarra, K.E.A., Schubotz, F., Samarkin, V., Yoshinaga, M.Y., Hinrichs, K.-U., and Joye, S.B., 2015, High rates of anaerobic methane oxidation in freshwater wetlands reduce potential atmospheric methane emissions: Nature Communications, v. 6, doi:10.1038/ncomms8477.

Shreve, R.L., 1985, Esker characteristics in terms of glacier physics, Katahdin esker system, Maine: Geological Society of America Bulletin, v. 96, p. 639–646, doi:10.1130/0016-7606(1985)96<639:ECITOG>2.0.CO;2.

Siegel, D.I., 1983, Ground Water and the Evolution of Patterned Mires, Glacial Lake Agassiz Peatlands, Northern Minnesota: The Journal of Ecology, v. 71, p. 913, doi:10.2307/2259601.

Siegel, D.I., 1981, Hydrogeologic setting of the Glacial Lake Agassiz peatlands, northern Minnesota:.

Siegel, D.I., and Glaser, P.H., 1987, Groundwater flow in a bog-fen complex, Lost River Peatland, northern Minnesota: Journal of Ecology, v. 75(3), p. 743–754, doi:10.2307/2260203.

Sjörs, H., 1961, Surface patterns in boreal peatlands: Endeavour, v. 20, p. 217–223.

Slater, L.D., and Reeve, A., 2002, Investigating peatland stratigraphy and hydrogeology using integrated electrical geophysics: Geophysics, v. 67, p. 365–378, doi:10.1190/1.1468597.

Troll, C., 1944, Strukturböden, solifluktion und frostklimate der Erde: Geologische Rundschau, v. 34, p. 545–694.

Turunen, J., Tomppo, E., Tolonen, K., and Reinikainen, A., 2002, Estimating carbon accumulation rates of undrained mires in Finland–application to boreal and subarctic regions: The Holocene, v. 12, p. 69–80.

Waddington, J., and Roulet, N., 1996, Atmosphere-wetland carbon exchanges: Scale dependency of CO2 and CH4 exchange on the developmental topography of a peatland: Global Biogeochemical Cycles, v. 10, p. 233–245, doi:10.1029/95GB03871.

Wik, M., Varner, R.K., Anthony, K.W., MacIntyre, S., and Bastviken, D., 2016, Climate-sensitive northern lakes and ponds are critical components of methane release: Nature Geoscience, v. 9, p. 99, doi:10.1038/ngeo2578.

ACKNOWLEDGMENTS

This material is partly based upon work supported by the National Science Foundation under grant EAR 1623895. We thank Andy Baird, Paul Glaser, Joel E. Johnson and other anonymous reviewers for their valuable suggestions to enhance the quality of this manuscript.

FIGURE CAPTIONS

Figure 1. A: Peat thickness distribution from spatial interpolation of all GPR datasets from Caribou bog. B: Map of Kanokolus Bog (ME, aerial photograph acquired on July 6, 2015). C: GPR profile and coring datasets across the Central Unit of Caribou bog. D: Dissolved CH_4 concentrations at different depths for three sites G1, G2 and G3 in Caribou bog. E: GPR profile from Kanokolus Bog, again showing pools coincidental with permeable mineral deposits, along with a secondary band of pools away from the mineral deposits). F: Maine, U.S.A (Caribou Bog - A1; Kanokolus Bog - A2).

Figure 2. A-B: Hydraulic head across wells W8-W5-W6-W7 and W10-W9-W5-W4-W3-W2-W1. The flow direction in the upper layer of peat soil is nearly lateral from peatland dome center (between W5 and W6) to lagg. The flow direction in the lower layer is downward towards the esker, i.e. acting as a point sink on the bottom boundary of the peat soil. C-F: NH_4^+ concentration (mg N L^{-1}). G-J: soluble reactive phosphorous (P) concentration (mg P L^{-1}). K-L: LiDAR data mapping of the water levels of pools and topography elevation, respectively. The differences in the water levels suggest the flow direction in the upper layer is from dome center to lagg, consistent with the well data (Fig. 2A). Date is in the format: yyyymmdd.

Figure 3. Conceptual model of influences of eskers on hydrology via locally downward drainage in eccentric bogs. The outcrop of the esker crest is verified from GPR profiles and direct sampling (rectangle in Fig. 2C) as shown. Water flows

vertically from shallow peat soil towards the permeable esker crest, suggesting enhanced downward transport of labile organic carbon that presumably accelerates decomposition rates of methanogenesis in deep peat. a) Lateral pool spreading associated with the transport of labile organic carbon in shallow peat (lateral green arrows) is constrained by opposing groundwater flow from surrounding highlands. b) Pools spread from the outcrop of the esker crest to a point of lower elevation relative to the dome of the eccentric bog, as a result of the lateral downward transport of labile organic carbon.

Figure 4. Examples of the spatial distribution of eccentric bogs in relation to known eskers (Based upon data from (Shreve, 1985; Davis and Anderson, 1991; Turunen et al., 2002; Gunnarsson and Löfroth, 2009)**)**. A: Maine, northern U.S.A (Caribou Bog - A1; Kanokolus Bog - A2); B: Finland, Northern Europe; C: Sweden, Northern Europe. D: The ranges of A, B and C. E: Histogram of the distances between eccentric bogs and nearest major esker systems, showing a skewed normal distribution (Mean = 9.06 km, Std. Dev. = 5.85 km, Skewness = 2.05, see Supplementary S3).

FIGURES

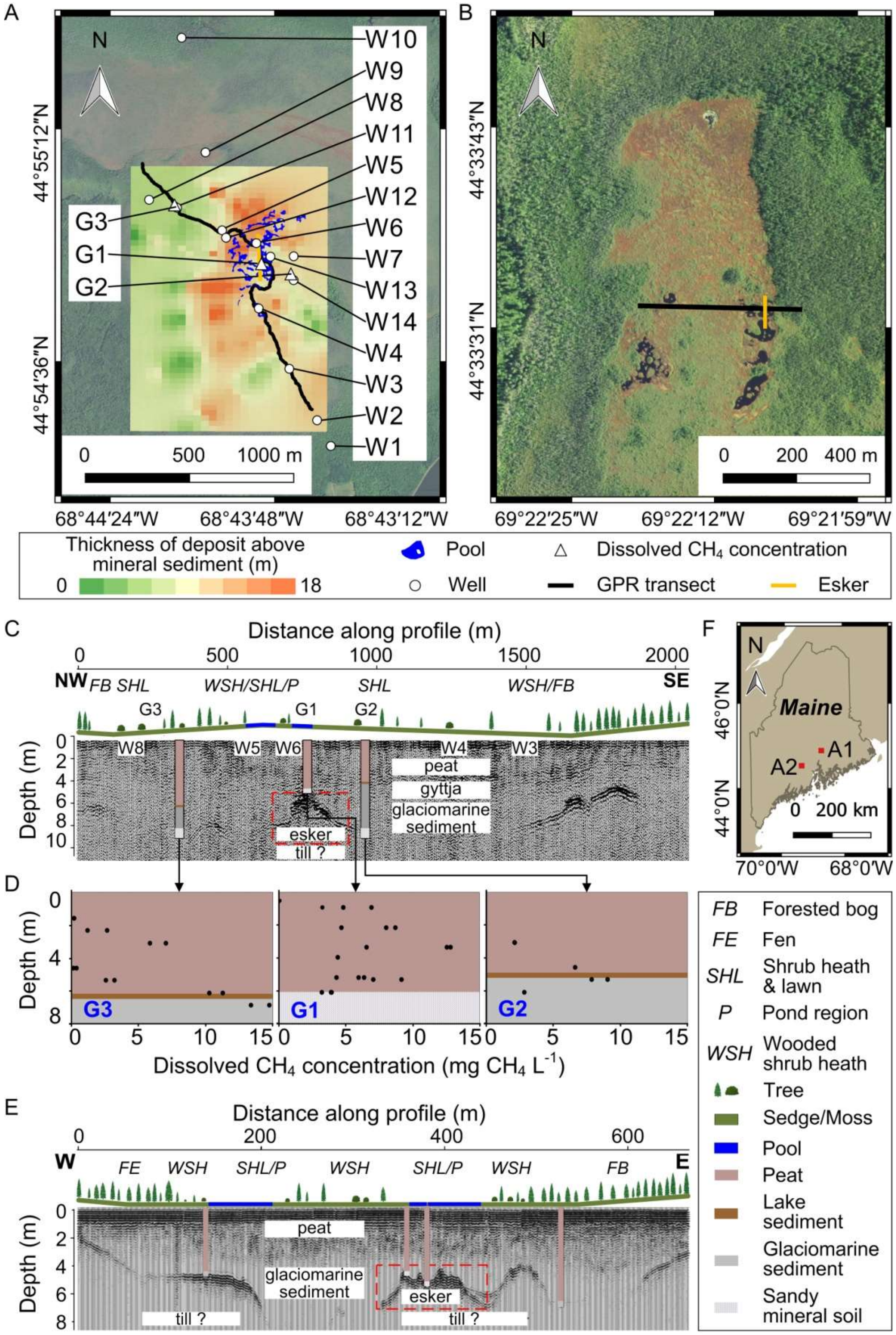

Figure 1. A: Peat thickness distribution from spatial interpolation of all GPR datasets from Caribou bog. B: Map of Kanokolus Bog (ME, aerial photograph acquired on

July 6, 2015). C: GPR profile and coring datasets across the Central Unit of Caribou bog. D: Dissolved CH_4 concentrations at different depths for three sites G1, G2 and G3 in Caribou bog. E: GPR profile from Kanokolus Bog, again showing pools coincidental with permeable mineral deposits, along with a secondary band of pools away from the mineral deposits). F: Maine, U.S.A (Caribou Bog - A1; Kanokolus Bog - A2).

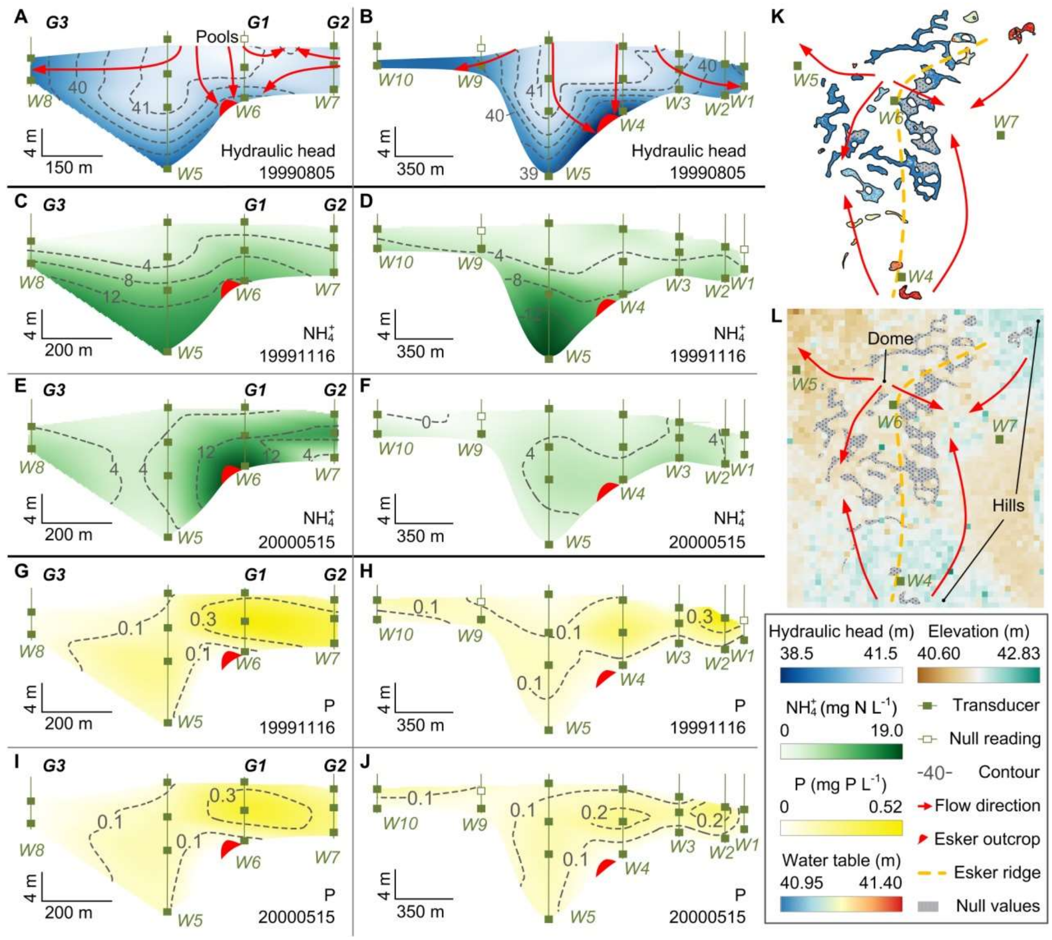

Figure 2. A-B: Hydraulic head across wells W8-W5-W6-W7 and W10-W9-W5-W4-W3-W2-W1. The flow direction in the upper layer of peat soil is nearly lateral from peatland dome center (between W5 and W6) to lagg. The flow direction in the lower layer is downward towards the esker, i.e. acting as a point sink on the bottom boundary of the peat soil. C-F: NH_4^+ concentration (mg N L^{-1}). G-J: soluble reactive phosphorous (P) concentration (mg P L^{-1}). K-L: LiDAR data mapping of the water levels of pools and topography elevation, respectively. The differences in the water levels suggest the flow direction in the upper layer is from dome center to lagg, consistent with the well data (Fig. 2A). Date is in the format: yyyymmdd.

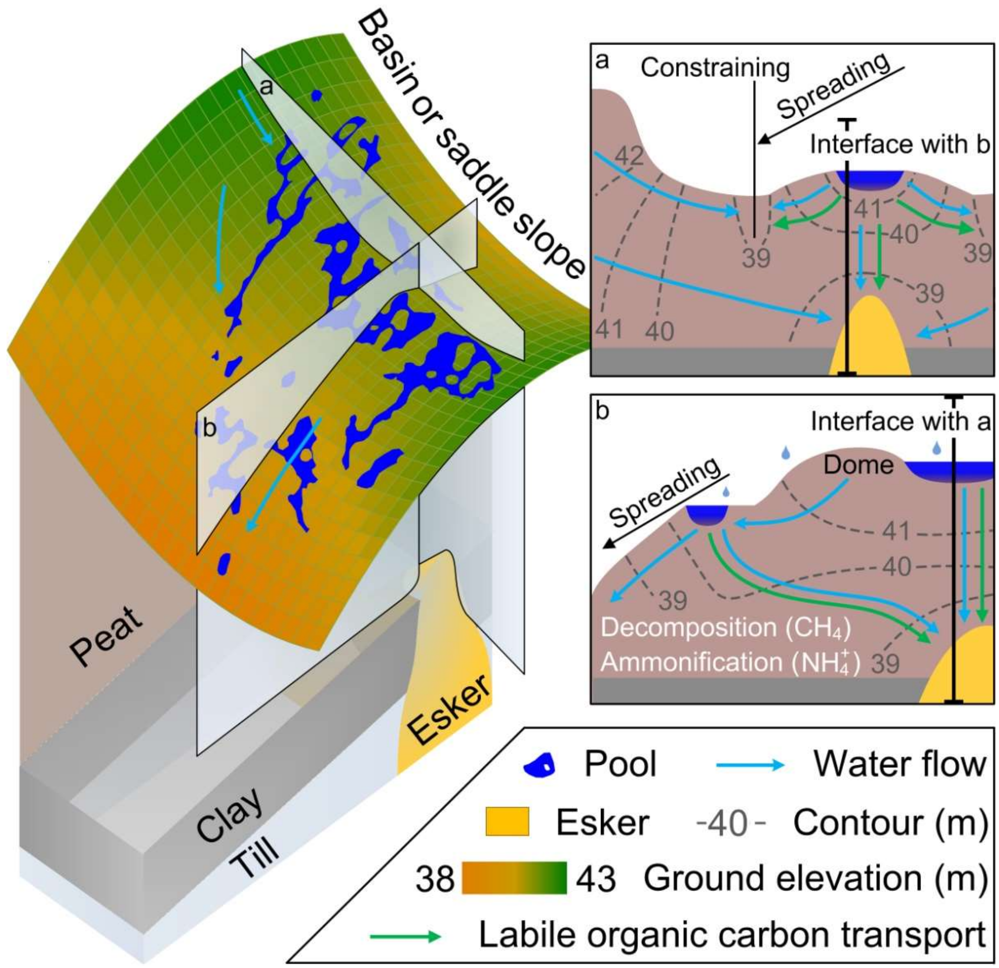

Figure 3. Conceptual model of influences of eskers on hydrology via locally downward drainage in eccentric bogs. The outcrop of the esker crest is verified from GPR profiles and direct sampling (rectangle in Fig. 2C) as shown. Water flows vertically from shallow peat soil towards the permeable esker crest, suggesting enhanced downward transport of labile organic carbon that presumably accelerates decomposition rates of methanogenesis in deep peat. a) Lateral pool spreading associated with the transport of labile organic carbon in shallow peat (lateral green arrows) is constrained by opposing groundwater flow from surrounding highlands. b) Pools spread from the outcrop of the esker crest to a point of lower elevation relative to the dome of the eccentric bog, as a result of the lateral downward transport of labile organic carbon.

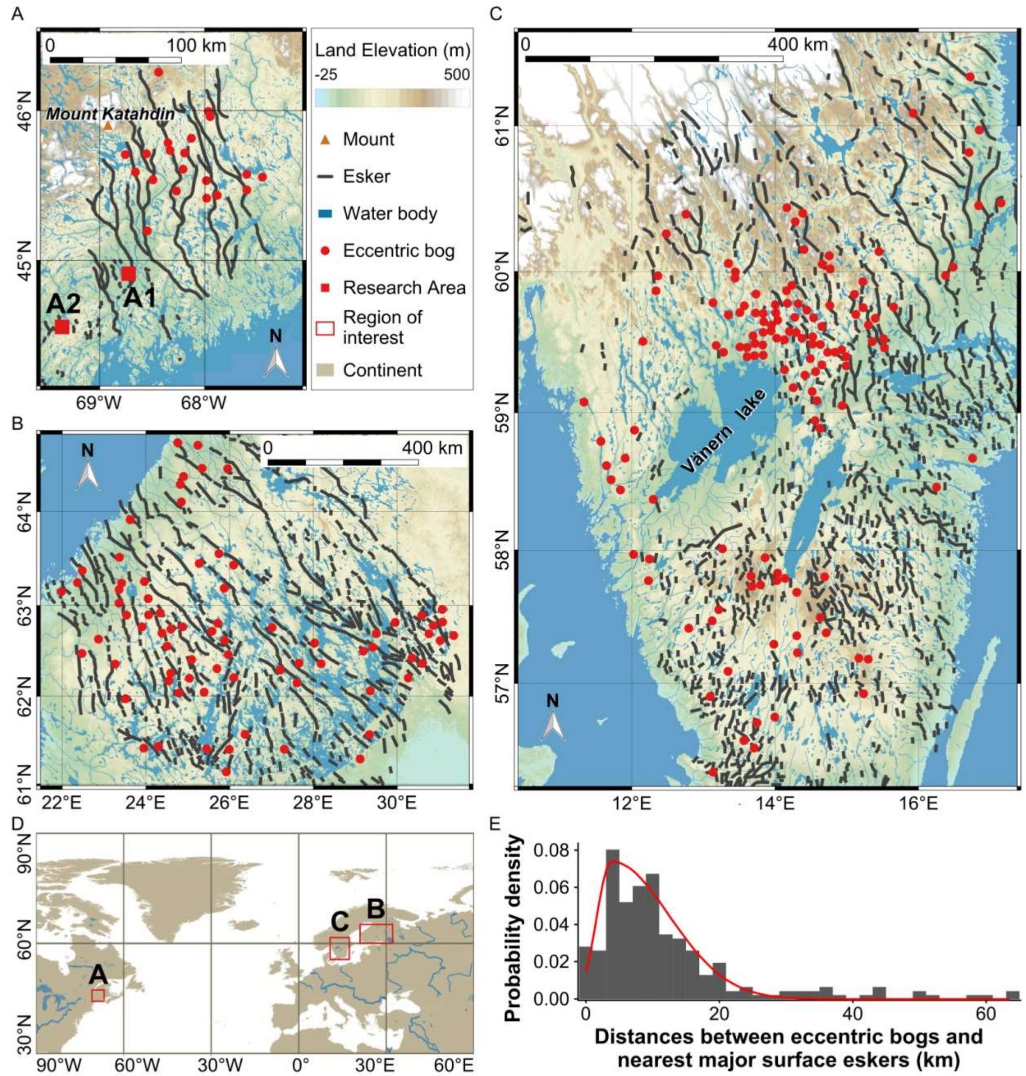

Figure 4. Examples of the spatial distribution of eccentric bogs in relation to known major eskers (Based upon data from (Shreve, 1985; Davis and Anderson, 1991; Turunen et al., 2002; Gunnarsson and Löfroth, 2009). A: Maine, northern U.S.A (Caribou Bog - A1; Kanokolus Bog - A2); B: Finland, Northern Europe; C: Sweden, Northern Europe. D: The ranges of A, B and C. E: Histogram of the distances between eccentric bogs and nearest major esker systems, showing a skewed normal distribution (Mean = 9.06 km, Std. Dev. = 5.85 km, Skewness = 2.05, see Supplementary S3).