

**Wetlands across time: exploring, understanding, and predicting their development and functions at the local and global scale**

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***EARLY WETLANDS*** Wetlands' history on Earth is highly complex and still not sufficiently explored. Their earliest origins are poorly understood, resulting in a scarcity of reliable geological records accessible for appropriate interpretation. However, available data allow us to determine the appearance of wetlands' beginnings and peat-forming conditions. The story starts with stromatolite (cyanobacteria) mounds, the oldest fossil life on Earth, dating to over 2 billion years. However, the origin of wetlands was directly related to the appearance and evolution of vascular plants and mosses and their adaptation to thrive in wet conditions ca 420 Ma (Greb et al., 2006). The oldest marshes were identified in Middle Devonian (Eifelian) 410 Ma, and the continuous peat appeared in Late Devonian 370 Ma. The onset of the first peatlands on Earth is a fascinating step into terrestrial wetland conditions, and it relates to new plant function in the peatland ecosystem as it begins the carbon accumulation process on a global scale. The initial peat arrived in the middle-late Devonian; however, peat accumulation on the full scale began in the late Devonian–Carboniferous 350-360 Ma. Different wetlands were identified at that time, resembling coastal marshes or mangroves (Greb et al., 2022).

***CARBONIFEROUS*** The Carboniferous starting ca 360 Ma was the period of peatlands, where new ecosystems emerged together, shaping new biodiversity. N America and Europe were covered with peatlands during the "Coal Age" (Thomas, 2012). Peat-forming wetlands were affecting the climate by removing CO2 and storing it for the next millions of years. Simultaneously, other wetland types, such as lakes and rivers, have developed globally. Peat accumulation stopped for millions of years with the Permian extinction (ca. 250 Ma), with no peatlands/coal known anywhere until the Middle Triassic (243 Ma) (Retallack et al., 1996; Thomas, 2012). Then, it started again later in the Mesozoic period when peatlands and other freshwater wetlands were redeveloped. Despite the global extinction, billions of tons of carbon are stored in the geological strata. Mosses also formed Carboniferous peatlands, but their fossils are rarely found (Hübers and Kerp, 2012). Phylogenetic analyses tell that Bryophyta (mosses) diverged from other land plants before the vascular plants diversiﬁed during the mid-to-late-Paleozoic (Shaw and Renzaglia, 2004).

***CENOZOIC*** Wetlands in the Cenozoic starting 66 Ma became more diverse while vascular plants adapted to the salty water, and a new taxon/engineer evolved - *Sphagnum*, diversified in Miocene which started constructing new acid peatlands just about 14 mya, coinciding with the end of the mid-Miocene climatic optimum and the appearance of peatland ecosystems in the northern boreal zone (Shaw et al., 2010). Miocene peatlands provided thick deposits of lignites (Widera, 2021). Earth wetlands history occurred in the complex geological scene of the moving continents and evolutionary processes stopped by extinctions. It led to many adaptations and various taxa that cannot be recognized today. The palaeoecology of wetlands possesses many gaps, one of which is the underrepresentation of non-peat-forming wetlands in contrast to well-preserved coal strata. Another problem is the limited information about the past biodiversity, including functional traits and evolutionary aspects of organisms constructing wetland ecosystems. However, it is intriguing how well plants adapted to peat accumulation through growth in optimally inundated conditions and effective accumulation of thick peat deposits.

***QUATERNARY*** After over 470 My of evolution, the Quaternary (starting 2,58 Ma) marked the time of the modern wetland, which existed in pulses of glacial-interglacial cycles. While time, climate, geology, and astronomic drivers were shaping them in deep time, the Quaternary provided another evolutionary product that started changing wetlands on a global scale — humans. Wetlands were destroyed and then regenerated by ice sheet expansions. In the Quaternary *Sphagnum* peatlands started to dominate in the N hemisphere peatlands. Then, 12,000 years ago, when humans started to change landscapes, wetland functions began to be modified due to deforestation and the neolithic agrarian revolution (Ellis, 2021; Ellis et al., 2021). The Holocene wetlands have been crossing tipping points related to global warming, drainage and exploitation (Fluet-Chouinard et al., 2023; Treat et al., 2024}. For example, high-resolution multi-proxy studies showed that in Europe, the most intensive changes in wetland ecosystems started in Medieval times (ca 700 yrs BP) and were initially related to deforestations that accelerated lake terrestrialization and lake-to-peatland transitions (Karpińska-Kołaczek et al., 2022). Subsequently, modern forestry ca 200 years BP affected wetlands again (Bak et al., 2024). Combining palaeoecology with experiments and monitoring provides a complete picture of changes connected with hydrological change (Jassey et al., 2018 03; Lamentowicz et al., 2019). Much stronger cooperation between scientists to better protect wetland ecosystems is now needed. In the recent two decades, scientists better understood GHG fluxes vs hydrological conditions using chamber and EC approaches {Evans et al., 2021, #180210}. However, we need a deeper understanding of palaeoecology and long-term processes reaching wetlands’ origin on Earth to predict their future during the progressing ecological crisis.

**REFERENCES**

Bak, M., Lamentowicz, M., Kołaczek, P., Wochal, D., Matulewski, P., Kopeć, D., Wietecha, M., Marcisz, K., 2024. Integrating palaeoecological, dendrochronological and remote sensing data to explore the impact of climate and forest management on a Sphagnum peatland (Tuchola Pinewoods, N Poland) 0. https://doi.org/10.5194/egusphere-egu24-546

Ellis, E.C., 2021. Land Use and Ecological Change: A 12,000-Year History. Annual Review of Environment and Resources 46, 1–33. https://doi.org/10.1146/annurev-environ-012220-010822

Ellis, E.C., Gauthier, N., Klein Goldewijk, K., Bliege Bird, R., Boivin, N., Díaz, S., Fuller, D.Q., Gill, J.L., Kaplan, J.O., Kingston, N., Locke, H., McMichael, C.N.H., Ranco, D., Rick, T.C., Shaw, M.R., Stephens, L., Svenning, J.-C., Watson, J.E.M., 2021. People have shaped most of terrestrial nature for at least 12,000 years. Proceedings of the National Academy of Sciences 118, e2023483118. <https://doi.org/10.1073/pnas.2023483118>

Evans, C., Peacock, M., Baird, A., Artz, R., Burden, A., Callaghan, N., Chapman, P., Cooper, H., Coyle, M., Craig, E., Cumming, A., Dixon, S., Gauci, V., Grayson, R., Helfter, C., Heppell, C., Holden, J., Jones, D., Kaduk, J., Levy, P., Matthews, R., McNamara, N., Misselbrook, T., Oakley, S., Page, S., Rayment, M., Ridley, L., Stanley, K., Williamson, J., Worrall, F., Morrison, R., 2021. Overriding water table control on managed peatland greenhouse gas emissions. Nature 593, 548–552. https://doi.org/10.1038/s41586-021-03523-1

Fluet-Chouinard, E., Stocker, B., Zhang, Z., Malhotra, A., Melton, J., Poulter, B., Kaplan, J., Goldewijk, K., Siebert, S., Minayeva, T., Hugelius, G., Joosten, H., Barthelmes, A., Prigent, C., Aires, F., Hoyt, A., Davidson, N., Finlayson, C., Lehner, B., Jackson, R., McIntyre, P., 2023. Extensive global wetland loss over the past three centuries. Nature 614, 281–286. https://doi.org/10.1038/s41586-022-05572-6

Greb, S.F., DiMichele, W.A., Gastaldo, R.A., 2006. Evolution and importance of wetlands in earth history, in: Wetlands through Time. Geological Society of America, p. 52. https://doi.org/10.1130/2006.2399(01

Greb, S.F., DiMichele, W.A., Gastaldo, R.W., Eble, C.F., Wing, S.L., 2022. Prehistoric Wetlands, in: Encyclopedia of Inland Waters. Elsevier, pp. 23–32. https://doi.org/10.1016/b978-0-12-819166-8.00066-9

Hübers, M., Kerp, H., 2012. Oldest known mosses discovered in Mississippian (late Visean) strata of Germany. Geology 40, 755–758. https://doi.org/10.1130/g33122.1

Jassey, V., Reczuga, M., Zielińska, M., Słowińska, S., Robroek, B., Mariotte, P., Seppey, C., Lara, E., Barabach, J., Słowiński, M., Bragazza, L., Chojnicki, B., Lamentowicz, M., Mitchell, E., Buttler, A., 2018 03. Tipping point in plant-fungal interactions under severe drought causes abrupt rise in peatland ecosystem respiration. Glob Chang Biol 24, 972–986. https://doi.org/10.1111/gcb.13928

Karpińska-Kołaczek, M., Kołaczek, P., Czerwiński, S., Gałka, M., Guzowski, P., Lamentowicz, M., 2022. Anthropocene history of rich fen acidification in W Poland - Causes and indicators of change. Sci Total Environ 838, 155785. https://doi.org/10.1016/j.scitotenv.2022.155785

Lamentowicz, M., Gałka, M., Marcisz, K., Słowiński, M., Kajukało-Drygalska, K., Dayras, M., Jassey, V., 2019 04 26. Unveiling tipping points in long-term ecological records from Sphagnum-dominated peatlands. Biol Lett 15, 20190043. https://doi.org/10.1098/rsbl.2019.0043

Retallack, G.J., Veevers, J.J., Morante, R., 1996. Global coal gap between Permian–Triassic extinction and Middle Triassic recovery of peat-forming plants. Geological Society of America Bulletin 108, 195–207.

Shaw, A., Devos, N., Cox, C., Boles, S., Shaw, B., Buchanan, A., Cave, L., Seppelt, R., 2010. Peatmoss (Sphagnum) diversification associated with Miocene Northern Hemisphere climatic cooling. Mol Phylogenet Evol 55, 1139–45. https://doi.org/10.1016/j.ympev.2010.01.020

Shaw, J., Renzaglia, K., 2004. Phylogeny and diversification of bryophytes. American Journal of Botany 91, 1557–1581. https://doi.org/10.3732/ajb.91.10.1557

Thomas, L., 2012. Coal Geology. John Wiley & Sons.

Widera, M., 2021. Geologia polskich złóż węgla brunatnego. Bogucki Wydawnictwo Naukowe, Poznań.