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Advances in Canadian wetland hydrology and biogeochemistry

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Abstract:

Wetlands comprise 14% of the land area of Canada. They have considerable impact on water storage and runoff, water quality, atmospheric exchanges of carbon, and important elements such as nitrogen. In less remote parts of Canada, wetlands have suffered from reclamation, exploitation, contamination and degradation, which have seriously impaired their ecological function. Public recognition of their environmental significance has highlighted the need for a better understanding of the hydrological processes, to better plan and manage wetland areas, restore degraded systems, and predict responses to global change. This paper reviews current hydrological research in all types of Canadian wetlands. The scope of hydrological processes discussed herein includes runoff, surface and groundwater flows, evaporation, microclimate, water balance, geochemical and solute transport phenomenon, carbon dynamics, isotope studies, exploitation and restoration. Field, laboratory and modelling studies are included. Copyright © 2000 John Wiley & Sons, Ltd.

KEY WORDS Canadian wetlands; hydrology; biogeochemistry; peatlands, review solute transport; human impacts; carbon cycling

PREAMBLE

This paper provides an overview of recent advances in wetland hydrology in Canada. To facilitate this, background information is provided to define the setting and fundamental hydrological processes. Where necessary, we have drawn upon other literature on wetlands both within and outside of Canada, to provide the context for more recent initiatives. It is important to note that research effort has not focused evenly on the various wetland classes defined below, most of it reporting on peatland systems, which represent over 90% of Canadian wetlands (Tarnocai, 1998). This review necessarily reflects that bias.

BACKGROUND

Wetlands are areas with the water table at, near or above the land surface for long enough to promote hydric soils, hydrophytic vegetation and biological activities adapted to wet environments (Tarnocai, 1980). In Canada these may be classified a bog, fen, swamp, marsh or shallow water (National Wetlands Working Group, 1997). This categorization recognizes that hydrological processes resulting from water exchanges dictated by climate and landscape factors, largely determine wetland form (National Wetland Working Group, 1997). Wetlands may be mineral–soil wetlands or peatlands. Mineral wetlands include marsh, shallow water and some swamps, and produce little or no peat, because of climatic or edaphic conditions (Zoltai and Vitt, 1995). Peatlands are wetland areas with an accumulation of peat exceeding 40 cm, and

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include bogs, fens and some swamps. Fens and swamps are mineratrophic, receiving water and nutrients from atmospheric and telluric sources, whereas bogs are ombrotrophic, receiving water and nutrients only from direct precipitation (National Wetland Working Group, 1997).

WETLAND DISTRIBUTION AND DEVELOPMENT

The Ecological Stratification Working Group (1998) has recently characterized the general climate, soil and vegetation of the Canadian wetland regions, and noted the various wetland forms therein. The regional distribution of bogs, fens, swamps, marshes and shallow water wetlands in Canada (National Wetlands Working Group, 1986) is related to latitudinal and meridianal gradients. Latitudinal effects control peat accumulation and other aquatic processes through differences in (i) productivity rates as influenced by radiation and temperature (Frolking *et al.*, 1998), and (ii) decomposition rates as influenced by moisture availability and temperature (Clymo, 1997). Moisture availability is a function of atmospheric water supply and energy available for evapotranspiration. Meridianal effects are related to the degree of continentality, hence moisture restrictions that are associated with temperature and precipitation gradients (Halsey *et al.*, 1997a). Damman (1979) noted that in eastern North America there is a northern and southern limit to bog occurrence, as they are reliant on ombrogenous water. Similar climatic and physiographic effects were noted in Manitoba wetlands (Halsey *et al.*, 1997b). Precipitation and evapotranspiration decrease northwards and limit water supply. Therefore, only limited occurrence of bogs is noted in more continental and Arctic locations. Wetlands with surface water or groundwater inflows are more common outside the range most suited to bogs. In fact, most wetland forms are derived from minerogenous settings, where water interacts with mineral soils. Plant succession in these settings is strongly related to hydrological conditions and the associated flow of nutrients and mineral elements (Klinger and Short, 1996). This may result in the accumulation of peat, which can alter recharge/discharge functions, such as occurs in the Hudson Bay lowland where marsh and fen give way to bog after a long period of succession (N. T. Roulet, unpublished data). Sometimes these processes are related to other physical changes that cause water table rises, such as the aggradation of permafrost (Vardy *et al.*, 1998), or land clearance and climatic change (Campbell *et al.*, 1997). Thermal and hydrological feedback in the Arctic perpetuates patchy wetlands, and frost heave or stream capture can cause degradation (Woo and Young, 1998). Other edaphic controls such as iron-pan formation (Lapen *et al.*, 1996) or simply peat development (Emili *et al.*, 1998), can cause changes in drainage and wetland evolution. The percentage cover of the ground surface that is peatland, however, depends strongly on local topographic and hydraulic constraints. For example (Graniero and Price, 1999a) showed that topography can explain the occurrence of 22% of the blanket bogs in a Newfoundland landscape. Nevertheless, this could be used to model bog occurrence with $>70\%$ accuracy (Graniero and Price, 1999b), because to a large extent topographic structure controls peat diagenesis. New techniques using testate amoebae (Charman and Warner, 1997) enable reconstruction of past water table regimes associated with wetland evolution.

ATMOSPHERIC PROCESSES

Soil–vegetation–atmosphere exchanges of moisture and energy essentially drive the hydrological system and all other hydrological processes. The type and distribution of wetland vegetation affect patterns of rain, snow and fog precipitation. Forested wetlands, in particular, are susceptible to complex patterns of precipitation input resulting from the disturbance of airflow by wetland tree species, radiative snowmelt characteristics (Lafleur *et al.*, 1997; Hamlin *et al.*, 1998), and interception (Dubé *et al.*, 1995). Interception by trees in a Quebec swamp was 35 to 41% of rainfall (Dubé *et al.*, 1995). Similarly, Van Seters (1999) recorded seasonal interception of 32% in a spruce bog, and 12% by timber harvest debris. Dissolved organic carbon (DOC) in throughfall and stemflow comprised up to 20% of total export (Hinton *et al.*, 1998). The geochemical signature of intercepted water can be markedly different from rainfall (Cox *et al.*, 1996), and may significantly affect wetland chemistry.

Evaporation from non-vascular *Sphagnum* mosses was shown to be well below potential evaporation (Campbell and Williamson, 1997), compared with relatively efficient latent heat transfer by (vascular) sedges (Lafleur *et al.*, 1997). Price (1996) noted that daily net radiation and evaporation flux from a *Sphagnum*-dominated surface were similar to a bare peat surface — the latter having an effective capillary water supply. Evaporation from shallow Arctic lakes was 15–70% greater than values predicted from standard evaporation maps of Canada (Gibson *et al.*, 1996). Models of evapotranspiration continue to be an important approach. The Priestly–Taylor (1972) combination model of evaporation was used successfully in a variety of settings, including shallow water (Gibson *et al.*, 1996), fen (Rouse, 1998) and bog (Price, 1996). Soil water balance models driven by precipitation and wetland evaporation were used to simulate water table response in boreal peatlands (Metcalfe and Buttle, 1999; Cuenca *et al.*, 1997), subarctic fens (Boudreau and Rouse, 1995; Rouse, 1998) and prairie sloughs. There have been recent efforts to try and improve the representation of wetlands in global climate modelling. Letts *et al.* (in press) have proposed a new set of soil parameters for peat to be included in the Canadian Land Surface Scheme (CLASS) model (Verseghey *et al.*, 1993), which have resulted in improved estimates of water table and soil temperature in wetlands. Estimates of turbulent fluxes from CLASS, incorporating the new soil climate parameters, indicate good results for fen and marsh wetlands, but non-vascular bog-type wetlands remain relatively poorly modelled (Comer *et al.*, in press).

SURFACE AND GROUNDWATER FLOW AND RUNOFF

Field studies of surface flows have provided new insight into water pathways within, and runoff from wetlands. The pathways include vertical and horizontal movement within the various layers, and sheetflow and channel flow over the surface (Taylor, 1997), as well as water exchanges with upland systems (Branfireun and Roulet, 1998; Hayashi *et al.*, 1998a). Devito *et al.* (1996) found that during seasons with large water inputs, swamps were hydrologically connected to uplands, and that overland flow dominated in the wetland. Quinton and Roulet (1998) and Glenn and Woo (1997) noted that peatlands operate as a single source area with rapid response for spring runoff when the water table exceeded the depression storage capacity of patterned wetland pools. Relatively slow responses occurred when pools became 'disconnected' into separate micro-catchments during drier periods (Quinton and Roulet, 1998). Similarly, in an Arctic hillslope high water table conditions in riparian peat offered little attenuation to drainage, but at lower water tables inter-hummock drainage pathways decreased the source area and hence drainage rate (Quinton and Marsh, 1998a,b). Comparable results were noted by Devito *et al.* (1996) who found little runoff attenuation from a headwater conifer swamp on the southern Canadian Shield. Other studies also indicated the importance of assessing storage capacity in wetlands, for example with permafrost (Boudreau and Rouse, 1995; Woo and Xia, 1996; Glenn and Woo, 1997; Woo and Young, 1998) and with beaver pools (Butler and Malanson, 1994; Hillman, 1998). Metcalfe and Buttle (1999) found that soil moisture deficits during dry years in the wetland regions of a forested boreal watershed had a significant impact on the magnitude of the subsequent spring runoff peak.

Modelling studies of surface and subsurface flows in swamps incorporating hummock terrain and organic layers have demonstrated the complexity and variability in the hydrological response to even a single precipitation input (McKillop *et al.*, 1999a). Relatively simple models based on storage and transport relationships in a series of reservoirs have been used to track stormwater in unregulated swamps (McKillop *et al.*, in press), and wetland responses around an urban stormwater framework (McKillop *et al.*, 1999b). Such models were sensitive to precipitation input and antecedent saturation (McKillop *et al.*, 1999c) as noted in field studies above.

Groundwater transport theory does not always readily suit wetland hydrological conditions because of high cation exchange capacity of organic sediments, intensive biological activity, and soil structural characteristics (Price and Schlotzhauer, 1999). Moreover, strong surface–groundwater interactions (Branfireun and Roulet, 1998) are difficult to model. Nevertheless, groundwater movement in near-surface peat layers can be most important when water inputs are from shallow soil layers (Devito *et al.*, 1996). Evaporative water loss and water table drawdown caused groundwater flow reversals in peatlands in Ontario and Sweden (Devito *et al.*, 1997), and in a drained peatland in Quebec (Van Seters, 1999). Deeper groundwater inflows were important in some fens and swamps (Devito, 1995). A Prairie slough was observed to have a deep seepage component comprising as much as 75% of the annual outputs, much of this infiltrating radially outward beneath the upland (Hayashi, *et al.*, 1998a), where evapotranspiration drives water and salt upwards (Hayashi *et al.*, 1998b). Indeed, land-use in adjacent areas plays a critical role in the water balance of Prairie sloughs (Van der Kamp *et al.*, 1999). In a study of a Lake Erie lakeshore marsh, precipitation and surface inflow were the main water inputs, except in the barrier bars where precipitation and lake water intermix (Huddart *et al.*, 1999). They found also that the width of the barrier bar, and its consequences on the hydraulic gradient, were important in regulating water and nitrate exchanges.

Relatively few micro- or meso-scale studies of surface and groundwater flow were reported. At the meso-scale, drainage through soil pipes was noted to be important in several Arctic wetlands (Quinton and Marsh, 1998c; Carey and Woo, 1999). These are known to be very important in increasing hydraulic conductivity of forest soils (Buttle and House, 1997), and blanket bogs in the UK (Sklash *et al.*, 1996). At the micro-scale, peat properties and flow dynamics have been shown to be sensitive to compression and expansion of the peat deposit, as the water pressure changes. Price and Schlotzhauer (1999) found the resultant specific storage to be larger than specific yield and only when considered together could the predicted seasonal water storage changes simulate the observed values. Schlotzhauer and Price (1999) showed that hydraulic conductivity decreased, and water retention increased as the peat underwent seasonal subsidence. These processes were important to consider in parameterizing a numerical model of groundwater flow in peat (Schlotzhauer, 1998).

SOLUTE TRANSPORT AND WETLAND GEOCHEMISTRY

Under certain conditions solutes may move quickly in surface water (Prescott and Tsanis, 1997) and in the substrate (Fernandes *et al.*, 1996). However, in peat, retardation of a conservative solute (Cl^-) was observed in a blanket bog (Hoag and Price, 1995) and in the laboratory (Hoag and Price, 1997). Hoag and Price (1997) attributes this to matrix diffusion of solute into closed pores and cellular remains of peat forming vegetation. The ability of wetlands to attenuate contaminant flows has long been recognized, and natural and artificial wetlands have been used in locations as diverse as the Canadian Arctic (Doku and Heinke, 1995), southern urban systems (Helfield and Diamond, 1997), natural marshland (Fernandes *et al.*, 1996) and abandoned mine sites (Sobolewski, 1996). Wetlands were shown to have a large capacity to remove contaminants, such as landfill leachate, for long periods (Fernandes *et al.*, 1996). However, removal is not permanent, because wetlands have a limited capacity and offer only temporary storage of contaminant inputs (Helfield and Diamond, 1997). Artificial wetlands are typically better at this because of superior control of water inputs and residence time (Mulamoottil *et al.*, 1996).

Upland–wetland groundwater interactions not only provide an important hydrological function, but also provide a critical geochemical function (Hill, 1996; Devito and Hill, 1997; Hill and Devito, 1997; Branfireun and Roulet, 1998; Branfireun *et al.*, 1998; Hayashi *et al.*, 1998b). Devito (1995) demonstrated that greater sulphate (SO_4^{-2}) retention occurred in headwater wetlands receiving groundwater rich in SO_4^{-2}. Sites with ephemeral groundwater inputs resulted in SO_4^{-2} exports after drought periods (Devito, 1995; Devito and Hill, 1997). Devito *et al.* (1998) used till thickness as an indicator of upland–wetland groundwater connectivity. They discovered high (>20 mg/l) SO_4^{-2} concentrations occurred only in streams in thin till (limited groundwater) catchments during dry summers. Branfireun *et al.* (1996) demonstrated that micro-scale groundwater recharge and discharge zones corresponded to sites of low and high pore water methylmercury (MeHg) concentrations, respectively. They also found that when the water table rose to the surface in these discharge 'hot-spot' zones, MeHg laden pore water moved into local streams. Branfireun *et al.* (1998) also used a simple catchment-scale, cascade model to demonstrate the importance of peatland presence on catchment MeHg yield. The presence of peatlands in northern watersheds has been used to explain the acidity of lakes in northeastern Alberta (Halsey *et al*., 1997a). Fens, with higher flow and hydrological connection to the surrounding watershed, were found to be more effective in altering the acidity of downstream lakes than bogs.

PEATLAND CARBON CYCLING

Peatlands represent a long-term net sink of atmospheric carbon dioxide (CO_2) and a net source of atmospheric methane (CH_4) and play an important role in the global carbon cycle. These factors are both directly and indirectly influenced by hydrology (Moore *et al*., 1998), which increases the interannual variability in carbon storage. For example,during wet summers anaerobic conditions in wetland soils reduce organic matter decomposition and stimulate CH_4 production (Moore *et al*., 1998; Worthy *et al*., 1998). During hot dry summers when there is a drop in moisture availability, peatlands can become a net source of atmospheric CO_2 (e.g. Lafleur *et al*., 1997; Schreader *et al*., 1998; Joiner *et al*., 1999) as photosynthesis is decreased and respiration loss enhanced (Schreader *et al*., 1998). It is important to note, however, that CO_2 fluxes from open water pools to the atmosphere may become sinks (Waddington and Roulet, 1996) when groundwater flow reversals can cause the pools to become disconnected from groundwater flow (Devito *et al*., 1997). The resulting lower water table position may permit vegetation to colonize former pool areas, leading to higher CO_2 fixation. Groundwater flow reversals (Devito *et al*., 1997) have also been linked to the episodic release of dissolved CH_4 in peat pore waters (Waddington and Roulet, 1997).

The concentration of dissolved methane, inorganic and organic carbon within peat pore water, therefore, is also a function of the seasonal patterns of production and decomposition (Waddington and Roulet, 1997). The mass flux of dissolved carbon in groundwater flow can also be significant in both the redistribution of dissolved carbon within peatlands and in the export to surrounding landscapes (Waddington and Roulet, 1997), especially during baseflow conditions (Schiff *et al*., 1997). Export of DOC during storms has been shown to dominate the total DOC export in autumn and winter in two Precambrian Shield catchments. Moreover, Schiff *et al*. (1997) found that the relative proportions of old groundwater and young surface water DOC changed seasonally in response to changes in carbon cycling dynamics and hydrological flowpaths. Lower DOC export and concentrations in wetlands occurred during successive storms as DOC was flushed from riparian areas (Hinton *et al*., 1998). Seasonality in surface runoff from wetlands has also been shown to alter the composition of particulate organic matter inputs to streams (Hill and Brooks, 1996).

HUMAN IMPACTS ON WETLANDS

Canadian wetlands are experiencing direct (e.g. drainage) and indirect (e.g. climate change) impacts. Wetlands are vulnerable to climate change because of the delicate balance between precipitation and evaporation that controls them (Clair, 1998), which could lead to shifts in wetland distribution, extent and function (Larson, 1995). Greater seasonal water deficits will affect water tables and runoff (Clair and Ehrman, 1998). Although winter snowmelt may full recharge a wetland, it will remain at its capacity for a shorter time under a warmer climate (Rouse, 1998).

A $2 \times CO_2$ climate warming scenario will likely lead to a greater summer water deficit in northern peatlands (Rouse, 1998). Because storage of carbon in peatlands is sensitive to changes in hydrology, dramatic changes in the peatland carbon cycling are expected (Moore *et al*., 1998). A lower water table position will probably result in increased respiration (Waddington and Roulet, 1996), lower CH_4 fluxes (Roulet and Moore, 1995; Waddington *et al*., 1996) and lower DOC flux (Moore *et al*., 1998). However, recent research suggests that given the complexity of changes in the hydrology of some regions, different responses are possible. Waddington *et al*. (1998) predict that some peatlands may increase carbon storage under a $2 \times CO_2$ climate scenario. A hydrological control on net ecosystem productivity suggests that present-day ‘wet’ wetlands may undergo a net increase in carbon storage as net ecosystem production is enhanced in presently unvegetated pools. Transitions from open water to fen have been shown to coincide with early Holocene warm periods (Vardy *et al*., 1998). Emissions of CH_4 may remain high or increase in regions where the peat surface adjusts to change in water storage (Price and Schlotzhauer, 1999) and where water levels remain high with the formation of collapse scars from melting permafrost (Liblik *et al*., 1997). Hinton *et al*. (1997) have noted that because of the variability of the relationship between DOC export and stream discharge, the effects of climate change on DOC export are unclear.

Direct impacts occur when peatlands are drained for forestry, agriculture, peat harvesting or land reclamation. Drains provide a pathway for water to exit peatlands even when the water table is low (Prevost *et al*., 1997), thereby lowering the water table and CH_4 emissions (Roulet and Moore, 1995). Drainage also increased summer baseflow, suspended sediments, maximum stream temperature, specific conductivity, pH, and NH_4^+, NO_3^-, Ca^{2+}, Mg^{2+} and Na^+ stream concentrations (Prevost *et al*., 1999). The consequences of the increased soil aeration in an Alberta peatland (Silins and Rothwell, 1999) was enhanced soil oxidation (Waddington and Roulet, 1996) and subsidence associated with the loss of buoyancy of the overlying material as the water table dropped. Although both processes decrease water storage capacity, they also have the effect of increasing soil bulk density, and therefore decreasing saturated and unsaturated hydraulic conductivity, and increasing water retention (Silins and Rothwell, 1998). The higher water retention capacity caused a rise in the thickness of the zone of capillary saturation (Silins and Rothwell, 1999). Closer ditch spacing may result in better drainage, but soil moisture variability was shown to be greater within specified drain spacings than between (Rothwell *et al*., 1996).

Forest harvesting typically follows drainage. Site disturbance during the frost-free season transfers more humified peat to the surface, which along with soil compaction can cause a water table rise. This had less effect on the water table, however, than removing trees (Groot, 1998). By reducing site interception, harvesting caused a water table rise of about 20 to 50 cm (Dubé *et al*., 1995).

Peat harvesting is an important industry in Canada and Europe (Lapalainen, 1996). However, the hydrology (Price, 1997), hydrochemistry (WindMulder *et al*., 1996) and ecological functions (Lavoie and Rochefort, 1996) are seriously impaired. Consequently, water management strategies are required to ameliorate the hydraulic conditions. Blocking drainage ditches can restore the water balance (Price, 1996), but mining the upper layer destabilizes the water table sufficiently that water tension near the cutover surface exceeds the capacity of (recolonizing) *Sphagnum* mosses to draw moisture from the soil (Price, 1997). Consequently, *Sphagnum* becomes desiccated and may die (Sagot and Rochefort, 1996). Restoration, therefore, may require more invasive management, such as the use of surface microtopography and mulches (Price *et al*., 1998), surface reprofiling (Bugnon *et al*., 1997), passive seepage reservoirs (LaRose *et al*., 1997; Schlotzhauer and Price, 1999), or pumped seepage reservoirs (Price, 1998). The capacity of passive seepage reservoirs to ameliorate surface conditions was modelled numerically by Schlotzhauer (1998), who found surface moisture conditions were sensitive to unsaturated hydraulic conductivity.

Hydroelectricity reservoir development (flooding) can have a large impact on wetland hydrology and geochemical cycling. Hydroelectric flooding results in an increase in peatland temperature and anaerobic conditions, leading to an increase in CH_4 production rates (McKenzie *et al*., 1998), MeHg production (Kelly *et al*., 1997) and emissions of greenhouse gases (Kelly *et al*., 1997). Pietroniero *et al*. (1999) used remote sensing as a tool to monitor hydrological conditions in the Peace–Athabasca Delta caused by flow regulation. Major floods in the delta have not occurred since a major tributary has become regulated, and the absence of significant ice-jamming since 1974 (Prowse *et al*., 1996). The use of rock weirs and artificially induced ice-jams is being tested as a remedial tool to flood the highly productive perched basin wetlands (Prowse and Demuth, 1996).

Although not a human impact, beaver dam construction has similar impacts as hydroelectricity reservoir development. Beaver dam construction (Woo and Waddington, 1990) increases water storage (Roulet *et al*., 1997) and emissions of greenhouse gases (Roulet *et al*., 1997; Bourbonniere *et al*., 1997), and dam failure can result in episodic water release. Hillman (1998) demonstrated that a flood wave from such an extreme event, was attenuated to 6% of the estimated upstream flood peak as it flowed through a downstream wetland.

CONCLUSIONS

Relatively little work on the regional distribution and development of peatland forms in Canada has occurred recently, because of the difficulty of assembling reliable data at this scale, and because of the broad assumptions that necessarily underlie such work. Nevertheless, there has been confirmation that regional recharge and discharge patterns can dictate wetland form, for example in the Hudson Bay Lowlands. Other research has made refinements in defining the geographical limits of peatland form and related climatic variables. Progress has also been made in understanding topographic constraints and edaphic processes, but based on a much smaller spatial scale. Overall, there has been a tendency for more detailed studies at the local scale where the range of conditions and research costs are generally smaller.

Research into atmospheric processes has been dominated by gas-flux studies, many of these associated with the BOREAS experiments near Thompson, Manitoba. In particular carbon dynamics has become an important issue, more so since the Kyoto Protocol agreement. Recent research has given us a better understanding of the effects of seasonal climate and surface type on flux variability, but we still lack sufficient understanding of the subsurface processes, ranging from microscale gas production and transport, to the effect of macroscale groundwater flow processes.

Progress has been made in identifying and describing hydrological phenomena from runoff and surface flows to groundwater processes in a wide variety of wetland settings. Recharge–discharge relationships and connection to upland areas have been shown to be critical to understanding gas fluxes, nutrient flows and transport of various dissolved constituents in wetlands. More research is needed to identify their spatial and temporal variation, and, for example, their link to seasonal flow reversals in peatlands. Runoff from many wetland types has been shown to be strongly affected by macropores, yet few studies have examined this above the plot or slope scale. At the microscale level, flow and transport processes relating to matrix diffusion, peat volume changes and geochemical transformations have been recognized, but are not generally integrated into hydrological models or interpretation of hydrological data.

Wetlands are recognized as being important in issues relating to climate change. In addition to being sensitive to climate in an ecological capacity, they play an integral role in climate change through feedback mechanisms. Canadian peatlands represent a significant portion of the global terrestrial carbon reservoir. Its stability is strongly reliant on the hydrological processes that control the carbon balance of a peatland. More direct human impacts on wetlands resulting from drainage for forestry or peat mining result in a significant release of carbon. Approaches to wetland restoration have forged collaborative study of hydrological, biogeochemical and ecological processes. Biological and mechanical changes to peat soil after disturbance discourage regeneration of peat-forming plants, thus carbon accumulation.

Continued efforts in the characterization of water and nutrient pathways in all types of wetlands are needed to improve our understanding of the processes operating at all scales in natural systems. This has obvious important in predicting impacts on natural systems, but it is also important for constructed wetlands, which hold promise for improving water quality. Efforts to manage wetlands in a resource context, either for wildlife, timber, peat products, or water quantity and quality will become increasingly important, especially in view of current funding restrictions. Ecosystem management requires that we integrate responses beyond the soil and plot scale, to reasonably encompass all hydrological processes of the system. Although many modelling studies have done just this for water quantity and quality, and atmospheric responses, many barriers remain, because of weaknesses in understanding the smaller scale processes resulting from mechanically unstable and geochemically complex soils. This includes hydraulic, mechanical and biotic processes that affect system parameterization. Many of these processes are too difficult to control for in the field, so laboratory experiments provide an important base. It is critical that we take careful steps to ensure that laboratory results are applicable to both field and modelling studies.

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