Peatlands and Global Change: Response and Resilience

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Abstract

Peatlands are wetland ecosystems that accumulate dead organic matter (i.e., peat) when plant litter production outpaces peat decay, usually under conditions of frequent or continuous waterlogging. Collectively, global peatlands store vast amounts of carbon (C), equaling if not exceeding the amount of C in the Earth's vegetation; they also encompass a remarkable diversity of forms, from the frozen palsa mires of the northern subarctic to the lush swamp forests of the tropics, each with their own characteristic range of fauna and flora. In this review we explain what peatlands are, how they form, and the contribution that peatland science can make to our understanding of global change. We explore the variety in formation, shape, vegetation type, and chemistry of peatlands across the globe and stress the fundamental features that are common to all peat-forming ecosystems. We consider the impacts that past, present, and future environmental changes, including anthropogenic disturbances, have had and will have on peatland systems, particularly in terms of their important roles in C storage and the provision of ecosystem services. The most widespread uses of peatlands today are for forestry and agriculture, both of which require drainage that results in globally significant emissions of carbon dioxide (CO_2), a greenhouse gas (GHG). Climatic drying and drainage also increase the risk of peat fires, which are a further source of GHG emissions [CO_2 and methane (CH_4)] to the atmosphere, as well as causing negative human health and socioeconomic impacts. We conclude our review by explaining the roles that paleoecological, experimental, and modeling studies can play in allowing us to build a more secure understanding of how peatlands function, how they will respond to future climate- and land-management-related disturbances, and how best we can improve their resilience in a changing world.

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1. WHY PEATLANDS? WHY PEATLANDS AND GLOBAL CHANGE?

Walk across the soggy surface of any bog, fen or swamp and you are walking across one of the planet's most carbon (C) dense terrestrial ecosystems. Containing between 500 and 700 billion tonnes (Gt = Pg) of C on only 3% of the Earth's land surface (1), these peat-forming systems collectively store more C than that contained in the world's tropical rainforest biomass [360 Gt (2)] and more than half of the C in the atmosphere [750 Gt (3)]. Dig a hole and put your hand below the surface and you are reaching down into one of the most important long-term C reserves on the planet that has formed as an accumulation of layer upon layer of C-rich peat over hundreds or thousands of years. However, the important functions of peatland ecosystems in the global C cycle and in climate regulation often go largely unrecognized, as does their capacity to be shaped by and retain a record of environmental change.

Peatlands deliver a range of beneficial but often undervalued ecosystem services including C storage and sequestration, water regulation, biodiversity protection, natural risk mitigation, food and fuel, and recreation opportunities (**Figure 1**). In addition, they host many unique and rare habitats and species, and the layers of accumulated peat contain an archive of information that is valuable in deciphering past changes in climate, vegetation, and human activity.

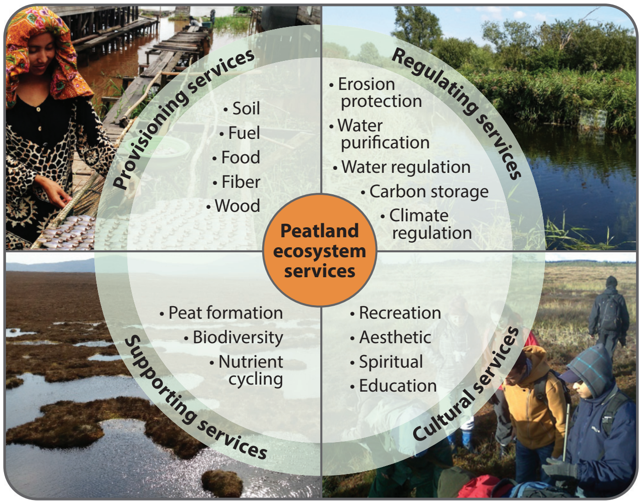

Figure 1

The range of ecosystem services provided by intact peatlands. Photos by Sara Thornton (provisioning services) and Susan Page (all others).

Peat can be defined as a type of soil that consists of partially decomposed organic material, derived mostly from plants, that has accumulated under conditions of waterlogging and oxygen deficiency. In temperate, boreal, and subarctic regions, where low temperatures reduce the rate of decomposition, peat is formed from the remains of various mosses, grasses, sedges, shrubs, and even trees. In the humid tropics, it is mostly formed from rainforest trees under near constant conditions of high humidity, rainfall, and temperature. Peat has an elevated organic matter content, typically greater than 30% (dry weight), which ensures a high C content (in general approximately 50% dry weight of the organic material). It also has a low bulk density owing to the intrinsic low mass and organic nature of the soil-forming parent material.

Peatlands are landscapes that have naturally accumulated layers of peat on the land surface. By most definitions, the peat thickness must exceed 40 cm, but there is also C contained in shallower organic deposits where peat is currently accumulating or has the potential to form if peat-forming plants are present. Peatlands can prove resilient to gradual, long-term changes in climate and hydrological conditions, but they also respond rapidly to more profound, short-term anthropogenic disturbances. C storage is ensured as long as the peat remains waterlogged; however, any disturbance that results in lowering of the peat water table allows oxygen to enter the peat column, disturbing the balance between peat accumulation and decay and resulting in oxidative microbial degradation of the peat and release of stored C to the atmosphere. Peatlands have been described as analogous to living organisms because they grow, mature, and may even die, the latter often at the hands of humans (4).

Most of the world's peatlands have formed since the most recent ice age, i.e., over the past 10,000 years (1), but during this time period there have been changes in both their location and rates of peat accumulation, reflecting shifts in climatic and other environmental controls, for example sea level. Present-day peat accumulation and degradation rates are still controlled largely by climate but with an increasing role played by direct human activity. At a low level of intensity, the exploitation of a peatland's resources by people may be considered sustainable, as long as the hydrological functioning of the peatland remains more or less natural and net C accumulation is maintained. But more intensive uses that require, for example, drainage result in the loss of the peatland C storage function and, critically, the release of greenhouse gases (GHGs) to the atmosphere, which contributes to global warming. Although most of the world's peatlands remain in a natural state and unaffected by anthropogenic drainage or other disturbances, they are such C-dense ecosystems that drained peatlands are responsible globally for approximately 10% of all GHG emissions from the agriculture, forestry, and other land-use sectors (5, 6). As a result, these ecosystems have started to receive increased attention from not only science but also policy communities, with a particular focus on safeguarding or re-establishing those peatland functions that relate to the protection of C storage and climate change mitigation.

This review explores the contribution that peatland science can make to the study of global environmental change. Not only do the thick layers of peat provide an opportunity to investigate records of past environmental transformations and controls on peat formation, but their large reservoir of C plays a critical role in contemporary global change processes. We explain why an understanding of how peatlands have responded to past environmental and climatic changes, how they function today, and how they will behave under future global changes are vital areas of study of increasing relevance to today's environmental challenges.

2. GLOBAL PEATLANDS: DIVERSITY AND DIFFERENCE

Peatlands occur on every continent and take many different forms from the tropics to the circumpolar regions. The largest area of peatland occurs in the Northern Hemisphere in the temperate, boreal, and subarctic climatic zones where there are extensive landscapes covered in bog, fen and, at high latitudes, frozen peatlands making up approximately 64% of all peatlands by area (4). These northern peatlands cover an estimated 3.6 million km^2 and have a C pool of between 400 and 600 Gt (1). In the tropics, most peat forms beneath forested swamps in lowland subcoastal settings, with some localized peat formation in coastal mangroves and at high altitudes. Tropical peatlands cover no less than 0.4 million km^2 with a C pool of at least 80 to 90 Gt (7). This section introduces the diversity of global peatland ecosystems, emphasizing some of the differences in peatland form and vegetation between climatic zones, while also highlighting similarities.

Northern peatlands comprise a wide variety of types, from raised and blanket bogs to nutrient-rich floodplain fens. The characteristic vegetation of these various types reflects differences in their water supply, geomorphological setting, and climate. Rydin & Jeglum (8) provide a comprehensive review of the different peatlands found at mid- to high latitudes. A fundamental distinction is often made between bogs and fens. The former derive all of their water from precipitation and are, accordingly, called ombrotrophic (Greek for cloud- or rain-fed) peatlands. In contrast, a portion of the water supplying fens contains dissolved minerals after being in contact with nonorganic soils or rocks, giving rise to the term minerotrophic. Fens are supplied by a combination of rain water and soil-, ground-, and river water. Bogs often comprise a large mound or dome of peat—hence the name raised bog—and the surface at the center of the dome may be several meters higher than the surface at the margin, several hundred meters or even several kilometers away. Raised bogs are often patterned with pools, *Sphagnum*-moss-covered hollows, *Sphagnum* lawns, and hummocks or ridges containing *Sphagnum* and dwarf shrubs and even coniferous trees (see also 9) (**Figure 2**). Sedges from the genus *Eriophorum* may also be common in some of the wetter microforms (pool edges, hollows, and lawns). In extensive peatland landscapes such as the huge peatland complex in the James Bay Lowlands of Canada, which at 325,000 km^2 is the second largest area of peatland after the Western Siberian Lowlands, there is a mosaic of different types of bog and fen, with each type merging into the other depending on position in the landscape.

Figure 2

Aerial view of Siikaneva mire in central Finland; a characteristic northern raised bog and fen complex. Photo credit Lentokuva Vallas.

In some parts, the peatlands are ombrotrophic, whereas in others, where the precipitation input is supplemented by minerotrophic water from local slopes, so-called poor fens may occur. Along the bog–poor fen gradient, there are subtle changes in the vegetation, with sedges from the genus *Carex* becoming more abundant, coupled with less acidic water held within the peat (pH of 4–5.5 compared with a pH in the range of 3.5–4.2 that is more typical of bogs). In fens where there is a greater input of ground water and where that ground water is base rich (rich in bases such as calcium and with a pH of up to 7), the vegetation is very different from that found in bogs; if the macronutrient content of the minerotrophic water feeding the fen is low, the vegetation may comprise a highly diverse (rich) range of herbaceous species and brown mosses. Some fens are wooded, containing species such as *Alnus glutinosa* that are adapted to waterlogging. These are typically common in floodplains and may form thick layers of woody peat that has a greater affinity with the wooded peats found in tropical peatlands than the bryophyte-rich peats of bogs. Northern peatlands may also contain sedge- and grass-rich peats. Some bogs naturally may have a rather low cover of mosses, and layers of *Eriophorum* peat are common in bogs found across northwest Europe, for example. Grass-rich peats often comprise the remains of common reed—*Phragmites australis*—which can form monocultures in some floodplain fens. Areas dominated by tall sedges from genera such as *Cladium* can also form extensively in floodplains and give rise to thick peat deposits, sometimes in association with *Phragmites*. At the highest latitudes, peatlands may be affected by permafrost, which is an additional influence on water supply to the growing surface of the peatland. The presence of ice in areas of discontinuous permafrost can also lead to distinctive peatland types such as subarctic palsa mires that undergo characteristic cycles of change from small mounds with bog vegetation to collapse features with fen vegetation (10). Clearly, northern peatland is a rather limited term for the great array of different peat-forming ecosystems that are found at mid- to high latitudes.

In the tropics, the largest extent of peatland occurs in Southeast Asia, in Indonesia, Malaysia, Papua New Guinea, and Brunei; this accounts for 56% of the global tropical peatland area and 77% of tropical peat C storage (7). The peatlands of this region typically form large domes located behind mangroves along coastal plains and between major rivers. During their development, the peat surface of these systems became increasingly elevated above the surrounding land. As peat accrued, rainwater replaced tidal and riverine flood waters as the principal water source, and the domed peat surface (see, also, raised bog, above) became increasingly nutrient poor and acidic. The peat-forming vegetation is a type of tropical rainforest—peat swamp forest—that, despite the stressful environmental conditions of anoxia, acidity, and low nutrient availability, has a relatively high tree species diversity (**Figure 3**) and provides a habitat for noteworthy animal species, including Bornean and Sumatran orangutans (*Pongo pygmaeus and P. abelii*), Sunda clouded leopards (*Neofelis diardi*), and, in the peat-stained river waters, habitat-specialist species of blackwater fish. There is typically a zonation of plant communities across the peat dome: Marginal, tall mixed swamp forest is replaced by increasingly smaller-stature, lower-biomass pole forest communities reflecting the gradient of decreasing nutrient availability and increasing duration of waterlogging toward the dome center (11). The peat is dominated by woody remains; trunks, branches, and leaves are incorporated at the peat surface, but there are also significant inputs from dead root material below ground. Average peat thickness is 5 to 7 m, but in some locations can exceed 10 or 15 m. A low ash (inorganic) content (typically less than 2%) and high C content (50–60% dry weight) combined with the considerable area and volume of peat in Southeast Asia means that these ecosystems are highly dense C stores. In Indonesia, some 74% of the total C stored in the country's forest biomass and soils can be attributed to peatland ecosystems (7).

Analogous domed peatlands have been described from other parts of the humid tropics. Along the Caribbean coasts of Central and South America, peat-forming wetlands are characterized by

Figure 3

Tropical peat swamp forest, Sabangau peatland, Central Kalimantan, Indonesia.

vegetation zones that mirror increasing peat thickness and decreasing nutrient availability (e.g., 12, 13). Some, such as the peatlands in Panama, have developed as back-swamps behind coastal mangroves (14), whereas others, for instance in the valley of the River Orinoco in Venezuela, have formed in deltaic fresh and brackish water settings (15). Tropical peatlands in South America are also quite varied systems that have developed in river floodplains under the influence of regular seasonal flooding by the Amazon River and its tributaries. In Peru, the diversity ranges from nutrient-rich to nutrient-poor systems with some of the thickest peatlands, up to 8 m deep, having developed initially under minerotrophic conditions with regular inundation by river floodwaters through to ombrotrophic, shallowly domed forms, dependent entirely on precipitation for water and nutrient inputs to the peat surface (16, 17). This diversity of environmental conditions for peat formation is reflected in the vegetation, which varies from palm-dominated (*Mauritia flexuosa*) and open swamp communities at minerotrophic sites to mixed hardwood swamp forests on ombrotrophic peats, with distinct vegetation zones on larger domes (18). There has been limited investigation of the floristic diversity of Amazonian peatlands, but initial findings indicate low tree species diversity and a lack of endemic species, perhaps as a consequence of environmental instability over millennial timescales (19).

On the African continent, extensive peatlands are a feature of the central Congo basin, although they have only recently been described and are far less studied than those in either Southeast Asia or the Americas. They encompass a considerable land area estimated at 146,000 km^2 and, as such, represent the single largest tropical peatland complex in the world, with an estimated C store of 30 Gt (20). These flat, rain-fed, nutrient-poor peatland systems occupy large, shallow basins between rivers. The peat achieves a maximum thickness of 6 m with a vegetation cover of either mixed-species hardwood swamp forest or palm swamp, dominated by *Raphia laurentii* (20). The exciting recent discovery of these remote peatlands increases the global assessment of the tropical peat C store from 89 Gt (7) to approximately 120 Gt. Elsewhere in tropical Africa, lowland peat-forming systems are more limited in extent and usually associated with *Papyrus* swamps fringing lake basins and rivers. Not all of these swamps form peat; many have strongly inorganic sediments and precise information on the extent of peat-forming swamps and their contribution to regional C storage is limited.

Peat is found also in tropical upland environments where the climate is cool and temperate or even alpine in character. In Southeast Asia, peatlands occur above 1,000 m on the island of New Guinea, with peat becoming the dominant substrate above 3,000 m (21). The vegetation comprises swamp forest at lower levels, replaced by grass and sedge communities at greater altitude. In South America, comparable peatlands are a feature of the alpine zone of the Andes Mountains (e.g., 22). These small, headwater wetlands can play an important role in providing a water supply for downslope agriculture. Typical vegetation comprises low growing cushion- and rosette-forming vascular plants and *Sphagnum* spp. On the African continent, montane peatlands occur at elevations above 2,000 m in, for example, Uganda, Kenya, Burundi, and Rwanda (e.g., 23), but there are very limited accounts of their biodiversity, C storage, and ecosystem service provision.

A further setting for tropical peat formation is in coastal mangroves where there is limited or no supply of mineral material into the mangrove system, for example on oceanic islands. Here the sediments are derived entirely from the remains of the mangrove vegetation, which accumulate slowly under conditions of waterlogging and low nutrient supply. Along the Central American and Caribbean coastlines, these peats have accrued to depths of 10 m or more (24, 25).

3. PEATLAND FUNDAMENTALS: PEAT-ENVIRONMENT RELATIONSHIPS

Despite their great variety in shape, vegetation type, and soil pore-water chemistry, all peatlands share some fundamental features. All comprise a peat deposit that has formed because the addition of organic matter to the peatland has exceeded the loss of organic matter over long periods of time (decades to millennia), allowing the body of peat to build up. The amount of peat within a peatland will depend on the age of the peatland and the rate at which new peat forms. Conceptually, the organic matter mass balance of a peatland is very simple. Additions of organic matter occur mainly in the form of litter produced by the peatland vegetation, whereas losses occur through the decay of this litter and the peat it forms.[1] Products arising from this decay include carbon dioxide (CO_2) and methane (CH_4) [in both the free (gaseous) and dissolved phases] and dissolved organic compounds that leave the peatland via the water flowing from it (see, also, 26). Organic matter may also be lost more directly via peat erosion. It is common to conceptualize this mass balance in terms of C; **Figure 4** shows the C balance of a peatland, with the principal components of the balance shown in bold. The C content of organic matter, by mass, is typically approximately 0.5 (or 50%).

A question often asked is, Why is there peat (or why do peatlands form)? From the foregoing, we may conclude that peat forms whenever C inputs to a peatland exceed C outputs. This simple condition may arise in a variety of circumstances. In temperate and boreal peatlands it is, in general, the "failure" of decay that leads to peat formation; even relatively low rates of above- and

[1]A distinction may be made between litter and peat. Litter may be defined as unaltered dead plant remains, whereas peat is litter that has undergone a degree of decomposition. In practice, such a distinction tends to be arbitrary—for example, well-preserved layers of plant remains may be found at depth within a peat deposit—and it would be odd to single out such layers as being in some way "non-peat" while the layers above and below them are classified as peat.

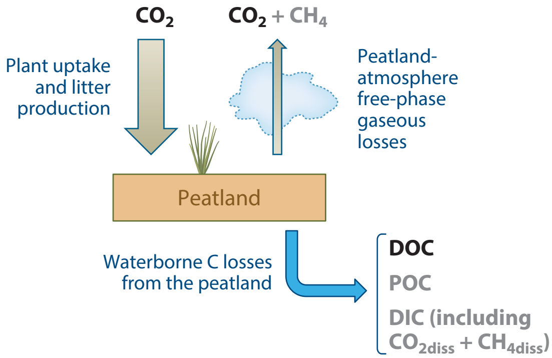

Figure 4

The principal components of the peatland carbon (C) balance. Atmospheric CO_2 is taken up by plants and the C is stored as plant tissue. The decay of the plant litter and peat making up the peatland produces both CO_2 and CH_4. These are lost mainly in the free-phase (gaseous) form from the peatland, but they may be lost also in the dissolved form in water flowing out of the peatland. Other waterborne losses of C are dissolved organic carbon (DOC), particulate organic carbon (POC), and dissolved inorganic carbon (DIC) (the latter includes dissolved CO_2 and CH_4). Very minor components such as DOC additions via rainfall are not included here. Key components of the C balance are indicated in black text; relatively minor components are in gray text.

belowground litter production can be sufficient to outstrip the depth-integrated decay through the peat profile such that peat accumulates. In tropical peatlands the picture is less clear because of a paucity of studies; decay rates are generally high but are apparently offset by even higher rates of litter production. For a temperate northern bog, Belyea & Clymo (9) found that mean rates of litter production are *c.* 0.5 kg m^{-2} $year^{-1}$. This figure represents the combination of aboveground (leaves and shoots) and belowground (roots and rhizomes) production and may be exceeded in tropical peatlands by a factor of two or more for aboveground litter production only (see, also, 27). However, much aboveground production in tropical peats—the leaves especially—is readily decomposed and does not contribute much to the makeup of the peat (28). Although overall litter production may be dominated by the aboveground component in the tropics, it may actually be the belowground component—fine roots in particular—that is critical in peat formation. This certainly seems to be the case for Southeast Asian peatlands (29) and Caribbean mangrove peats (25). Nevertheless, as noted by Sjögersten et al. (27), the picture is unclear and decay rates of different litter components in tropical peatlands appear to be highly variable.

Decay of organic matter is often expressed using a decay constant—k—that, over short periods, represents the proportion of mass lost. Example units for k are day^{-1} or $year^{-1}$. From an initial mass of organic matter, such a description gives an exponential decline in the mass remaining over time (30, 31). Decay rates expressed using k vary with both the type of material making up the organic matter and the environmental conditions such as the degree of anoxia (or the moisture content) of the peat and its temperature. On the basis of a limited dataset, Sjögersten et al. (27) note that the leaf component of litter in tropical peatlands has oxic or aerobic k values as high as 5 $years^{-1}$ (0.014 day^{-1}; as such, an initial mass of leaf litter would have a half-life of approximately 51 days), but k values for leaves can be as low as 0.1 $year^{-1}$. For branches and roots, the k value is highly uncertain; only one study has measured the k of these components in situ (28), and in both cases $k < 1$ $year^{-1}$. Moore et al. (32) estimated in situ oxic k values for a range of litter types typical of temperate bogs and fens. They found that the values varied between 0 and 0.37 $year^{-1}$; although overlapping with the range found in tropical peats, k for northern peatlands appears generally to be much lower.

There has long been interest in simulating or modeling peatland C accumulation. A notable early model was that of Clymo (33), who suggested that there is a limit to peat bog growth, with the maximal thickness of a peatland being reached when litter production is balanced by the integrated decay of peat through the peat profile. Clymo's simple analysis relies on some assumptions that may not be reasonable, including the assumption that the position of the water table with respect to the peatland surface remains constant as a peatland thickens or grows (34), and has been superseded by several models that simulate the peat profile as a column of layers or cohorts, each cohort representing (usually) an annual addition of organic matter. Notable recent examples are the Holocene Peat Model (HPM) (35, 36), DigiBog (37, 38), and MILLENNIA (39). These models do not simply simulate the thickness of the peat deposit like Clymo's (33) model; they also simulate peatland hydrological conditions (water-table depth), the decomposition of the peat in each cohort over time, the hydraulic conductivity (permeability) of the peat in each cohort and how it changes over time as the peat decomposes (HPM and DigiBog), and the composition of the peatland vegetation (HPM and MILLENNIA). These models, are, in effect, ecosystem models and produce a virtual peat profile that can be "cored" at any stage of a peatland's development. The models contain important feedbacks between hydrological and ecological processes. For example, litter production is driven in part by water-table depth, which in turn is affected by the permeability of the peat, which depends on the rate of peat decay, which depends on the depth of the water table. The models can simulate peatland development over millennial (Holocene) timescales and can be driven by climate records and reconstructions in which there is interannual variability rather than a constant climate. The models were developed originally for temperate and boreal peatlands but are now being extended to represent permafrost and tropical peatlands (e.g., 40). **Figure 5** shows the basic structure of peatland models such as HPM.

By definition, models are simplifications of the real world, and HPM, DigiBog, and MILLENNIA are no exception. However, the models represent key processes and feedbacks observed in real peatlands and can prove useful for exploring how peatlands respond to changes in climate. For example, in a version of DigiBog that includes the effects of temperature on evapotranspiration, litter production, and peat decay, Morris et al. (38) explored the relative importance of changes in net rainfall and temperature on peatland structure and function. They found that, although raised bogs are generally resilient (see 41) to climatic changes in wetness (net rainfall), they may undergo structural shifts in response to changes in temperature, especially cooling. Morris et al. (38) were also able to identify the situations in which the peatland archive provides a reliable record of past climate conditions and the circumstances when any signal in the archive is degraded or "overwritten." For example, poorly decomposed layers of peat may form during a wet climatic phase but these may be exposed to aerobic decomposition during a later dry or droughty climate phase and undergo "secondary decomposition," such that they no longer preserve information about the wet phase.

Models are required to simulate the response of peatlands to changes in climate, to human impacts such as drainage and deforestation, and to ecosystem restoration initiatives, and will likely assume increasing importance as scientists and policy makers attempt to understand how best to manage the global peatland resource as a C store and as an important range of ecosystems. Undoubtedly, the demands made of models will see further refinements to them. For example, currently, most model simulations are of a one-dimensional (1D) peat profile. DigiBog is capable of simulating whole peatlands, which are conceptualized as contiguous, interacting, columns of peat, but models with multiple columns are computationally expensive—they have very long run times. To make 2D and 3D peatland development models a practical reality, it will be necessary to parallelize their computer code so that the many millions of calculations required for an individual

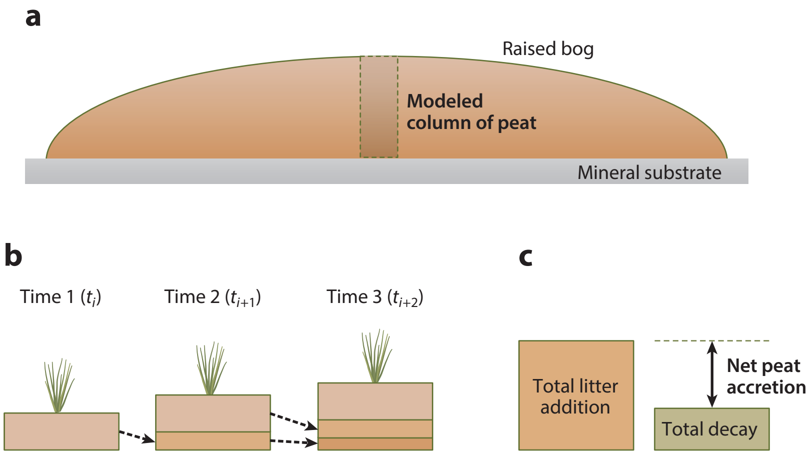

Figure 5

The basic structure of a peatland development model such as HPM and DigiBog. Typically, these models are used to simulate the buildup of a column of peat (*a*). (*b*) Cohorts of new litter/peat are added during each time step of the model. At time step 1, the peatland consists of a single cohort of litter/peat. At time 2, a fresh cohort is added on top of the first cohort, which has undergone some decomposition and a decrease in thickness. At time 3, a further cohort is added, while the first and second cohorts undergo further decomposition. (*c*) The total litter added, as well as how much of the added litter has been lost to decay. The difference between these two, as shown by the double arrow, represents the increase in overall thickness of the peatland. Although not shown here, belowground litter production (e.g., roots) also occurs and can be added to existing cohorts of peat. Peatland development models can be used to simulate fens and tropical swamps as well as mid- to high-latitude raised bogs.

model run can be partitioned across multiple microprocessors to speed up the simulation time. Other likely developments of peatland models are the inclusion of temperature effects on litter production and decomposition [these effects are already in MILLENNIA and DigiBog (see 38, 39), but not in HPM] and the inclusion of intra-annual variability in climate forcing conditions (i.e., rainfall and air temperature). The use of peatland development models to explore the effects of management such as drainage on peatland functioning is in its infancy. An interesting but currently unpublished example concerns UK blanket peatland (a type of ombrotrophic peatland). Application of a 2D version of the DigiBog model (Dylan Young, University of Leeds, personal communication) has revealed that ditches that cut across a peat-covered hillslope have strong upslope and downslope effects. Net losses of peat (thinning of the peat) caused by oxidation occurred tens of meters away from the modeled ditch. Although ditch blocking was effective at reversing the loss of the peatland C sink function, even 100 years after the blocking of a ditch, the peatland in the vicinity of the ditch had not returned to its predrainage height. From one study on one type of peatland, it is too early to draw broader conclusions on how drain blocking affects peatland C balance over decadal and centennial timescales, but an obvious candidate for similar modeling work is the large area of tropical peat swamp that has been drained for palm oil and commercial timber production in Southeast Asia, particularly in Malaysia and Indonesia (42). After the devastating fires during El Niño 2015 (see Section 4), there is interest in how ditch blocking affects not just the hydrological functioning and fire resistance of these tropical peatlands but also, over the longer term (decades), how hydrological restoration might affect peat decomposition and net peat accumulation (43).

4. ANTHROPOGENIC IMPACTS: PEOPLE AND PEATLANDS

Despite the generally negative impact that human land uses have had and continue to have on peatland C storage and sequestration, which we discuss below, there can be situations in which anthropogenic activities have been involved not in the loss of peat from the landscape but in the initiation and stimulation of peat development. Evidence from the paleoecological record of peatlands in northwest Europe indicates that there may be locations where human activity, in particular deforestation, often in combination with grazing and burning, occurred synchronously with peat initiation and could be invoked as a causal factor. Loss or reduction in forest cover results in increased overland flow downslope (through reduced evapotranspiration), a loss of soil fertility, and reduced soil permeability through the development of gleyed and podzolized soil profiles, while soil infiltration capacity may be further reduced through compaction by grazing animals and fire. Some have argued that the combined effect of these changes resulted in increased soil wetness, as well as an increased tendency for the formation of peat in the UK uplands (44) and at sites elsewhere in Europe [e.g., central Europe (45), western Norway (46)]. Separating the impact of anthropogenic activities from climatic changes as initiators of peat formation is not easy, however, given they often occur simultaneously and may have a mutually reinforcing effect. Thus other studies have favored climatic rather than anthropogenic changes as the key drivers of peatland development [e.g., in the UK uplands (47, 48)].

We have already noted the important role of peatlands as archives of climatic and other environmental changes, but they can also be a source of evidence for prehistorical and historical human activities and their impacts on the wider landscape. This may take the form of human and other artifacts entombed within the peat. Examples include archaeological remains such as tools, ornaments, and even trackways [e.g., in the Somerset Levels of southwest England and the Irish Midlands (49, 50)], in addition to well-preserved human bodies (so-called bog bodies) discovered in peatlands across northwest Europe (e.g., 51). Although the wider sociocultural interpretation of archaeological remains from within and around peatlands is far from conclusive, it is likely that most human activity and settlement took place on the shallower peatland margins, particularly in fens in riverine or lake edge settings.

In addition to human artifacts, peat paleoecological and geochemical records have been central to developing our understanding of the extent and nature of past human activities and of environmental change. Studies of the peat pollen record have, for example, enabled us to examine the central role of agriculture in shaping cultural landscapes in northwest Europe (e.g., 52) and also in some parts of the tropics [e.g., New Guinea (53)]. The geochemical record, however, has provided fascinating insights into phases of metallurgical activity—mining and smelting of ores such as lead, zinc, iron—through analysis of trace elements. Examination of the record of past atmospheric pollution events preserved within peatland has provided evidence of the location of European metal mining activities during the Roman and medieval periods, as well as the impact that metalworking had on forest dynamics, given woodlands were exploited for timber and charcoal used in the smelting process (54, 55).

Most historic and contemporary peat exploitation has been and still is associated with economic development. Peat was used in Roman times to heat homes and continued to play an economic role in countries where other fuel sources, such as wood, were scarce. In the Netherlands, for example, extensive peatland exploitation started in the late Middle Ages, continuing until the early years of the Industrial Revolution. The Dutch mined peat on an industrial scale to provide an energy source for the production of glass, bricks, tiles, and ceramics, and for brewing and baking. Peat digging became so widespread that large areas of land started to go below the water table as the peat surface was progressively lowered; during the seventeenth century, several villages were "swallowed" by man-made peat lakes, and by the end of the nineteenth century peat had been removed from an estimated 10% of the total land surface of the Netherlands (56). On a smaller industrial scale, peat digging for fuel was responsible for creating a series of lowland lakes (the Broads) in the counties of Norfolk and Suffolk in eastern England. Although the Broadland lakes appear now to be quite natural, they are in fact flooded medieval peat excavations (57).

As in the past, peat exploitation continues to have a very direct influence on shaping both economies and landscapes in a number of countries around the world. Peat extraction for energy production is carried out on a commercial scale on approximately 2,000 km^2 to provide a fuel source for electricity generation and heating in Finland, Ireland, the Russian Federation, Sweden, Estonia, and Belarus (4). A similar area is mined to provide growing media (potting composts and soil improvers) for amateur gardeners and the horticultural industry, with more than half of this extraction focused in Canada and Germany (4).

Globally, the most widespread uses of peatlands today are for forestry and agriculture, covering a total area in excess of 1 million km^2 [$\sim$25% of the global peatland area (4)] and possibly exceeding twice this area if peatlands used as pasture for livestock are also included (5). Forestry use of peatlands is mostly focused in Finland, Russia, and Sweden, whereas agricultural uses occur widely in Europe, North America, and Southeast Asia. Research on the effects of commercial forestry on raised bogs in northern Europe suggests they may become stronger C sinks, remain unchanged as C sinks, or become C sources under forestry management (see, also, 58). In contrast, agriculture on peat involves more fundamental changes, including loss of the original peat-forming vegetation and the construction of drainage systems to provide a suitable water table depth for the growth of crops. Drainage significantly enhances oxygenation of the upper part of the peat column, stimulating microbial decomposition of organic matter and the release of C (as CO_2) to the atmosphere, with emission rate dependent on a range of factors, including the groundwater level, peat moisture content, and peat temperature (see, also, 59). Additional GHG emissions can occur from drainage ditches, which may be hotspots for CH_4 emissions despite lower overall emissions from the drained peat surface (60). High nitrous oxide (N_2O) emissions, particularly from the surface of nutrient-rich and/or fertilized peatlands (61), may also occur.

In Europe, approximately 125,000 km^2 of peat soils (4) are used for agricultural production with extensive areas in Russia, Germany, Belarus, Poland, and the Ukraine. In the United Kingdom, agricultural drainage of the fen peats of eastern England (an area from the Wash down to Cambridge) was initiated in the seventeenth century and continued into the late nineteenth century. An extensive system of drains and wind-powered pumps was installed to dewater the peat, thereby creating fertile agricultural land. Today, a large area of fen peat soil has been entirely lost or greatly reduced in thickness by centuries of drainage-induced oxidation (peat wastage), with loss rates as high as 1 to 2 cm per year. Where organic soils still remain they are used intensively to support vegetable and cereal crop production, although, given rates of peat wastage, this must be considered a finite land use. Peatland drainage for agricultural use is not confined to northern peatlands. In the countries of Indonesia and Malaysia, more than 30,000 km^2 of lowland peat swamp forest (approximately 20% of the regional peatland area) has been converted to oil palm and pulpwood tree plantations, with indications that this area could at least double by 2020 (42) (**Figure 6**).

It is estimated that GHG emissions from peatlands drained for forestry and agriculture in Europe are responsible for approximately 360 Mt CO_2 $year^{-1}$ (62), whereas peatland plantations in Southeast Asia, despite occupying a smaller area, account for a much higher emission approaching 700 Mt CO_2 $year^{-1}$ (63), reflecting the increased rate of peat oxidation driven by year-round high temperatures in a tropical climate. In addition to direct GHG emissions to the atmosphere, drainage also increases lateral transport of peat C into streams and drains in the form of dissolved

Figure 6

Oil palm plantation on peatland in Sarawak, Malaysia.

organic carbon (DOC) and particulate organic carbon (POC) (64, 65), and a further consequence is lowering of the height of the peatland surface (i.e., subsidence). In drained peatlands, the initial subsidence can be quite rapid and is caused largely by physical compression processes associated with loss of water from the peat profile. During subsequent years, the dominant subsidence process is peat oxidation proceeding at rates of 1–2 cm in temperate and 3–5 cm in tropical climates (66, 67). In some locations, fire also contributes to lowering of the peat surface (68, 69). Largely as a result of subsidence, some areas of peatland formerly drained for agriculture have now been abandoned or put to other land uses due to decreasing agricultural productivity, the increased costs of drainage, and the concomitant risks of flooding. On the Sacramento–San Joaquin River Delta in California, for example, peat drainage has been followed by subsidence of between 1 and 8 m, leading to levee failure, flooding, and saltwater intrusion and, in turn, an increasing amount of marginal or nonfarmable land (70, 71). Subsidence of peatlands used for agriculture is also reported from Southeast Asia (66, 72) and Northern Europe (73), including the Netherlands and the English Fens. In all cases, peatland exploitation has resulted in long-term, essentially irreversible changes in local environmental and hydrological conditions such that alternative land uses (e.g., nature conservation or wetland agriculture—rice production, in the case of the San Joaquin River Delta) have been put in place or may need to be implemented in the future.

Often the perturbations caused by human activities on peatlands have a cumulative effect, such that when combined, the impacts are greater than those expected from each disturbance operating separately (74). This is exemplified by the interaction between drought, drainage, and the risk of peatland fire. In intact, undisturbed peatlands, organic matter (vegetation and peat) is at very low risk of fire, either from lightning strike or anthropogenic ignition, because of the naturally high water table and the high moisture content of the vegetation. But drainage, often in combination with climatic drought, vegetation disturbance, and human access, greatly increases both the risk and incidence of fire. Peat fires have occurred recently in many parts of the world (including Canada and Russia), but those in Southeast Asia are rapidly escalating in extent, frequency, and severity with profound implications for climate, environment, and society (75, 76). The peatland fire dynamic of this region is the product of rapid loss of peatland forests, landscape-scale drainage, and widespread use of fire as a cheap tool for land clearance prior to agricultural development, particularly for the plantation crop oil palm. Unlike flaming vegetation fires, peat fires smolder at and beneath the peat surface under conditions of low oxygen availability (77). This results in incomplete combustion of organic matter, giving rise to high emissions of particulates, GHGs, and volatile organic compounds, and resulting in extreme air pollution incidents that are detrimental to human health and regional economies. Although peat fires now occur in Southeast Asia during most dry seasons, their extent and severity increase during prolonged droughts associated with the El Niño weather phenomenon. During El Niño 2015, fires raging across Indonesia during three months—from September to November—affected more than 15,000 km^2 of peatland (an area equivalent to half that of Belgium) and over that short time period gave rise to an estimated emission of more than 1 million tonnes of CO_2, a figure that exceeds the total annual emission from burning of fossil fuels in industrialized countries such as Germany (see **http://www.globalfiredata.org/updates.html**).

In contrast to the scale of anthropogenic impacts on peatlands in northwest Europe, the United States, and Southeast Asia, extensive areas of peatland in boreal and subarctic regions of Canada, Alaska, and Russia remain pristine. Increasingly, however, their peat C stores are influenced by the feedbacks between permafrost melting, fire, vegetation changes, and their effects on albedo, which may have particularly far-reaching consequences for the future security of the large C stores in permafrost peatlands (78).

5. FOR PEAT'S SAKE: CONSERVATION AND RESTORATION

Recognition of the scale of anthropogenic impacts on peatland ecosystems across the globe, combined with a growing awareness of their role in providing an array of valued ecosystem services, has resulted in the enactment of a range of national and international conventions and national policies aimed at protecting their habitats, biodiversity, and C stocks, alongside initiatives to rehabilitate and restore peatland ecosystem functions. In terms of international conventions, the United Nations (UN) Convention on Biological Diversity (CBD) and the UN Framework Convention on Climate Change (UNFCCC), both adopted at the Rio Earth Summit in 1992, are the most important and far-reaching. The CBD addresses the conservation of key ecosystems and the protection of habitats and species. Peatlands are prominent on the CBD target list, with national, regional, and local governments required to produce biodiversity action plans for their protection and enhancement. At an international scale, further protection is provided by the Ramsar Convention (1971), which facilitates conservation and wise use of all forms of wetlands, and within Europe, the EU Habitats and Species Directive (1992) specifically include mention of peatland ecosystems (raised bogs, blanket bogs, fens) as priorities for both conservation and, additionally, restoration where sites have been altered through agriculture, forestry, or peat extraction. The ultimate objective of the UNFCCC is to stabilize GHG concentrations "at a level that would prevent dangerous anthropogenic interference with the climate system" (**http://unfccc.int/essential_background/convention/items/6036.php**). The convention has important implications for peatlands because, for Annex 1 (economically developed) countries, GHG emissions associated with peatland use (forestry, agriculture, extraction) have to be accounted for in national GHG inventories for reporting to UNFCCC. Following agreement at the Durban Climate Summit in 2011, Annex 1 countries can also now include the rewetting of peatlands on a voluntary basis in national GHG accounting; i.e., they can seek to reduce their GHG emissions by rehabilitating drained peatlands.

International and national nongovernmental organizations, such as World Wide Fund for Nature, International Union for Conservation of Nature, Greenpeace, and Wetlands International, play an important role in influencing policy making and implementation with regard to peatlands. Over the past ten years, their various activities, stimulated by changing policy, as well as environmental and social circumstances, have led a number of countries and organizations to start taking steps toward increased protection of remaining peatlands and restoration of degraded sites, including those used formerly for industrial peat production. Ecological restoration is the practice of renewing and restoring degraded or damaged peatland ecosystems through active human intervention and action. There are a growing number of restoration projects underway in Europe and North America. These usually focus on peatland rewetting, e.g., through blocking of ditches, and restoration of the vegetation cover as prerequisites for both short-term mitigation of C loss and longer term re-establishment of the peat-forming, C sequestration "machinery." Several studies have indicated, however, that the road to recovery of peatland ecosystem functions can be unpredictable and also slow. In the United Kingdom, for example, studies of blanket bogs on which drainage ditches (grips) have been blocked show that the hydrological regime does not rapidly recover to resemble that of an intact peatland, and the effect on GHG emissions and fluvial C export is equivocal, at least over the short term (79). Restoration of peat-forming vegetation can also be an uncertain process, depending in some situations on natural recovery following raising of the water table, and in other settings on active interventions to kick-start the rehabilitation process (e.g., reseeding or planting of bare peat surfaces). Approaches to peatland restoration are still in their infancy, and the success or otherwise of intervention measures may become apparent only after extended periods of time; long-term monitoring will be essential to determine whether the goals of restoration are ultimately met. Nevertheless, work on the restoration of cutover peatlands in Canada has shown considerable success, including rewetting followed by active introduction of plants to re-establish the typical vegetation cover of *Sphagnum* spp. and organic matter accumulation (80, 81). Perhaps the biggest contemporary challenge for peatland restoration, however, is not in the Global North, but in Southeast Asia where there is an emerging, urgent need for peatland restoration initiatives aimed at rewetting drained peatlands to reduce the risk of fire and protect the integrity of the remaining peat swamp forest both as a C store and wildlife habitat (43).

6. APPROACHES TO UNDERSTANDING THE FUTURE OF PEATLANDS

Given the size of the global peatland C store and the importance of peatlands as distinctive ecosystems, there is interest in how they will respond to future changes in climate. For example, will northern peatlands under warmer and potentially drier climates destabilize and give up their C to the atmosphere, thereby reinforcing climate warming? Some modeling studies suggest they will. For example, Ise et al. (82) considered the effect of an instantaneous 4°C rise in temperature on the C stock of two types of northern peatland: a bog and a fen (see Section 2). They found that drying of the peatland associated with the warmer climate caused a loss, over a 500–800-year period, of 40% and 86% of the original C stock in the bog and fen, respectively. The study of Ise et al. (82) has proved influential but its message can be questioned. The model the authors use omits important negative feedbacks that are included in models such as HPM and DigiBog, as noted in Section 3. These feedbacks enhance the resilience (see 41) of peatlands. For example, the model of Ise et al. (82) does not consider changes in peat permeability in response to drying. As the climate warms and dries, the initial response of a peatland may be a lowering of water tables and an increase in the rate of both oxic and anoxic decomposition. However, these changes in decomposition rate may cause a decline in peat permeability (37), leading, in turn, to a slowing in rates of water loss from the peatland, so countering the drier climatic conditions. Feedbacks such as these may explain empirical observations of the sometimes weak response of peatlands to climatic forcing (e.g., 38, 83, 84).

As Belyea (85) notes, the paleorecord reveals that it is common for peatlands to experience long periods of stasis that are punctuated by sudden changes or switches. The switches may occur on a variety of scales and involve relatively subtle shifts in the plant assemblage—for example, from dominance by one species of *Sphagnum* to dominance by another—or more fundamental changes across the whole peatland in terms of its plant assemblage, its hydrological regime, and the rate of peat accumulation. The periods of stasis may be explained by negative feedbacks (stabilizing mechanisms) "outcompeting" (85) positive feedbacks (destabilizing mechanisms). When change does occur, destabilizing forces dominate stabilizing forces. A problem for predicting peatland responses to changes in climate and human modification is that we have almost certainly not yet identified all of the important feedbacks that affect peatland behavior. Even for the feedbacks we know about, we have not explored all of their effects through, for example, numerical experiments with peatland development models (see 38 and Section 3).

That many peatlands have persisted for millennia suggests they possess considerable resilience at the scale of the whole peatland. Paleoecological studies are proving useful at revealing the types of perturbation or disturbance that peatlands can absorb and those that have larger effects on peatland functioning, in other words, in identifying the circumstances when peatlands are resilient and those when they are prone to sudden shifts in state. Two recent examples are Cole et al. (86) and Swindles et al. (87). In a study of tropical peatlands in Sarawak, Malaysian Borneo, Cole et al. (86) analyzed peat cores from three coastal sites for pollen and charcoal and found strong evidence to suggest that the peatlands are resilient to quite extreme perturbations—fire and drought—associated with periods of enhanced El Niño–Southern Oscillation activity, and with a longer period between 3000 and 2000 calibrated BP, which they term the Arid Tropics Event. In response to both, they found that taxa associated with peat swamp forest tended to persist. One interesting aspect of their study is that the peatlands have experienced a greater frequency of disturbance (fire and forest clearance) in the past few centuries, and typical swamp forest communities have not been able to recover fully in response to these impacts. In a very different type of peatland—a northern temperate raised bog—Swindles et al. (87) used a paleoecological approach to investigate the effect on the peatland of severe disturbance caused by episodes of peat cutting. Peatlands that have been cut over are often assumed to present special challenges for conservationists wishing to restore them (e.g., 88–90). However, as Swindles et al. (87) show, even peatlands that are cut over on more than one occasion may recover spontaneously and become peat-accumulating systems again without any apparent attempt at restoration by humans, albeit over centennial timescales.

A problem with paleoecological studies is that, although peatlands are archives of their own developmental history, the archive can become corrupted (e.g., 38), such that it might not be possible to match effect with cause. Another problem is that the timescales of cause and effect may differ (85); for example, there may be lags between a disturbance and a peatland's response to it. As noted above, peatlands may also show threshold behavior; such behavior may be illustrated by a ball-and-bowl analogy, as shown in **Figure 7** (following 91). The peatland may show strong resilience to all perturbations within the A–B range in the figure; under this range, the system remains in State I, which is illustrated here as peatland vegetation dominated by sedges. However, at position B, the system is conditionally stable and a slight increase in the strength of the perturbation (a further "push" up the slope) can cause the system to switch to a new state (State II in the figure), which in this example is a peatland vegetation dominated by *Sphagnum*. Although threshold behavior such as this can be expected to be clear in the peatland archive, for example in the plant macrofossil assemblage within the peat profile, the cause of it may be less clear; the small push required to force a change in state may be hidden within the error bar range of, for example, a proxy-reconstructed temperature or net annual rainfall.

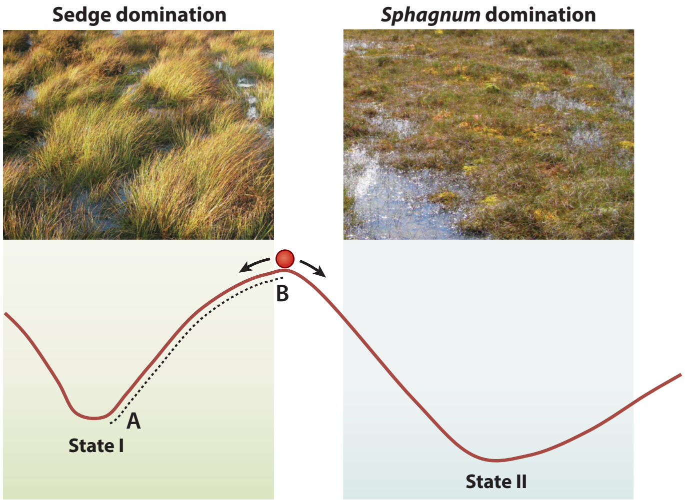

Figure 7

Peatland resilience. The two "bowls" represent stable states associated, respectively, with a vegetation cover dominated by cotton grasses (a type of sedge) (State I) and one dominated by *Sphagnum* (State II). Most disturbances fail to move the red ball beyond the bowl representing each state, such that the system recovers to its predisturbance condition. However, at position B, the system is at a threshold; a minor push up the side of the State I bowl causes the ball to cross a threshold and roll into the bowl representing State II. Multiple high-frequency disturbances may push the ball further up the side of a bowl to the threshold, but only one of these may appear to cause the switch in vegetation type. Photos courtesy of Richard Lindsay.

Given these problems, it may be tempting to investigate experimentally how peatlands respond to perturbations, and notable studies of this kind include Bridgham et al. (92) and Dorrepaal et al. (93). Experimental approaches are attractive because they allow precise control over factors that affect peatland function, consequently making it easier to link cause and effect. They can also offer powerful insights into some important feedbacks. For example, Bridgham et al. (92) used a mesocosm experiment to investigate how changes in water table position and air and peat temperature affect both bogs and fens. They found that, when the water tables of the different peatland types were altered, they rapidly gained or lost C until the depth of the water table below the peatland surface returned to its "characteristic" (pre-experimental) position. Interestingly, this type of homeostatic response has also been revealed in a theoretical study using a peatland development model (84). Despite the attraction of precise control of factors affecting a peatland, experimental studies come with their own problems, as may be illustrated by two studies on the response of subarctic peatlands to changes in climate. Using small plots, Dorrepaal et al. (93) manipulated the air temperature in situ at the surface of a subarctic peatland in northern Sweden and found that a 1°C experimental warming increased heterotrophic respiration (peat decay) by more than 50%. The authors found that in situ peat decay is more temperature sensitive than plant productivity (litter production; see Section 3); i.e., they found that increased decay is not offset by increased litter production, which led them to suggest that subarctic peatlands may be vulnerable to global warming. They suggested that the C stock of subarctic peatlands may become unstable and be returned to the atmosphere in the form of CO_2 and CH_4, thus providing a positive feedback with climatic warming. However, modeling work suggests that key peatland feedbacks may take decades to take effect (e.g., 84), and even long-term studies such as the eight-year experiment of Dorrepaal et al. (93) may be too short to provide a reliable indication of what will happen to an ecosystem over decadal to centennial timescales. Although it is unclear from their paper, Dorrepaal et al. (93) seem to have worked on a peatland dominated by *Sphagnum*. Where a peatland is dominated by sedges, climatic warming and drying may actually lead to a sharp increase in rates of C accumulation. Loisel & Yu (94) used a paleoecological approach to study the vegetation and C dynamics of a peatland in south central Alaska with a subarctic climate. They found that approximately 100 years ago the peatland underwent a sudden transition from a herbaceous (*Carex* sp.) fen to a bog dominated by *Sphagnum*; this switch coincided with a greater than twofold increase in the peatland's C sink capacity. The peatland had been dominated by herbaceous species (*Carex* sp.) for more than 3,000 years before the transition, and the change seems to have been triggered by climatic warming and drying. The peatland provides a good example of the long periods of stasis punctuated by the sudden changes Belyea (85) notes (see discussion above). Loisel & Yu (94) speculate on how both external factors (climate and peatland water supply) and internal feedbacks may combine to cause the observed change to *Sphagnum* domination. The very different conclusions Dorrepaal et al. (93) and Loisel & Yu (94) reach—respectively, that warming of subarctic peatlands may lead to a net C loss and that warming may lead to a significant increase in net C uptake—may simply reflect the differences between the two study sites. However, the comparison may also illustrate a problem with some experimental studies: Even studies that take place over periods of five to ten years are unable to account for feedbacks that may "play out" or have a characteristic reaction time of decades or even centuries.

The brief review above suggests that a single approach is unlikely to prove sufficient when trying to identify the stabilizing and destabilizing mechanisms acting within a peatland. We also need to gain a better understanding of how peatland resilience will be affected not only by changing climatic and anthropogenic disturbances but also by resultant alterations in fire frequency and severity and the impacts of changing fire regimes on the future peatland C balance (75). Currently, the greatest risk of peat fires exists in Southeast Asia. This is due to the extent and intensity of peatland drainage in this region and the socioeconomic pressures that are driving rapid land use changes. But in future decades, fire could become increasingly relevant to higher latitude peatlands, as a result of both intensifying levels of human disturbance and predicted climatic changes toward drier conditions and longer fire seasons (95). Such a shift could destabilize the much larger C stocks found in northern peatlands, with profound implications for the global climate system.

SUMMARY POINTS

1. Peatlands are one of the planet's most C dense terrestrial ecosystems, containing between 500 and 700 billion tonnes (Gt = Pg) of C on only 3% of the Earth's land surface.
2. In addition to C storage, peatlands deliver a range of other beneficial but often undervalued ecosystem services and host many unique and rare habitats and species.
3. Despite their great variety in shape, vegetation type, and soil chemistry across the globe, all peatlands comprise a peat deposit that has formed because the addition of organic matter to the peatland has exceeded its loss over long periods of time.
4. C storage is ensured as long as the peat remains waterlogged, but any disturbance resulting in lowering of the water table gives rise to oxidative microbial degradation of the peat and release of stored C to the atmosphere.
5. Peatlands can prove resilient to gradual, long-term changes in climate and hydrological conditions, but they also respond rapidly to more profound, short-term anthropogenic disturbances.

6. The most widespread uses of peatlands today are for forestry and agriculture; these uses require drainage, which results in globally significant emissions of CO_2, a GHG, to the atmosphere. Drainage also increases the risk of peat fires, which are a further source of GHG emissions (CO_2 and CH_4).
7. Peatland development models, along with paleoecological and process-based studies, play an important role in simulating the response of peatlands to changes in climate, to human impacts, and to ecosystem restoration initiatives.

FUTURE ISSUES

1. Will peatland development models assume increasing importance as scientists and policy makers attempt to understand how best to manage the global peatland resource as a C store?
2. How will peatlands respond to future climate changes and restoration measures? And will addressing this issue lead to a growing demand for multidisciplinary approaches to peatland management involving ecologists, climate modelers, and conservation practitioners?
3. Will warmer and potentially drier climates destabilize peatland C stores through enhanced microbial degradation and increased risk of fire?
4. Or can protection and restoration measures be designed to bring peatlands to a stable state that safeguards C storage and other vital ecosystem services?

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