Final Draft of 16 May 2002

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Chapter 2.

Mires and peatlands

The second chapter

- **sets down the basic concepts required in this document and the terms chosen to describe them,**
- **explains the natural properties of mires and peatlands,**
- **summarises the latest available information on the extent and location of mires and peatlands, and**
- **outlines some basic characteristics of mires and peatlands relevant to the functions discussed in the following chapter.**

2.1 Concepts and terms [1]

International peatland terminology is acknowledged to be in a state of confusion[2]. In order to communicate concepts are needed and terms are required to define these concepts. In this document, the following terms are used for the following concepts[3]:

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[1] This section has benefited from critical comments from John Jeglum and Juhani Päivänen.

[2] Cf. Guidelines for Global Action Plan for Peatlands theme 1. Every international approach in peatland science and policy is complicated by the multitude of terms, the inconsistencies in their definition, and the different concepts behind similar terms in different languages and disciplines (Overbeck 1975; Fuchsman 1980, Andrejko et al. 1983; Zoltai & Martikainen 1996). Multilingual lexicons and their precursors (e.g. Früh & Schröter 1904; Mali 1956; Masing 1972; Bick et al. 1973; Overbeck 1975; Gore 1983; International Peat Society 1984) have paid too little attention to this problem. Many concepts have further been confused by uncritical translation of terms, even in translations of important handbooks (Joosten 1995a). Some illustrations: the English "moor", the German "Moor", the Dutch "moer", the Swedish "myr" and the English "mire" do not have the same meaning and cannot be (but too often are…) translated one into the other. The same accounts for the German "Torf", the English "turf" and the Dutch "turf", although the meaning of the latter is somewhat similar to that of the Irish "turf". In one and the same language, the meaning of words is ambiguous and may change in time (cf. Wheeler & Proctor 2000) or may differ from discipline to discipline.

In some languages the words commonly used for the type of landscapes we want to discuss do not differentiate between areas with and without peat (cf. the English "moor", the French "fagne" and "marais", the Finnish "suo", the Russian "?????? (boloto)", the Georgian "tsjaowbi"), between peat forming or not peat forming (cf. the German "Moor", the Dutch "veen", the English "bog" and "fen"), or only indicate the presence of an economically extractable volume of peat (Cf. "tourbière", "torfeira", "turbera" in Romance languages).

[3] Communication takes place by means of terms (words, names) that represent concepts (contents, objects, ideas, notions). The concrete form of a term is of minor importance. Communication problems arise out of confusion about or disagreement on connections between terms and concepts (Hofstetter 2000a), as everybody (supported by valid semantic, etymologic, and historical arguments) prefers his or her own way of connecting terms and concepts. In international soil classification, this problem has been solved by introducing artificial terms (FAO-UNESCO 1988). This approach - for scientific purposes - has also been proposed for peatlands (Hofstetter 2000b). In this document, existing terms are used because they make possible an easier association with the subject (even where they also cause some confusion). The terms used are for the purposes of this document and their definitions are not intended to pre-empt further discussion. Definitions are only provided of terms and concepts that are essential for this document. Other than in quotations the document refrains from using confusing words such as "swamp" and "marsh".

A **wetland**[4] is an area[5] that is inundated[6] or saturated by water[7] at a frequency and for a duration sufficient to support[8] a prevalence of vegetation typically adapted for life in saturated soil conditions.

Peat is sedentarily[9] accumulated material consisting of at least 30%[10] (dry mass) of dead[11] organic[12] material.

A **peatland** is an area with or without vegetation with a naturally accumulated peat layer at the surface[13].

A **mire** is a peatland where peat is currently being formed[14].

A **suo**[15] is a wetland with or without a peat layer dominated by a vegetation that may produce peat.

Wetlands and suos can occur both with and without the presence of peat and, therefore, may or may not be peatlands. In our definition, a mire is always a peatland[16]. Figure 2/1 illustrates the relationship between the concepts.

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[4] For an extensive review of definitions of "wetland", cf. Tiner 1999. The definition presented here is based on the Ramsar definition modified with wording derived from the US Amy Corps of Engineers definition.

[5] Of marsh, fen, peatland or water, whether natural or artificial, permanent or temporary (cf. Ramsar definition)

[6] Up to a depth of six metres at low tide (cf. Ramsar definition).

[7] Surface or groundwater, static or flowing, fresh, brackish or salt (cf. Ramsar definition)

[8] And that under normal circumstances does support (cf. US Army Corps of Engineers definition)

[9] "Sedentary" (cf. Von Post 1922) is used in this document to mean formed on the spot and not transported after its formation and death. Peat differs in this respect from organic sediments like gyttjas and folisols (Blattmudde, "Waldtorf"), which originate from organic matter "falling" from above (planktonic material, resp. leaves and branches) (cf. Pakarinen 1984). Peat may have a sedimentary component (e.g. derived from algae in hollows, seeds and leaves, or in case of spring and flood mires consisting of mineral material), but a strict sedentary component derived from non-aquatic plants should always be present (cf. Succow & Stegmann 2001a).

[10] Varying with country and scientific discipline, peat has been defined as requiring a minimal content of 5, 15, 30, 50, 65% or more (dry mass) of organic material (cf. Andrejko et al. 1983, Agriculture Canada 1987, Driessen & Dudal 1991, Succow & Stegmann 2001b). The organic matter content is of importance for the use of peats. The different approaches, however, probably do not lead to strongly different global volumes of "peat" (Joosten 1999). The definition used here is proposed so as to provide this document with a consistent term. The 30% is a value often encountered in definitions of peats and organic soils in international literature.

[11] Peat may contain living organisms and (living and dead) biomass, even in deep layers, including micro-organisms, spores, and living roots (Cf. Belanger et al 1988, Küster 1990), but these do not dominate (Joosten & Couwenberg 1998).

[12] By "organic" is meant that the material results from carbon chemical biosynthesis. Organic materials belong to the larger group "organogenic" materials, which include all substances that have originated from organisms. For example, corals are organogenic, but not organic, sedentates (Joosten & Couwenberg 1998).

[13] Varying with country and scientific discipline, peatlands have been defined as having a minimum thickness of 20, 30, 45, 50 or 70 cm of peat. This question is discussed in detail in work on soil classification – for example in Agriculture Canada 1987. See also Joosten & Couwenberg 1998. The definition used here is proposed so as to provide this document with a consistent definition. It should be noted that – to provide a uniform standard - the inventories in section 2.4 use a minimum peat depth of 30 cm to which all available data were recalculated.

[14] Cf. Sjörs 1948. It is difficult to test in practice whether or not peat is accumulating. The dominance in the vegetation of species, whose remains are also found in peat, can together with the incidence of almost permanent waterlogged conditions, be taken as good indicators of peat formation.

[15] Some concepts of "mires" (e.g. the Finnish "suo", the Russian "??????" (boloto), and the mire definition of Löfroth 1994) in fact refer to what we here call "suo".

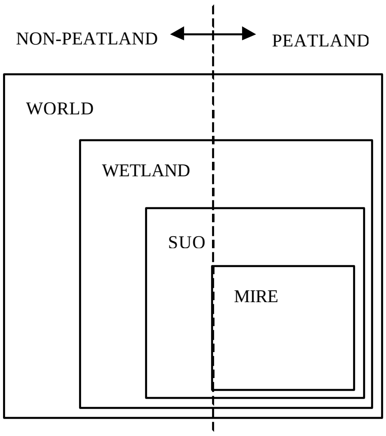

Figure 2/1 Relationship between mire, suo, wetland and peatland

2.2 Peat formation

The cycling of matter in most ecosystems is relatively fast and complete. In contrast, mires are characterised by an incomplete cycling resulting in a positive carbon balance. Because plant production exceeds decay, a carbon surplus is accumulated as peat. Peat accumulation generally takes place as a result of limited decay (decomposition) of plant material[17]. An important factor for peat accumulation is the chemical and structural composition of the organic material, determining the "ability to decay". The ability to decay varies with species (e.g. *Phragmites* versus *Typha*), plant parts (e.g. rhizoms versus flowers), and substances (e.g. waxes versus sugars)[18]. This means that some plant species, organs, and substances are more inclined to accumulate peat than others. A large number of plant species that occur in mires can contribute to peat formation, such as sedges, grasses, Sphagnum and other mosses, and woody plants. Consequently a wide variety of "botanical" peat types[19] exist.

Water is the most important external factor limiting decay. Because of its large heat capacity water induces lower than ambient temperatures[20]. The limited diffusion rate of gasses in water leads to a low availability of oxygen[21]. Both factors inhibit the activities of decomposing and decomposition-facilitating organisms, leading to a decreased rate of decay of dead organic material and, consequently, to the accumulation of peat[22].

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[16] Mires are wetlands, as peat is largely formed under waterlogged conditions. Approximately half of the world's wetlands are peatlands (Mitch et al. 1994, Lappalainen 1996). Peatlands where peat accumulation has stopped, e.g. following drainage, are no longer mires. When drainage has been severe, they are no longer wetlands.

[17] Clymo 1983, Koppisch 2001.

[18] Koppisch 2001.

[19] Cf. Succow & Stegmann 2001a. Peat types are furthermore distinguished on the basis of their degree of decomposition (cf. black peat, grey/white peat - Von Post scale), nutrient content, acidity, ash content/content of organic material (cf. Halbtorf, Volltorf, Reintorf), pedogenic alteration (cf. the German Ried, Fen, Mulm), fibre content (fibric, hemic, sapric), and other characteristics (cf. Fuchsman 1980, Andriesse 1988, Succow & Stegmann 2001b).

[20] Ball 2000.

[21] Denny 1993.

[22] Moore 1993, Freeman et al. 2001.

Mires have been developing on Earth since wetland plants first existed. Peat from the tropical mires of the Upper Carboniferous (320 - 290 million years ago) and the sub-tropical mires of the Tertiary (65 - 3 million years ago) is currently found as coal and lignite[23]. The great majority of present-day peatlands originated in the last 15,000 years. Since deglaciation, mires have developed into unique organic landforms with hydrological, biogeochemical, and biological links to upland and aquatic ecosystems. It is estimated that 4 million km^2 on Earth (some 3 % of the land area) is covered with peatlands. The largest known concentrations are found in Canada and Alaska, Northern Europe and Western Siberia, Southeast Asia, and parts of the Amazon basin, where more than 10 % of the land area is covered with peatlands[24]. Mires store about one third of the soil carbon in the world (see section 2.5 below), and contain some 10% of the global liquid fresh water resources[25].

2.3 Mire and peatland types

There are many different ways of classifying[26] wetlands, peatlands and mires that vary according to the purposes of the classification[27]. It is not possible to describe them all in this document. The typologies described here are those appropriate to the discussion in the rest of the document.

Historically peatlands were distinguished on the basis of their situation and the after-use of the remaining land, leading to the identification of:

- **bogs**, raised above the surrounding landscape. After peat extraction, which was normally carried out under dry conditions following drainage, a mineral subsoil suitable for agriculture often remained.
- **fens**, situated in depressions. After peat extraction, which was carried out by dredging, open water remained.

These 'pre-scientific' terms were adopted and adapted (on different conceptual bases) by various scientific disciplines, which has led to much confusion. More recently[28], mires have been classified into two main hydrogenetic types: **ombrogenous** mires that are fed only by precipitation, and **geogenous** mires[29] that are also fed by water which has been in contact with the mineral bedrock or substrate[30].

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[23] Demchuk et al. 1995, Lyons & Alpern 1989, Cobb & Cecil 1993.

[24] Lappalainen 1996

[25] Cf. Turunen et al. 2000a, UNESCO 1978.

[26] Classification comprises the sorting and grouping of things into classes ("classi"-fication) on the basis of their similarities and dissimilarities. The classification procedure results in a typology: a system of categories ("types", cf. "typ"-ology) on the basis of logical principles and functional interests. Classification is the process, typology is the result. Cf. Joosten 1998.

[27] Cf. Overbeck 1975, Gore 1983a, b, Moore 1984a, Eurola & Huttunen 1985, National Wetlands Working Group 1988, Brinson 1993, Finlayson & Van der Valk 1995, Wheeler & Proctor 2000, Succow & Joosten 2001, http://www.imcg.net/docum/greifswa/greifs00.htm.

[28] Dau (1823) was the first to acknowledge that bogs are fed "by merely rain and dew of heaven."

[29] Based on the origin of water, geogenous mires have been further subdivided into **topogenous** and **soligenous** mires. According to the original definitions (Von Post & Granlund 1926) topogenous mires depend on topographic conditions and are relatively independent of climate, because they "develop in terrestrialising lakes or river valleys, or at springs". In soligenous mires, peat formation is not only induced and continued by direct precipitation, but "also by meteoric water running off from the surrounding terrain" (Von Post 1926). See Table 2/2 below. In later publications the term "soligenous" has often been used differently to mean "originated under influence of streaming groundwater" (cf. Sjörs 1948) which a.o. leads to a typological switch of spring-fed mires from "topogenous" to "soligenous". To make the confusion even larger (cf. footnote 2), the term "soligenous" has also been used to describe solely spring mires (cf. Masing 1975, Wolejko 2000).

[30] Cf. Sjörs 1948.

All water on land ultimately originates from rain and other forms of atmospheric precipitation. Precipitation water is poor in nutrients and somewhat acid. In contact with the geosphere, the quality of the water changes. Depending on the chemical properties of the catchment area (determined by climate, bedrock, soil, vegetation, and land use) and the residence time of the water (determined by the extent, bedrock, and relief of the catchment), the electrolyte and O_2 concentrations, nutrient richness, pH, and temperature of the water change. The resulting differences in water quality lead to mire habitats with differences in nutrient availability (trophic conditions), base saturation (acidity), and characteristic plant species. These differences form the basis of the **ecological mire types** (Cf. Table 2/1).

Most mire and peatland typologies are based on water conditions, reflecting the central role of water in peat formation. A distinction is made between "**terrestrialisation**", when peat develops in open water, and "**paludification**", when peat accumulation starts directly over a paludifying mineral soil[31]. This distinction has been further developed into a system of seven basic hydrogenetic mire types, which is based on the processes underlying peat formation[32].

Hydrogenetic mire types: Water level fluctuations and water flow play an important role in peat and mire formation. Water level fluctuations influence, through redox-processes, the turn-over rate and solubility of chemical substances (nutrients, poisonous substances), and in that way the vegetation and eventually the composition of the deposited peats. Water level fluctuations furthermore condition the rates of oxidative decomposition, that lead to a change of coarse into fine plant particles and to a decrease in the porosity of the peat. Consequently as the hydraulic properties change the peats become less permeable to water (which decreases water flow) and they can store less water (which increases the water level fluctuations, Figure 2/2). Because of the strong relationship between water, vegetation and peat, hydrologic characteristics constitute one of the appropriate bases for classifying mires.

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[31] Weber 1900, Gams & Ruoff 1929. Kulczynski 1949 contributed to the development of a hydrological mire typology by pointing out the importance of water movement (Cf. Bellamy 1972, Moore & Bellamy 1974, Ivanov 1981.

[32] Succow 1981, 1983, 1999; Succow & Lange 1984, Joosten & Succow 2001.

Table 2/1: Ecological mire types in Northern Germany and their characteristic plant species (after Succow 1988). This table is included as an example.

ecological mire type species	oligo-trophic acid	meso-trophic acid	meso-trophic sub-neutral	meso-trophic calca-reous	eu-trophic	salt influence
Ledum palustre, Vaccinium myrtillus, V. uliginosum, Calluna vulgaris, Empetrum nigrum, Erica tetralix, Melampyrum pratense ssp. paludosum	■					
Calla palustris, Juncus bulbosus, J. filiformis, Ranunculus flammula, Veronica scutellata, Salix aurita, Luzula pilosa, Deschampsia flexuosa		■				
Scheuchzeria palustris, Andromeda polifolia, Drosera intermedia, Lycopodiella inundata, Rhynchospora alba, Eriophorum vaginatum	▓	▓				
Dactylorhiza majalis ssp. Brevifolia, D. incarnata, Liparis loeselii, Carex appropinquata, C. diandra, C. dioica, Juncus acutiflorus			■			
Menyanthes trifoliata, Carex lasiocarpa, C. echinata, C. nigra, C. canescens, Dryopteris cristata, Eriophorum angustifolium, Juncus acutiflorus, Calamagrostis stricta, Potentilla palustris, Viola palustris		▓	▓			
Drosera rotundifolia, Pinus sylvestris	▒	▒	▒			
Tetragonolobus maritimus, Schoenus ferrugineus, Primula farinosa, Dactylorhiza majalis, Cladium mariscus, Utricularia vulgaris, Pinguicula vulgaris, Parnassia palustris, Eriophorum latifolium, Juncus alpinus, Ophrys insectifera, Gymnadenia conopsea, Polygonum bistorta				■		
Polygala amara, Betula humilis, Carex buxbaumii, C. flacca, C. hostiana, C. pulicaris, Laserpitium prutenicum, Juncus subnodulosus, Dianthus superbus, Epipactis palustris, Serratula tinctoria, Briza media, Linum catharticum, Selinum carvifolia, Succisa pratensis, Salix repens			▓	▓		
Hammarbya paludosa, Carex limosa, Drosera longifolia	▒	▒		▒		
Carex panicea, Galium uliginosum, Lychnis flos-cuculi, Potentilla erecta, Cardamine pratensis, Cirsium palustre, Rumex acetosa		▒	▒	▒		
Molinia caerulea	░	░	░	░		
Circaea x intermedia, Senecio paludosus, Cicuta virosa, Carex cespitosa, C. gracilis, C. paniculata, C. vesicaria, Hottonia palustris, Lathyrus palustris, Oenanthe fistulosa, Teucrium scordium, Thalictrum flavum, Lemna minor, Phalaris arundinacea, Typha angustifolia					■	
Alnus glutinosa, Calamagrostis canescens, Juncus effusus		▓			▓	
Ranunculus lingua, Stellaria glauca, Carex disticha, C. acutiformis, Typha latifolia, Caltha palustris, Iris pseudacorus, Myosotis palustris, Ranunculus lingua, Rumex hydrolapathum, Sium latifolium			▓		▓	
Lysimacia thyrsiflora, Thelypteris palustris, Equisetum fluviatile, Salix cinerea, Agrostis stolonifera, Cardamine palustris, Lycopus europeus, Lythrum salicaria, Mentha aquatica, Peucedanum palustre		▒	▒		▒	
Carex elata		░	░	░	░	
Blysmus rufus, Oenanthe lachenali, Plantago maritima, Ruppia maritima, Samolus valerandi, Triglochin maritimum, Aster tripolium, Centaurium littorale, Eleocharis uniglumis, Festuca rubra ssp. littoralis, Juncus gerardii, Salicornia europaea, Bolboschoenus maritimus						■
Eleocharis quinqueflora, Triglochin palustre, Carex viridula, Schoenoplectus tabernaemontani				▓		▓
Pedicularis palustris, Valeriana dioica, Juncus articulatus			▒	▒		▒
Phragmites australis		▒			▒	▒

■	species restricted to one ecological mire type
▓	ecological amplitude of the species comprises two ecological mire types
▒	ecological amplitude of the species comprises three ecological mire types
░	ecological amplitude of the species comprises four ecological mire types

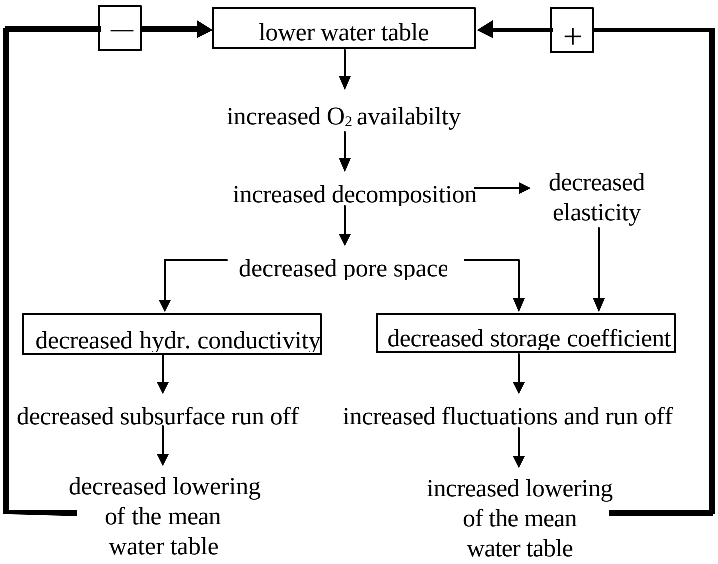

Figure 2/2. Positive and negative feedback between water table and hydraulic characteristics in a system consisting of organic matter and having significant lateral water flow[33].

Hydrogenetic mire types are defined by the role of water in peat formation and by the role of the mire in landscape hydrology. The following hydrogenetic mire types are distinguished:

Terrestrialisation mires (Verlandungsmoore), formed by peat formation in 'open' water, can be divided into **schwingmoor mires** (floating mats, e.g. *Papyrus* swamp islands) and **immersion mires** in which peat accumulates underwater on the bottom after the water body has become shallow enough to allow peat producing plants to settle (e.g. many *Phragmites* stands). The accumulation of terrestrialisation peat ends when the water is completely filled with peat.

Water rise mires (Versumpfungsmoore) result when the water level rises over a drier surface so slowly that no open water (lake, pool) is formed. A rise in the groundwater level may be caused by an increase in water supply (by changes in climate or land use) or a decrease in run-off (by sea level rise, beaver dams, the origin of water stagnating layers in the soil, etc.).

Flood mires (Überflutungsmoore) are located in areas that are periodically flooded by rivers, lakes or seas. Flood mires with a substantial peat thickness only occur under conditions of rising water levels (rising sea water level, rising river beds, etc.). As such they are related to water rise mires. The difference is the mechanical action of periodic lateral water flow and associated sedimentation of allogenic clastic materials such as sand and clay.

Mires of all the types listed in the previous paragraph are "passive", that is, they lie **horizontally** in the landscape, their basins fill gradually with peat, but their influence on the hydrology of their catchment areas is limited.

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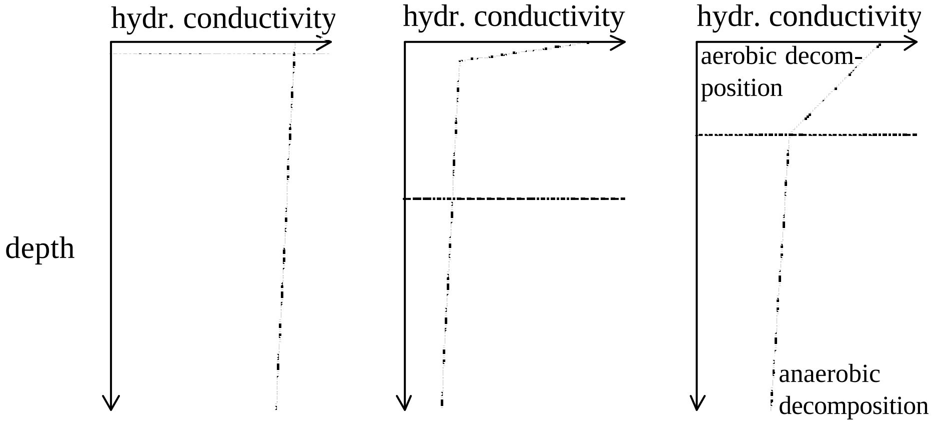
[33] Adapted from Couwenberg & Joosten 1999.

Mires with a substantial water flow (in peat or vegetation) behave differently. The mire surface shows a **slope**[34] and a significant amount of water is lost through lateral flow. This flow is retarded by the vegetation and the peat. Vegetation growth and peat accumulation thus lead to a rise in water table in the mire and often also in the catchment area.

Percolation mires (Durchströmungsmoore) are found in landscapes where water supply is large and evenly distributed over the year. As a result, the water level in the mire is almost constant. Dead plant material reaches the permanently waterlogged zone quickly, is therefore subject to fast aerobic decay for a short time, and the peat mostly remains weakly decomposed and elastic ('schwammsumpfig'[35], Figure 2/3a). Because of the large pores and the related high hydraulic conductivity, a substantial water flow occurs through the whole peat body[36]. The peat's ability to oscillate makes conditions for peat formation at the surface increasingly stable. Whereas at the start percolation mires are susceptible to water level fluctuations[37], with growing peat thickness any fluctuations in water supply and water losses are increasingly compensated by mire oscillation (Mooratmung).



a) percolation mire b) surface flow mire c) acrotelm mire

Figure 2/3: Hydraulic characteristics related to depth in different types of mire with substantial water flow. -------- = lowest water level (lasting for short durations only).

When water supply is periodically exceeded by evapotranspiration and run-off, the water level drops and oxygen penetrates the peat. The resulting strong decomposition (see Figure 2/2) causes the water to increasingly overflow the peat, and **surface flow mires** (Überrieselungsmoore) result. Also these mires can only endure if oxidative losses are small, i.e. if the water level only rarely drops. Surface flow mires are therefore only found in areas with almost continuous water supply, or hardly any water losses (in particular due to evapotranspiration). Because of the small storage coefficient of the peat the rare water shortages still lead to relatively large drops in water level (Figure 2/3b). Because of their low overall hydraulic conductivity and large water supply, surface flow mires can occur on and with steep

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[34] Sjörs 1948.

[35] Cf. Succow 1982.

[36] Cf. Wassen & Joosten 1996, Sirin et al. 1997, 1998.

[37] Couwenberg 1995, Joosten 1997.

slopes. Typical mires belonging to this type are blanket bogs, sloping mires (sloopy fens, Hangmoore), and most spring mires, which are fed by rainwater, surface run-off, and groundwater respectively.

A third type of water flow mire is the **acrotelm mire**[38], which accumulates organic material that combines a large storage coefficient (many large pores) with a limited ability to decay. The latter characteristic leads to a slow reduction in the pore size when subject to aerobic decay. As the deeper, older material has been prone to oxidation for longer, a distinct gradient in hydraulic conductivity develops in the upper part of the peat (Figure 2/3c). In times of water shortage, the water level drops into a less permeable range and run off is retarded. Evapotranspiration still leads to water losses, but because of the large storage coefficient of the peat resulting from its relatively large pores, the water level drops only to a small extent. In this way, the deeper peat layers are continuously waterlogged, even under fluctuating water supply. Globally the raised bog is the only acrotelm mire type so far identified. In the raised bogs of the northern hemisphere, a handful of *Sphagnum* species[39] combine a limited ability to decay[40] with favourable external (nutrient-poor and acidic) conditions. The world-wide distribution of raised bogs illustrates the effectiveness of this peat formation strategy.

The peat formation characteristics mentioned above can be combined with a classification based on the origin of water (see Table 2/2). The catchment area to a large extent determines the quantitative and qualitative characteristics of the input water. Under equal climatic, geological and geomorphologic conditions the amount, duration and frequency of water supply increase from

(a) ombrogenous – stemming solely from precipitation water; to
(b) soligenous – stemming from precipitation water and surficial run-off; to
(c) lithogenous – also stemming from deep groundwater.

Nutrient and base richness usually increase similarly. A tight correlation between quantity and quality of water and its origin is, however, not possible over larger areas. A continuous water supply not only occurs under spring-fed conditions: it can also be found in areas with very frequent rainfall. Ombrogenous water may show large differences in chemical composition[41]. When the substrate is inert, lithogenous water can to a large extent have the same qualities as rain water. Thallasogenous water (sea water) shows large differences in salt content (e.g. Baltic, North, and Dead Sea).

At a regional level, a correlation between quantity, quality and origin of water can more easily be made. Within a region, plant species are bound to certain water characteristics and, based on their material composition and hydraulic characteristics, to a large extent determine the peat formation strategy. Regionally therefore, strong correlations between abiotic conditions, vegetation, and hydrogenetic mire type can be found.

Under different bio-geographic conditions, different plant species can form equal hydrogenetic mire types. For instance, in the northern hemisphere ombrogenous surface flow mires (blanket

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[38] *Sensu* Couwenberg & Joosten 1999.
[39] Joosten 1993.
[40] Johnson & Damman 1991.
[41] Cf. Wolejko & Ito 1986, Damman 1995.

bogs) are largely built from Poaceae (grasses) and Cyperaceae (sedges) whereas in New Zealand and Tasmania they are built from Restionaceae[42].

Percolation mires are normally found as groundwater-fed mires, because only large catchment areas can guarantee a large and continuous water supply in most climates. The raised mires of the Kolchis area in trans-Caucasian Georgia, however, are *Sphagnum*-dominated ombrogenous percolation mires which exist under conditions of over 2000mm rain per year[43]. Also in SE Asia, in areas where the climate is extremely even and wet over the year, forested mires[44] form peats with very high hydraulic conductivity[45] and may also belong to this mire type. Ombrogenous terrestrialisation and water rise mires can be found in larger complexes of ombrogenous acrotelm or overflow mires.

Table 2/2 gives an overview of combinations of the peat formation strategy and origin of water with examples (as far as they are known). Some types thus far remain unidentified (and remain therefore without examples).

As a result of complex interactions of vegetation, water, and peat ("self-organisation"), mires may develop various morphological types, consisting of a characteristic landform (cross-sectional profile, Grossform) combined with characteristic configurations of microtopographic surface-elements (Kleinform)[46].

As well as such internal processes, external mechanisms may also be important in the configuration of peatland macro- and micro-structures. Frost activity may lead to features that also exist in mineral soils but which, in case of peat-covered areas, give rise to specific morphologic peatland types.

Parallel to polygon formation in mineral soils[47], "polygon mires" are formed in areas with continuous permafrost, especially in the arctic[48], but also in the east Siberian mountains as far as northern Mongolia[49]. The development of the polygon walls restricts water run-off during the short arctic summer, which provides enough water for peat formation[50]. Eventually such polygons may develop into "high centre polygons"[51]. Parallel to pingo formation in mineral soils[52], a local growth of ice nuclei may give rise to the origin of "palsa" (frost mound) mires and "peat plateau"[53] mires, that often start to develop because of the insulating capacity of *Sphagnum* and that "grow" because of the hygroscopic effect of ice. As this mound formation leads to

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[42] Agnew et al. 1993; Shearer 1997, personal communication from Ton Damman.
[43] Kaffke et al. 2000.
[44] Rieley & Page 1997.
[45] Cf. Driessen & Rochimah 1976; pers. comm. Herbert Diemont 1998.
[46] Examples include plateau bogs, concentric bogs, eccentric bogs, aapa fens etc. The origin and development of these striking patterns is still subject to considerable debate, particularly with regard to the processes that control them (see reviews in Glaser 1999 and Couwenberg & Joosten 1999).
[47] Alexandrova 1988.
[48] Cf. Tarnocai & Zoltai 1988, Glooschenko et al. 1993.
[49] Jeschke et al. 2001.
[50] Polygon mires are therefore a subtype of the water rise mire type.
[51] Tarnocai & Zoltai 1988, Glooschenko et al. 1993.
[52] For a review, see MacKay 1998.
[53] Åhman 1977, Zoltai et al. 1988, Glooschenko et al. 1993.

changes in local hydrological conditions, such ice core mire development leads to a change and often to an end to peat formation on the mound[54].

In mire types with water flow ice development leads to a stronger differentiation between, and a more explicit arrangement of, positive and negative microrelief elements (hummock and hollows, strings and flarks etc.)[55], which results in the development of “ribbed fens” / “aapa” mires and concentric and eccentric bogs[56].

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[54] Blyakharchuk & Sulerzhitsky 1999.

[55] Initial ice formation in surficial peat leads to an initial raising of the surface, because ice has more volume than a similar mass of water. As the more elevated elements get a thinner snow cover they are consequently less insulated in winter, and the ice nuclei thus get colder and expand. The drier surficial moss layer of the elevated element insulates the ice core against thawing in summer (Glooschenko et al. 1993). The formation of ice in the elevated elements also decreases their hydraulic conductivity (Glooschenko et al. 1993) and has a similar effect on pattern formation to that of stronger decomposition (cf. Couwenberg & Joosten 1999).

[56] Glooschenko et al. 1993, Jeschke et al. 2001.

Table 2/2: Hydrogenetic mire types

			level water level mires				inclining water level mires		
	peat formation strategy		**schwingmoor**	**immersion**	**water rise**	**flood**	**surface flow**	**acrotelm**	**percolation**
water supply			continuous	mostly continuous	Small	periodic	frequent	frequent	continuous
mire slope			none	none	None	none / small	small / large	small	small
internal water storage			large	mostly large	None	small / large	very small	rather large	large
effect on landscape water storage			storage <	storage <	storage <	storage < (>?)	storage >	storage >	storage >
Origin of the water	**ombrogenous** *bog*		ombrogenous schwingmoor mire *schwingmoor in bog*	ombrogenous immersion mire *terrestrialisation in bog*	ombrogenous water rise mire *water rise in bog complex*	ombrogenous flood mire *flood mire in bog*	ombrogenous surface flow mire *blanket bog*	ombrogenous acrotelm mire *raised bog*	ombrogenous percolation mire *percolation bog*
	geo-genous *fen*	**soli-genous**	soligenous schwingmoor mire *floating mat in moorpool*	soligenous immersion mire *terrestrialisation in moorpool*	soligenous water rise mire *Kesselmoor*	soligenous flood mire *Kessel-standmoor*	soligenous surface flow mires *sloopy fen, Hangmoor*	soligenous acrotelm mire	soligenous percolation mire *some sloping fens*
		litho-genous	lithogenous schwingmoor mire *floating mat on lake*	lithogenous immersion mire *lake terrestrialisation mire*	lithogenous water rise mire *groundwater rise mire*	lithogenous flood mire *river floodplain mire*	lithogenous surface flow mire *most spring mires*	lithogenous acrotelm mire	lithogenous percolation mire *typical percolation mire*
		thalasso-genous	thalassogenous schwingmoor mire	thalassogenous immersion mire *coastal terrestrialisation mire*	thalassogenous water rise mire	thalassogenous flood mire	thalassogenous surface flow mire	thalassogenous acrotelm mire	thalassogenous percolation mires
					coastal transgression mire, mangrove				

See footnote 29 re geogenous mires.

2.4 Extent and location of mires and peatlands[57]

There is a general lack of comprehensive and comparable data on the extent and location of mires and peatlands[58]. Because of different criteria used for definition (footnote 10) in different countries and different disciplines the available data do not compare like with like. However, in the absence of better information, the available data have been used here.

Subject to these caveats, this section sets out the most recent data on the former and present-day extent and distribution of mires, peatlands, and peat. Although many inventories of peatland resources exist[59], the status of mires has not hitherto been assessed systematically. Data were gathered from a wide variety of published sources and by consulting peatland experts, but a further inventory is certainly required[60].

2.4.1 The global picture

The peat formation process is strongly influenced by climatic conditions. Mires are predominantly northern ecosystems, especially abundant in continental boreal and

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[57] **Methodological remarks**: See Joosten 2002 for a detailed presentation and discussion of the basic data. For international comparison, existing data have been adjusted to a uniform standard. In this inventory (cf. § 2.1) 'peatlands' are areas with a minimum peat depth of 30 cm; peat consists of at least 30% (dry weight) organic material; 'mires' are peatlands with actual peat accumulation. The first criterion (depth of 30 cm.) excludes many (sub)arctic areas with a shallow peat layer, the second criterion is consistent with common definitions and does not greatly affect the inventory results. Because every peatland is or has been a mire, the former occurrence of mires have largely been reconstructed from the extent of peatlands and peat soils. For the 'original occurrence', the maximum mire extent in every region during the Holocene has been used. Applying a fixed time slice would have been complicated, as mires were already being destroyed in some regions, very early and extensively, while still expanding in other places. There are no indications that a substantial area of mires disappeared naturally since the Holocene maximum. Anthropogenic losses (losses due to human activity) also include indirect effects, e.g. consequent hydrological changes outside the mire area itself. Peat subsidence, oxidation, and erosion following human activities have changed many former peatlands into mineral soils according to geological or pedological definitions, excluding them from recent inventories. These sources of error have been corrected for by taking historic land use intensity into account. Human activities have not only led to a destruction of mires, but also to their origin and expansion (Moore 1975, Törnqvist & Joosten 1988). It is difficult to judge to what extent these processes would have taken place without human interference (Cf. Moore 1993). For this reason these possible 'constructive' activities have not been balanced with those of a 'destructive' nature. National borders have been changing considerably in the 20th century, particularly in Central Europe, complicating the use of older inventories. Where reliable data for individual countries are unavailable, the data for former collective states are presented (e.g. former Yugoslavia).
The figures of losses presented here are to a large extent "guesstimates", as adequate data are not available for the majority of countries. Available data are largely out-of-date, inconsistent, and difficult to compare. This applies to peatlands in general, but especially to mires. Little doubt can, however, exist about the order of magnitude and the trend of the changes. Data for different types of mires are even more difficult to obtain on a global scale, because of non-compatible classification systems and typologies.

[58] "Many of the data on peat resources are published on the basis of undisclosed modes of computation. Field mapping, coring, and analyses are often inadequate or wholly lacking, so that the published values for such cases should be considered as well-intentioned speculations rather than as reliable geological data." (Fuchsman 1980).

[59] Most recent world-wide overview Lappalainen 1996. See also Rubec 1996, Zoltai & Martikainen 1996.

[60] The absence of reliable data on the actual mire and peatland resource and its recent changes underlines the necessity for further inventory, as recommended by the 6th and 7th Conferences of the Contracting Parties of the Ramsar Convention and the Global Action Plan for Peatlands Theme 1.

sub-arctic regions, but they are also found in the tropics. The occurrence of mires and peatlands is strongly related to topography, with the greatest abundance found on flat land areas, such as western Siberia, the Hudson Bay Lowlands, SE Asian coastal plains, and the Amazon Basin. Figure 2/9 at the end of this Chapter outlines global peatland distribution[61].

The total area of boreal and sub-arctic mires is estimated to be 3,460 10^3 km^2.[62] The global peatland area is about 3,985 10^3 km^2 [63], but these estimations remain uncertain owing to different typologies in different countries.

Within the non-tropical world (Table 2/3) less mires have survived in continents with few resources (Africa, South America) than in continents with abundant resources (North America, Asia). Europe has suffered the largest losses, both absolutely and relative to its former mire extent. Approximately 80% of both the original tropical and non-tropical mires are still in a largely pristine condition[64]. In 25% of these pristine mires, both in permafrost and in tropical peatlands, net peat accumulation may have stopped because of natural processes and recent climate change[65]. But even then, peat is still actively accumulating on 60% of the former global mire extent.

Table 2/3: Former extent of mires in the non-tropical world and losses by human activities[66].

	Former extent of mires and peatlands	Current extent of peatlands		Current extent of mire losses	
	000 km^2	000 km^2	%	000 km^2	%
Europe	495			308	62
Asia	1070			90	8
Africa	10			5	50
North America	1415			65	5
South America	25			5	20
Australia	p.m.			p.m.	
Antarctica	p.m.			p.m.	
Total	> 3015			> 473	16

Outside the tropics, human exploitation has altered 500,000 km^2 of mires so severely that peat accumulation has stopped completely. Peat has been and continues to be extracted to be used for the purposes outlined in paragraph 3.2 in Chapter 3. Currently new peat extraction commences each year on some 10 km^2 of mire[67]. The available water, nutrients, organic soils, and space make mires also attractive for agriculture and forestry. 80% of global mire losses are attributable to the latter two types of land use (cf. Table 2/4). Prior to 1992, the global rate of mire destruction for

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[61] The map is taken from Lappalainen 1996.

[62] Gorham 1991.

[63] Lappalainen 1996.

[64] Joosten, 1999, Safford and Maltby, 1998.

[65] Vitt and Halsey 1994, Oeckel et al. 1993, 1995, Malmer & Wallén 1996, Vompersky et al. 1998, Sieffermann et al. 1988.

[66] Joosten 1999.

[67] Guesstimate based on production figures corrected for extraction on already-drained areas. Additional contemporary information is sought on this figure.

forestry amounted to 4,500 km^2, that for agriculture to 1,000 km^2 per year[68]. These rates are an order of magnitude larger than the mean annual mire expansion rate during the Holocene. As a result, the global mire resource is decreasing by approximately 0.1% **net** per year[69].

Table 2/4: Causes of anthropogenic mire losses in the non-tropical world[70].

	1000 km^2	%
Agriculture	250	50
Forestry	150	30
Peat extraction	50	10
Urbanisation	20	5
Inundation	15	3
Indirect losses (erosion, other)	5	1
Total	490	100

2.4.2 Europe

Its long history, high population pressure, and climatic suitability for agriculture have made Europe the continent with the largest mire losses (Fig. 2/4). Peat has ceased to accumulate in 60% of the former mire area. Possibly 10 - 20% of the original mire area no longer exists as peatland. In many European countries ≤ 1 % of the original resource remains (Table 2/5). Denmark and the Netherlands succeeded in destroying a dominant landscape type almost completely. Only Russia, Norway and Sweden still have more than half of their original mire area left (Table 2/5).

The European experience shows clearly that an abundance of mires is no guarantee of their long-term survival. Finland has lost almost 60% of its formerly extensive mire area, largely by drainage for forestry since the 1950s[71]. Ireland, where mires originally covered 17% of the country, has lost 93% of its raised bog and 82% of its blanket bog mire resource[72]. The mires of Polesia in Belarus and Ukraine, one of the largest continuous mire areas of the former Soviet Union have largely been drained in the 1970s and 1980s[73].

Mires have primarily survived in the northern parts of Europe, where peat accumulation rates are relatively low. Destroyed mires are mainly found in the other parts of Europe, in some of which (the more continental regions) peat losses by oxidation are extremely rapid.

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[68] Immirzi & Maltby 1992. Additional contemporary information is sought on this figure. It is likely that the order of magnitude of the combined figure remains valid, given recent large projects in South East Asia.

[69] Additional contemporary information is required to verify this figure.

[70] Joosten 1999.

[71] Paavilainen & Päivänen 1995.

[72] Foss 1998.

[73] Bambalov 1996, Belokurov et al 1996.

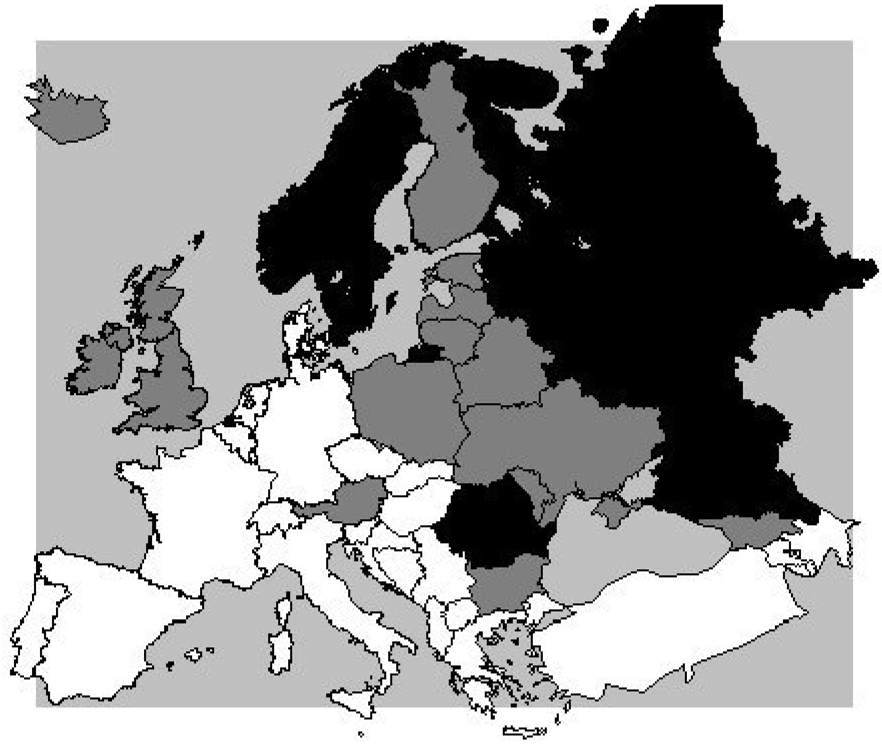

Figure 2/4: Remaining mire area in Europe per country. Black: > 50 % of the original mire area remaining; grey: 10 - 50 % remaining; white: < 10% remaining. No differentiation is made within countries [74].

Tables 2/5 to 2/9 which follow give the estimated peatland/mire area where the peat is more than 30 centimetres thick (> 30 cm peat) and contains more than 30% organic material (> 30% organic material). The areas are given in km^2 per country or region grouped by continent. Total area (1998) of each country or region is given according to Encarta. The following figures are used with the following meanings:

0 = no peatland occurrences encountered, peatlands probably absent.
? = no peatland occurrences encountered, peatland probably present.
1 = peatland occurrence recorded, but may be (substantially) smaller than 1 km^2.

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[74] Joosten & Couwenberg 2000.

Table 2/5: Mire and peatland resources of Europe

Estimated peatland/mire area (> 30 cm peat, > 30% organic material) per country/region in km^2. Total area (1998) of country/region according to Encarta.

0 = no peatland occurrences encountered, peatlands probably absent
? = no peatland occurrences encountered, peatland probably present
1 = peatland occurrence recorded, but may be (substantially) smaller than 1 km^2

Country	Total area (km^2)	Original peatland area (km^2)	2002 peatland area (km^2)	2002 mire area (km^2)
Albania	28,748	600	179	4
Andorra	468	10	5	2
Austria	83,858	500	200	100
Azores	2,335	1	1	1
Belarus	207,595	29,390	23,500	11,412
Belgium	30,528	700	160	3
Bosnia and Herzegovina	51,129	200	150	10
Bulgaria	110,994	800	25	5
Channel Islands	205	?	?	?
Croatia	56,510	5	1	1
Cyprus	9,251		1	
Czech Republic	78,864	500	200	50
Denmark	43,094	10,000	1,400	50
Estonia	45,227	11,000	10,000	3,000
Faroe Islands	1,400	30	30	25
Finland	338,145	96,000	85,000	32,000
France	543,965	2,000	1,500	100
FYRO Macedonia	25,713	50	30	5
Germany	356,970	16,250	13,000	100
Gibraltar	6	0	0	0
Greece	131,957	500	71	13
Hungary	93,030	1,000	330	30
Iceland	103,000	9,000	8,000	3,500
Ireland	70,273	12,000	11,500	2,100
Isle of Man	572	?	?	?
Italy	301,323	1,200	300	30
Jan Mayen	373	0	0	0
Latvia	63,700	7,000	6,600	4,663
Liechtenstein	160	1	1	1
Lithuania	65,300	4,800	3,520	750
Luxembourg	2,586	4	3	1
Madeira (Portugal)	794		???	
Malta	316	1	0	0

Country (continued)	Total area (km^2)	Original peatland area (km^2)	2002 peatland area (km^2)	2002 mire area (km^2)
Moldova	33,700	30	10	1
Monaco	2	0	0	0
Netherlands	41,526	15,000	2,350	150
Norway	385,639	30,000	28,000	22,000
Poland	312,684	20,000	12,500	2,000
Portugal	92,345	200	20	2
Romania	237,500	2,000	1,000	500
Russia European part	17,075,200	343,000	213,000	150,000
San Marino	61	0	0	0
Slovakia	49,035	260	26	13
Slovenia	20,253	150	100	10
Spain	505,990	300	60	10
Svalbard /Spitsbergen	62,160	10	10	10
Sweden	449,964	70,000	66,000	55,000
Switzerland	41,285	2,000	300	200
Ukraine	603,700	11,000	8,000	5,800
United Kingdom	244,110	19,000	17,500	1,000
Vatican City	0,44	0	0	0
Yugoslavia (Serbia and Montenegro)	102,173	1,000	300	50
Total	20,119,741	717,492	514,883	294,702

2.4.3 Asia

Table 2/6 Mire and peatland resources of Asia

Estimated peatland/mire area (> 30 cm peat, > 30% organic material) per country/region in km^2. Total area (1998) of country/region according to Encarta.

0 = no peatland occurrences encountered, peatlands probably absent
? = no peatland occurrences encountered, peatland probably present
1 = peatland occurrence recorded, but may be (substantially) smaller than 1 km^2

Country	Total area	Peatland area
Afghanistan	652,225	120
Armenia	29,800	55
Azerbaijan	86,600	10
Bahrain	707	0
Bangladesh	147,570	300
Bhutan	47,000	1
Brunei	5,765	1,000
Cambodia	181,035	7,000
China	9,571,300	7,000
East-Timor	14,609	???
Fiji	18,376	40
Georgia	69,700	200
India	3,165,596	300
Indonesia	1,904,443	270,000
Iran	1,648,000	10
Iraq	438,317	100
Israel	21,946	40
Jammu and Kashmir	222,236	100
Japan	377,837	2,000
Jordan	89,556	1
Kazakhstan	2,717,300	50
Kuwait	17,818	0
Kyrgyzstan	198,500	100
Laos	236,800	200
Lebanon	10,452	1
Malaysia	329,758	25,000
Maldives	298	1
Mongolia	1,566,500	50
Myanmar	676,552	500
Nepal	147,181	1
North Korea	120,538	1,300
Oman	309,500	0
Pakistan	796,095	100
Papua New Guinea	462,840	28,942
Philippines	300,000	100
Qatar	11,427	0

Country (continued)	Total area	Peatland area
Russia Asian part		1,177,000
Saudi Arabia	2,240,000	0
Seychelles	454	0
Singapore	648	1
South Korea	99,268	5
Sri Lanka	65,610	35
Syria	185,180	3
Taiwan	36,000	???
Tajikistan	143,100	???
Thailand	513,115	500
Turkey	779,452	120
Turkmenistan	488,100	0
United Arab Emirates	83,600	0
Uzbekistan	447,400	???
Vietnam	331,690	1,000
Yemen	527,970	???
Total	32,532,764	1,523,286

2.4.4 Africa

Table 2/7 Mire and peatland resources of Africa

Estimated peatland/mire area (> 30 cm peat, > 30% organic material) per country/region in km^2. Total area (1998) of country/region according to Encarta.

0 = no peatland occurrences encountered, peatlands probably absent
? = no peatland occurrences encountered, peatland probably present
1 = peatland occurrence recorded, but may be (substantially) smaller than 1 km^2

Country	Total area	Peatland area
Algeria	2,381,741	10
Angola	1,246,700	100
Benin	112,622	100
Botswana	581,730	3,000
Burkina Faso	274,200	10
Burundi	27,834	150
Cameroon	475,442	100
Canary Islands	7,273	0
Cape Verde	4,033	0
Central African Republic	622,436	100
Chad	1,284,000	10
Comoros	1,862	???
Congo	342,000	4,000
Democratic Republic of the Congo	2,344,885	14,000
Djibouti	23,200	0
Egypt	997,739	10
Equatorial Guinea	28,051	???
Eritrea	121,144	???
Ethiopia	1,133,380	200
Gabon	267,667	80
Ghana	238,500	100
Guinea	245,857	1,000
Guinea-Bissau	36,125	???
Ivory Coast	322,462	300
Kenya	582,646	1,600
Lesotho	30,355	20
Liberia	99,067	400
Libya	1,757,000	0
Madagascar	587,041	1,500
Malawi	118,484	900
Mali	1,240,192	400
Mauritania	1,031,000	60
Mauritius	2,040	1
Morocco	453,730	10
Mozambique	799,380	1,000
Namibia	824,269	10
Niger	1,267,000	30
Nigeria	923,768	120

Country (continued)	Total area	Peatland area
Réunion	2,512	1
Rwanda	26,338	800
São Tomé and Príncipe	1,001	???
Senegal	196,722	20
Sierra Leone	71,740	1
Somalia	637,700	0
South Africa	1,219,090	300
St Helena (UK)	324	80
Sudan	2,505,800	1,400
Swaziland	17,363	???
Tanzania	945,100	100
The Gambia	11,295	100
Togo	56,785	10
Tunisia	164,418	1
Uganda	241,138	14,000
Zambia	752,614	10,000
Zimbabwe	390,759	1,400
Total	30,077,554	57,534

2.4.5 North, Central and South America

Table 2/8 Mire and peatland resources of North, Central and South America

Estimated peatland/mire area (> 30 cm peat, > 30% organic material) per country/region in km^2. Total area (1998) of country/region according to Encarta.

0 = no peatland occurrences encountered, peatlands probably absent
? = no peatland occurrences encountered, peatland probably present
1 = peatland occurrence recorded, but may be (substantially) smaller than 1 km^2

Country	Total area	Peatland area
Antigua and Barbuda	442	???
Argentina	2,780,400	2,400
Bahamas	13,939	10
Barbados	430	0
Belize	22,965	680
Bermudas	53	1
Brazil	8,547,404	55,000
Bolivia	1,098,581	20
Canada	9,970,610	1,235,000
Chile	756,626	10,470
Colombia	1,141,748	10,000
Costa Rica	51,060	370
Cuba	114,525	6,000
Dominica	750	1
Dominican Republic	48,400	10
Easter Island (Chile)	117	1
Ecuador	272,045	5,000
El Salvador	21,041	90
Falkland Islands / Islas Malvinas	12,173	11,510
French Guiana	91,000	1,620
Galápagos Islands (Ecuador)	7,844	1
Greenland	2,175,600	5
Grenada	344	???
Guadeloupe (France)	1,780	2
Guatemala	108,889	1
Guyana	214,969	8,000
Haiti	27,750	1
Hawaii (USA)	16,179	1
Honduras	112,492	4,530
Jamaica	10,991	100
Juan Fernández Islands (Chile)	180	1
Mexico	1,964,382	1,000
Nicaragua	129,494	3,710
Panama	75,517	7,870
Paraguay	406,752	100
Peru	1,280,000	50,000
Puerto Rico	9,104	100
St Kitts and Nevis	269	1

Country (continued)	Total area	Peatland area
St Lucia	616	???
St Vincent and the Grenadines	389	???
Suriname	163,265	1,130
Trinidad and Tobago	5,128	10
United States of America	9,629,047	625,000
Uruguay	176,215	1,000
Venezuela	912,050	10,000
Total	42,373,555	2,050,746

2.4.6. Australia, New Zealand, the Pacific and Antarctica

Table 2/9 Peatland resources of Australia, New Zealand, the Pacific and Antarctica

Estimated peatland/mire area (> 30 cm peat, > 30% organic material) per country/region in km^2. Total area (1998) of country/region according to Encarta.

0 = no peatland occurrences encountered, peatlands probably absent
? = no peatland occurrences encountered, peatland probably present
1 = peatland occurrence recorded, but may be (substantially) smaller than 1 km^2

Country	Total area	Peatland area
American Samoa (USA)	195	0
Antarctica	14,200,000	3,000
Auckland Islands (New Zealand)	570	560
Australia (excl. Tasmania)	7,614,500	1,330
Chatham Islands (New Zealand)	963	450
Guam (USA)	541	0
Kiribati	811	2
Marshall Islands	181	0
Martinique	1,102	1
Micronesia (Federated States of)	702	33
Nauru	21	0
New Caledonia and Dependencies (France)	19,058	1
New Zealand	270,534	2,600
Palau	488	1
Samoa	2,831	1
Solomon Islands	27,556	10
Tasmania	68,331	20
Tonga	750	???
Tuvalu	26	0
Vanuatu	12,190	???
Total	22,221,350	8009

2.5 Rates of peat and carbon accumulation[75]

Global interest related to rising atmospheric CO_2 content has led to numerous attempts to ascertain the role of peatlands in the global carbon (C) cycle as sinks for organic C[76]. Peat deposits are characterised by a high C content, about 50% of the dry organic matter. A high abundance of peat thus signals a significant net transfer of C to the soil.

In a natural state, mires accumulate C because the rate of biomass production is greater than the rate of decomposition. The accumulation of peat involves an interaction between plant productivity and C losses through the process of decay, leaching, mire fires and deposition of C into the mineral soil beneath peat layers.

Most peat-forming systems consist of two layers: an upper aerobic layer of high hydraulic conductivity, the acrotelm, in which the rate of decay is normally high; and the predominantly anaerobic underlying layer, the catotelm, of low hydraulic conductivity with a lower rate of decay[77]. The boundary between these layers is approximately at the mean depth of the minimum water table in summer, about 10-50 cm below surface[78], depending on the mire type and the micro-sites of the mire area. Carbon is added to the surface of the peat through net primary production, the acrotelm takes in CO_2, converts it to plant material, and finally passes it on to the catotelm. About 5-10% of the biomass produced annually ends up as peat[79]. Most of the C loss occurs relatively quickly and with increasing age, decay slows considerably[80]. Thus, the catotelm is the true site of peat accumulation, where slow anaerobic decomposition results in additional C loss. Generally, as peat accumulates the rate of loss from the whole catotelm increases, because there is more peat to decay.

The recent rate of C accumulation normally refers to young peat layers some hundreds of years old. Depending on the mire type and decay rates, the recent C accumulation can range from 10 to 300 g m^{-2} yr^{-1} in boreal regions[81]. The long-term apparent rate of C accumulation (LORCA) throughout the Holocene is relatively easy to calculate once a profile of dry bulk density from surface to the bottom of the mire and a basal date have been obtained. Analysis of 1302 dated peat cores from Finnish mires gives a LORCA of 18.5 g m^{-2} yr^{-1} for the entire Finnish undrained mire area[82], indicating great C loss compared to the recent average C accumulation rates. Generally, bogs have a higher average LORCA than fens. In Russian Karelia, the LORCA for the whole Holocene can be calculated as 20 g m^{-2} yr^{-1},[83] 19.4 g m^{-2} yr^{-1} in continental western Canada[84], and 17.2 g m^{-2} yr^{-1} in West Siberian[85] mires[86]. In arctic and subarctic regions the LORCA normally range from 1.2 to 16.5 g m^{-2} yr^{-1}.[87]

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[75] Based on information from Jukka Turunen.

[76] E.g. Botch et al. 1995; Kauppi et al. 1997; Clymo et al. 1998; Turunen et al. 1999; Vitt et al. 2000; Turunen et al. 2000.

[77] Ingram 1978; Clymo 1984.

[78] Ivanov 1981; Clymo 1984.

[79] Clymo 1984; Gorham 1991; Warner *et al*. 1993

[80] Tolonen *et al*. 1992

[81] Tolonen & Turunen 1996.

[82] Turunen et al. 2000a.

[83] Elina et al. 1984.

[84] Vitt et al. 2000.

It is important to emphasise that LORCA can be misleading simply because of the ongoing decay in the catotelm. However, LORCA provides insight into the balance between long-term input and decay. The true net rate of C accumulation (ARCA) can be determined by peat accumulation models[88], and has been estimated as 2/3 of LORCA[89]. The relationship of these three different measures of peat accumulation rate is illustrated in Figure 2/5. The differences between these three different measures increase with time.

The mineral subsoil under mires is an additional C sink that may account for approximately 5% of the unaccounted C in the global carbon budget[90].
The present-day sequestering rate of C in global mires is estimated to be 40-70 $\cdot 10^{12}$ g y^{-1} (= 40 – 70 million tonnes C y^{-1}) [91].

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[85] Turunen et al. 2000b. These data concern old watershed ombrotrophic mires in the middle taiga zone. New research gives LORCA values for the south taiga zone of West Siberia of 41.2±12 (SE) (n= 14), with values ranging from 24.9 to 56.4 g m^{-2} yr^{-1} (pers. comm. Elena Lapshina, cf. Lapshina et al. 2001).

[86] These new estimates are lower than earlier estimates of 26-30 g m^{-2} yr^{-1} for boreal and sub-arctic regions, e.g. Gorham 1991; Botch et al. 1995; Tolonen & Turunen 1996; Clymo et al. 1998. The difference in LORCA estimates is mainly due the fact that shallow mires have been under-represented in previous studies. There has also been great uncertainty in average dry bulk densities of peat layers. The bias of data towards deeper peat deposits is also evident through the classification of mires in northern latitudes based on the minimum thickness of peat deposits, as noted in Note 13 above. For example, the minimum thickness for geological mires in Finland, Canada and Russia is 30, 40 and 70 cm (Lappalainen & Hänninen 1993, Zoltai et al. 1975, Botch and Masing 1979), respectively.

[87] Summarised by Vardy *et al*. 2000.

[88] Clymo 1984, Clymo et al. 1998.

[89] Tolonen & Turunen 1996.

[90] Turunen et al. 1999.

[91] Gorham 1991, Clymo et al. 1998, Turunen et al. 2000a.

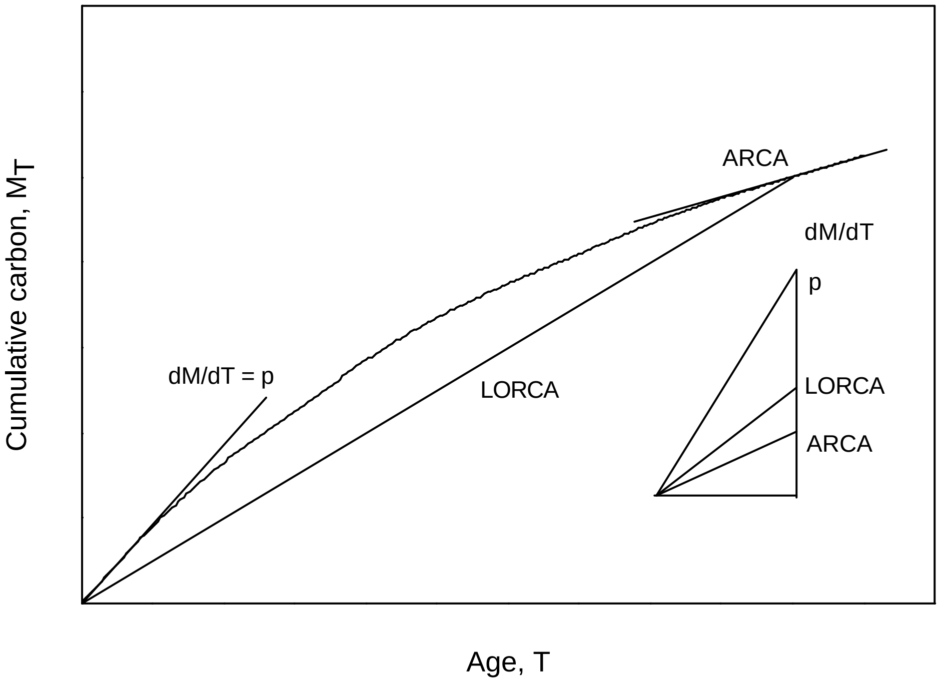

Figure 2/5: Relationship of three different commonly used measures of ”peat accumulation rate”. The slope at the origin is p, the rate at which dry matter is added to the system; the chord from the origin to the present is LORCA, the long term apparent rate of carbon accumulation.; the slope at the present time is ARCA, the true rate of carbon accumulation. In the inset these three rates are compared. The numerical values are always, for T>0, in the order p>LORCA>ARCA. It is often assumed (wrongly, if there is any decay) that p = LORCA = ARCA[92].

270-370·10^{15} g of carbon (C) is stored in the peats of boreal and sub-boreal peatlands alone[93]. This means that globally peat represents about one third of the total global soil carbon pool (being 1395·10^{15} g)[94]. It contains an equivalent of approximately 2/3 of all carbon in the atmosphere and the same amount of carbon as all terrestrial biomass on the earth[95].

Peat extraction is presently responsible for oxidative peat losses of approximately 15·10^{12} g of carbon per year[96], while agriculture and forestry consume 100 – 200 ·10^{12} g C per year[97]. As global peat accumulation is about 40 - 70 ·10^{12} g C per year, the

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[92] After Clymo et al. 1998.

[93] Turunen et al. 2000a. The large range of these C storage estimates reflects the uncertainty in the depth and dry bulk densities of global peat deposits.

[94] Post et al. 1982.

[95] www.wri.org/climate/carboncy.html, Houghton et al. 1990.

[96] This figure does not include carbon emissions from peat oxidation in peatlands drained for and by extraction.

[97] Immirzi & Maltby 1992.

world's peatlands have changed from a carbon sink to a carbon source, with an annual global loss of the peat carbon resource of about 0.5 ‰[98].

2.6 Characteristics of mires and peatlands

The essential features of mires and peatlands – peat accumulation and peat storage – are associated with a number of other characteristics[99] that distinguish them from most other ecosystem types. As peatlands largely consist of water[100], hydrological characteristics play a central role. There follow four characteristics or processes which lie at the basis of many peatland-specific conflicts. They are therefore especially relevant to the rest of this document. (The characteristics of mires and peatlands that relate directly to "benefits", "resources" and "services" are dealt with in extenso in Chapter 3).

i) *Their principal characteristic is that the water level should - on average in the long-term - be near the surface[101] for a mire to exist, i.e. to make peat accumulation possible.*

Water levels which are too low[102] and too high[103] are detrimental to peat accumulation. This means that activities which substantially lower or raise the water level in peatlands, including their use for many production and carrier functions, negatively affect their peat accumulation capacity and the associated functions.

ii) *Oxidation processes[104] change the physical, chemical, hydraulic, and biological properties of peats and peat soils, and these changes are often irreversible[105].*

Drainage of mires brings about changes in the properties of the peat and hence in the functioning of the peatland ecosystem. Processes induced by drainage include among others[106]:

- subsidence, i.e. the lowering of the surface,
- shrinkage and swelling, and increased soil loosening by soil organisms,
- increased mineralisation (conversion of organic material to mineral substances).

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[98] See also Armentano & Menges 1986, Botch et al. 1995, Lappalainen 1996, Vompersky et al. 1996, Joosten 1999.

[99] See also §§ 2.2, 2.3, and 2.7. The characteristics outlined in this chapter are principally those relevant to the functions discussed in Chapter 3.

[100] Undrained peatlands contain between 85% and 95% water, making them often "wetter" than unskimmed milk. Undrained peatlands can often be regarded as "mounds of water kept together by some organic material".

[101] = just below, at, or just above the surface, cf. Edom 2001a.

[102] See § 2.1.2, Ivanov 1981, Koppisch 2001.

[103] Because of erosion and the lack of oxygen and carbon dioxide, c.f. Ivanov 1981, Ingram & Bragg 1984, Alexandrov 1988, Sjörs 1990, Lamers et al. 1999.

[104] Resulting from aeration or input of specific ions (e.g. nitrates, iron, sulfates) (Edom 2001a, Koppisch 2001).

[105] Kløve 2000, Edom 2001a, Stegmann & Zeitz 2001, Pozdnyakov et al. 2001. Similar changes also result from the imposition of weight.

[106] Schmidt et al. 1981.

As peat largely consists of water[107], drainage of peatlands leads to subsidence[108] and peat oxidation[109] and compaction. Consequently the hydraulic properties[110] (those which govern water movement) of the peats change. This may decrease the peatland's capacities for water storage and regulation[111]. These processes also take place in deep tropical peats[112]. The shrinkage and swelling of the peat as a result of increased water level fluctuations cause the formation of vertical and horizontal fissures, particularly in drier climates. These impede upward (capillary) water flow and lead to a more frequent and deeper drying out of the soil[113]. Through increased activity of soil organisms, drained peat soils become loosened and fine-grained and may eventually become unrewettable[114].

Aeration leads to oxidation and mineralisation of the uppermost peat layers. It also produces remobilisation of formerly fixed substances, and increased emissions of greenhouse gasses[115] and nutrients[116]. The dry peat following drainage can result in dust storms and fires below the surface[117]. Subsidence and oxidation lower the peatland surface[118], necessitate a continuous deepening of drainage ditches (the "vicious circle of peatland utilisation"[119]), and make drainage increasingly difficult[120].

These processes take place world-wide wherever the protective natural vegetation of peatlands is removed and the peat is drained. They are accelerated by tillage[121]. Most types of peatland agriculture show oxidation rates ranging from some millimetres up to several centimetres of peat per year depending on the microclimate[122]. In general the addition of lime, fertilisers and mineral soil material increases the rate of mineralisation in drained peatlands. In the case of agriculture these processes frequently lead to the abandonment of peatlands[123].

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[107] Moisture contents of undrained peats of 90 - 95 % are not uncommon (cf. Segeberg 1960).

[108] Subsidence is the lowering of the peatland surface level as a result of decreased water pressure. A lowering of the moisture content of peat from 95% to 90%, for example, halves the volume of the water in the peat, and affects substantially the height of the mire (Segeberg 1960). Five years after drainage, the height of a bog in Germany had already decreased by more than 2 metres (Baden 1939). Construction of a road through Clara Bog (Ireland) lowered the surface in the centre of the remaining mire by possibly 4 metres (Van der Schaaf 1999).

[109] See Figure 2/2 and § 2.3.

[110] Including porosity, storage coefficient, and hydraulic conductivity (Edom 2001a).

[111] Edom 2001b. See also paragraph 3.4.3 (o).

[112] Suhardjo & Driessen 1977, Maltby 1986, Stewart 1991.

[113] Cf. Brandyk & Skapski 1988.

[114] Stegmann & Zeitz 2001.

[115] See § 3.4.3. (m), Table 2/17 and 2/18 and Fig. 2/8.

[116] Including nitrates and phosphates, which may cause water eutrophication (Gelbrecht et al. 2001).

[117] Maltby 1986.

[118] Long-term observations show height losses of up to 4 metres in 130 years, c.f. Hutchinson 1980, Eggelsmann 1990.

[119] "Teufelskreis der Moornutzung", c.f. Kuntze 1982.

[120] Gravity drainage becomes increasingly difficult as the water level difference with the main drainage canal (river, sea) becomes smaller. When water level differences - as in case of many fens - become negative, the instalment of polders - including dike construction and maintenance and continuous pumping - becomes necessary.

[121] See § 3.4.1. (ea).

[122] Eggelsmann 1976, 1990; Dradjad et al. 1986, Stegmann & Zeitz 2001.

[123] The rate of surface lowering in Florida peatlands, for example, is 2.5 cm per year, even with careful management. It is estimated that market garden crops can only be grown on an area for about 20 years (Stewart 1991). Oxidation can eventually lead to the loss of the entire peat profile and the exposure of underlying nutrient-poor substrates with waterlogged, potentially toxic (acid sulphate) soils. In sub-coastal situations this may be followed by marine inundation (Page & Rieley 1998). A combination of

iii) *In mires, very close relationships exist between the vegetation type, the peat type occurring at the surface, and the hydrologic properties of the site (water levels, water level fluctuations, water quality).*

Because of this intimate interaction, changes in one of these components lead to changes in the properties of the other components. A change in mean water level of some centimetres in a mire may lead to a change in the vegetation[124] and consequently to changes in the peat that is formed[125].

iv) *Water flow connects the catchment area with the peatland[126] and various parts of a peatland with each other[127].*

A change in the water flow of the catchment or of part of the peatland may, therefore, influence every part of a peatland[128]. Such interconnections may function over many kilometres[129].

2.7 Peatlands as habitats and ecosystems

Mires and peatlands are generally characterised by extreme conditions, which call for special adaptations of the species that live there.

The high water level and the consequent scarcity of oxygen in the root layer[130] requires from mire plants adaptations in

- physiology, to deal with the toxic substances[131] that originate under anaerobic conditions,
- anatomy, such as aerenchyms, plant tissues that lead oxygen from the parts above ground to the root system[132], and/or
- growth form, including aerial roots that protrude above ground or (paradoxically) xeromorphy (morphological adaptation to dry conditions) that reduces water movement in the soil zone around the roots by restricting evapotranspiration losses and so increases the time available for the oxidation of phytotoxins[133], or that enables plants to root solely in the uppermost peat layers

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socio-economic changes, drainage problems, and soil deterioration has recently led to a massive abandonment of agricultural peatland areas in Central Europe (Succow & Joosten 2001).

[124] Ivanov 1981, Davis et al. 2000. Small hydrologic changes may hence induce large losses in biodiversity.

[125] Changes in the vegetation and consequently the peat by century-long mowing of sedge mires in many parts of Europe is possibly, next to shallow drainage of peatland and catchment, one of the prime reasons for scrub encroachment after abandonment of these originally open species-rich fens (cf. Wassen & Joosten 1996).

[126] E.g. Wassen & Joosten 1996, Edom 2001b.

[127] E.g. Glaser et al. 1997, Couwenberg & Joosten 1999, Edom 2001b.

[128] Kulczynski 1949, Ivanov 1981.

[129] Cf. Schot 1992, Joosten 1994, Van Walsum & Joosten 1994, Glaser et al. 1997, Wetzel 2000.

[130] Cf. Hook & Crawford 1978.

[131] Including possible high concentrations of sulphides and reduced iron and manganese (cf. Sikora & Keeney 1983).

[132] Cf. Grosse et al. 1992.

[133] Armstrong 1975

Peat accumulation in mires results in an immobilisation of nutrients in the newly formed peat and a consequent scarcity of nutrients. Nutrients may further fail because of limited supply (as in ombrogenous mires) or inaccessibility (as in calcareous mires, where all phosphates are bound to calcium[134]). Mire plants therefore generally show various adaptations to nutrient shortage:

- Moss species have cation exchange mechanisms, that enable them to exchange the rare cations in the water for self-produced hydrogen ions. This mechanism is particularly well developed in *Sphagnum*[135]
- Trees often show stunted growth, e.g. conifers and *Nothofagus* species[136]
- Many species have large rhizome and root systems that function for several years[137]
- Dwarf shrubs are slow-growing and often have perennial or “xeromorphic” (small and thick) leaves, which reduce their need for nutrients, e.g. Ericaceae, Empetraceae, Betulaceae, Salicaceae, Rosaceae, Myrtaceae
- Monocotyledon[138] herbs often have perennial or thin, blade-like leaves, e.g. Cyperaceae, Poaceae, Juncaceae, Juncaginaceae, Scheuchzeriaceae, Iridaceae, Restionaceae[139],
- Various dicotyledon vascular plants on mires are parasitic and have developed specialized organs to “steal” nutrients from other plants, e.g. Scrophulariaceae, Santalaceae
- Other herbs are carnivorous[140] and catch insects for food, e.g. Droseraceae, Lentibulariceae, Sarraceniaceae, Cephalotaceae, Nepenthaceae
- Many higher plants live in symbiosis with fungi or bacteria that help them to retrieve rare nutrients[141] (e.g. Orchidaceae, Ericaceae[142]) or that fix atmospheric nitrogen (e.g. in *Alnus, Myrica*, and Fabaceae[143]).

A third complicating factor for plant growth is the continuous cover by accumulating “peat” and the constantly rising water levels[144]. Perennial plants must be capable of continuous upward growth and must be able to develop new roots every year on a higher level[145]. Few tree species are able to make new roots on the stem[146] leading to a general scarcity or stunted growth of trees in temperate and boreal bogs.
The growth of tall and heavy trees is also hampered because the surface-rooting trees easily fall over or, in mires with a spongy peat structure such as percolation and schwingmoor mires, drown under their own weight.

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[134] Boyer & Wheeler 1989.

[135] Clymo & Hayward 1982.

[136] Roosaluste 1982.

[137] Bliss 1997

[138] The flowering plants are subdivided into two large groups: the monocotyledons and the dicotyledons. In dicotyledons the embryo sprouts two cotyledons, which are seed leaves that serve to provide food for the new seedling. Monocotyledon embryos only have one such cotyledon. The two groups differ in a number of ways. Dicotyledons have floral organs (sepals, petals, stamens, pistils) in multiples of four or five, monocotyledons generally in multiples of three. The leaves of dicots have a netlike vein pattern, while those of monocots have parallel veining.

[139] Tüxen 1982.

[140] Givnish 1988

[141] Marschner 1995. See also Keddy 2000 who points to the fact that compared to other habitats mycorrhizae are relatively uncommon in wetlands and soil nutrient gradients may therefore be even more important in wetlands than in terrestrial habitats.

[142] Burgeff 1961.

[143] Hall et al. 1979, Chartapaul et al. 1989.

[144] Cf. Van Breemen 1995.

[145] Grosse-Brauckmann 1990, Malmer et al. 1994.

[146] *Picea mariana* in North America is an important exception.

Peats generally conduct heat poorly, causing a relatively short growing season for vascular plants in boreal areas. The prevalence of water and the limitations to tree growth provide mires with a climate that is generally cooler and more extreme than that of its surroundings[147], which leads to ecosystem features which are not typical of the climate zone. In forested boreal and temperate areas, open mires represent tundra-like conditions and often harbour "ice-age relicts" and disjunct[148] species and communities[149].

The acidity caused by cation exchange and organic acids, especially in the case of *Sphagnum*-dominated mires[150] and the production of toxic organic substances[151] form additional handicaps to organisms.

As a result of these extreme conditions, mires in general are relatively poor in species as compared with mineral soils in the same biographic region. This is true for temperate, boreal and tropical mires[152]. Many peatland species are, however, strongly specialised and not found in other habitat types.

The fauna of mires is also generally influenced by the scarcity of water nutrients and ions, the acidity of the water, the relative coolness, and (in the case of non-forested mires) the strong temperature fluctuations. *Sphagnum*-dominated mires in particular are characterised by poor nutrient availability because "almost nothing eats *Sphagnum*"[153]. The scarcity of ions in the mire water requires considerable energy to maintain the chemical concentration in the body water (osmosis!), which probably causes the pigmy forms of many mire organisms. In acid mires, Gastropoda (snails), Bivalvia (molluscs) and Crustaceae (crayfish) are generally absent, because of the scarcity of calcium carbonate. The radiation intensity and temperature fluctuations cause a melanismus (dark colour)[154].

Their inaccessibility and peacefulness have frequently made mires the last refuges of species that have been expelled from intensively-used surroundings[155]. In this manner the peat swamp forests of Borneo and Sumatra are among the last refuges for orang utan (*Pongo pygmaeus pygmaeus*) in the midst of intensively-logged forests on mineral soils[156]. Similar phenomena are also known in Europe and North America[157].

Various mire types develop sophisticated self-regulation mechanisms over time[158] and acquire an exceptional resilience against climatic change[159]. As a result such mires

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[147] See also § 3.2.3 (n).

[148] Disjunct species are related, through ancestors, to populations found in distant locations from which they have been separated by time and geologic events. Arctic/alpine disjunct species, for example, occur in the Arctic and in various alpine areas outside the Arctic, but not inbetween. Their distribution was fractured by climatic change.

[149] Peus 1932, 1950, Burmeister 1990, Masing 1997, Schwaar 1981.

[150] Ross 1995, Van Breemen 1995.

[151] Verhoeven & Liefveld 1997, Salampak et al. 2000.

[152] Rieley 1991, Page et al. 1997, Rieley et al 1997.

[153] Clymo & Hayward 1982.

[154] Burmeister 1990.

[155] Burmeister 1990.

[156] Page et al. 1997. See also the long list of endangered mammal, bird, and reptile species that find a refuge in Southeast Asian peat forests in Page & Rieley (1998).

[157] Cf. for example Van Seggelen 1999 and § 3.4.1 (d).

[158] Cf. Ivanov 1981, Joosten 1993.

[159] Couwenberg et al. 2000.

have characteristics similar to a living organism and are thus almost ideal examples of ecosystems. Related features are the inherent tendency of mires to develop complex surface patterning[160] and ecosystem biodiversity[161] (see Table 3/20).

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[160] Cf. various papers in Standen et al. 1999.

[161] Couwenberg 1998, Couwenberg & Joosten 1999. See also § 3.4.4 (u).